A CATALOGUE OF NATURE-BASED SOLUTIONS FOR COASTAL RESILIENCE

GLOBAL PROGRAM ON NATURE-BASED SOLUTIONS FOR CLIMATE RESILIENCE
JAPANGov THE GOVERNMENT OF JAPAN
GFDRR Global Facility for Disaster Reduction and Recovery
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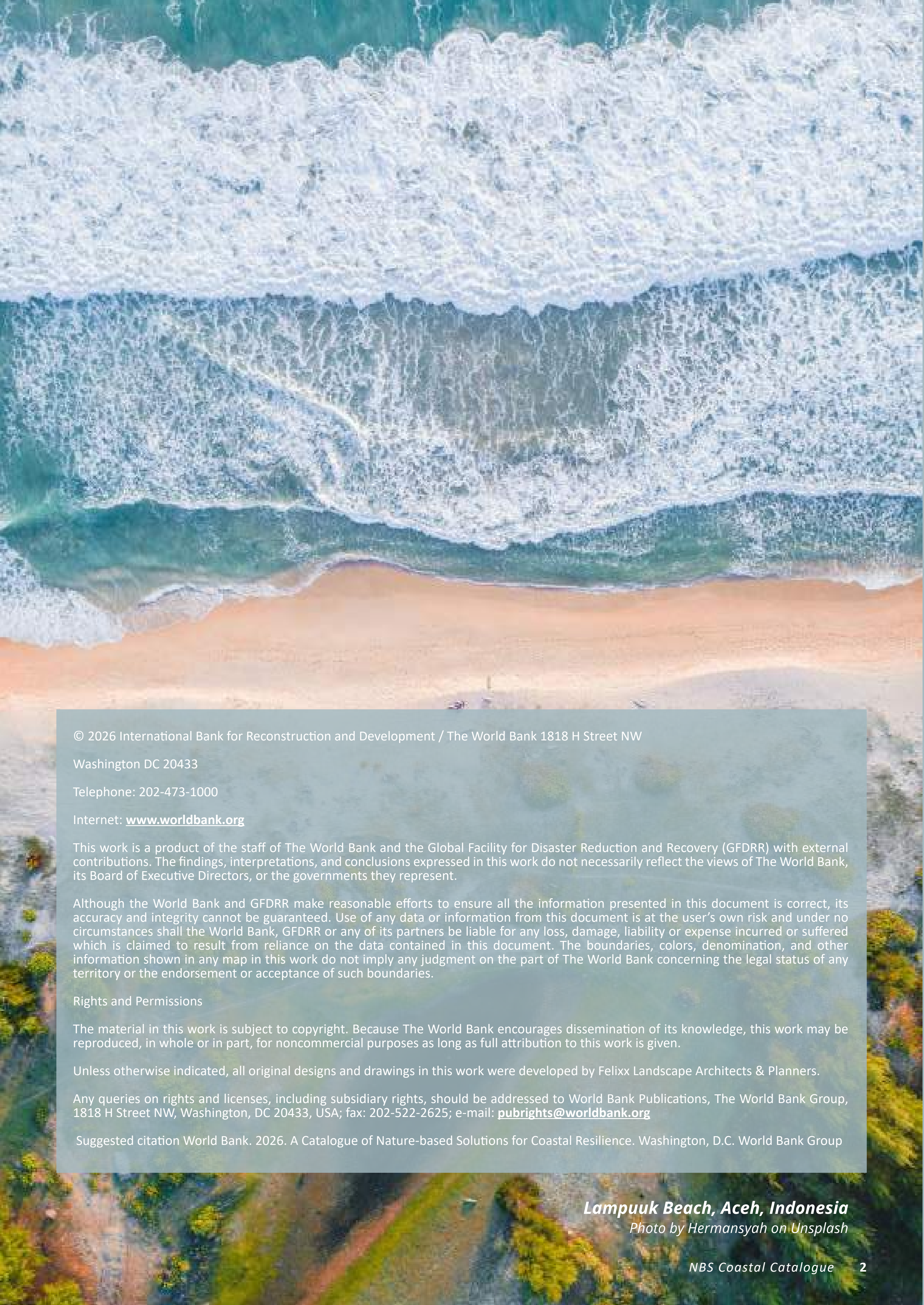
PROBLUE



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Lampuuk Beach, Aceh, Indonesia
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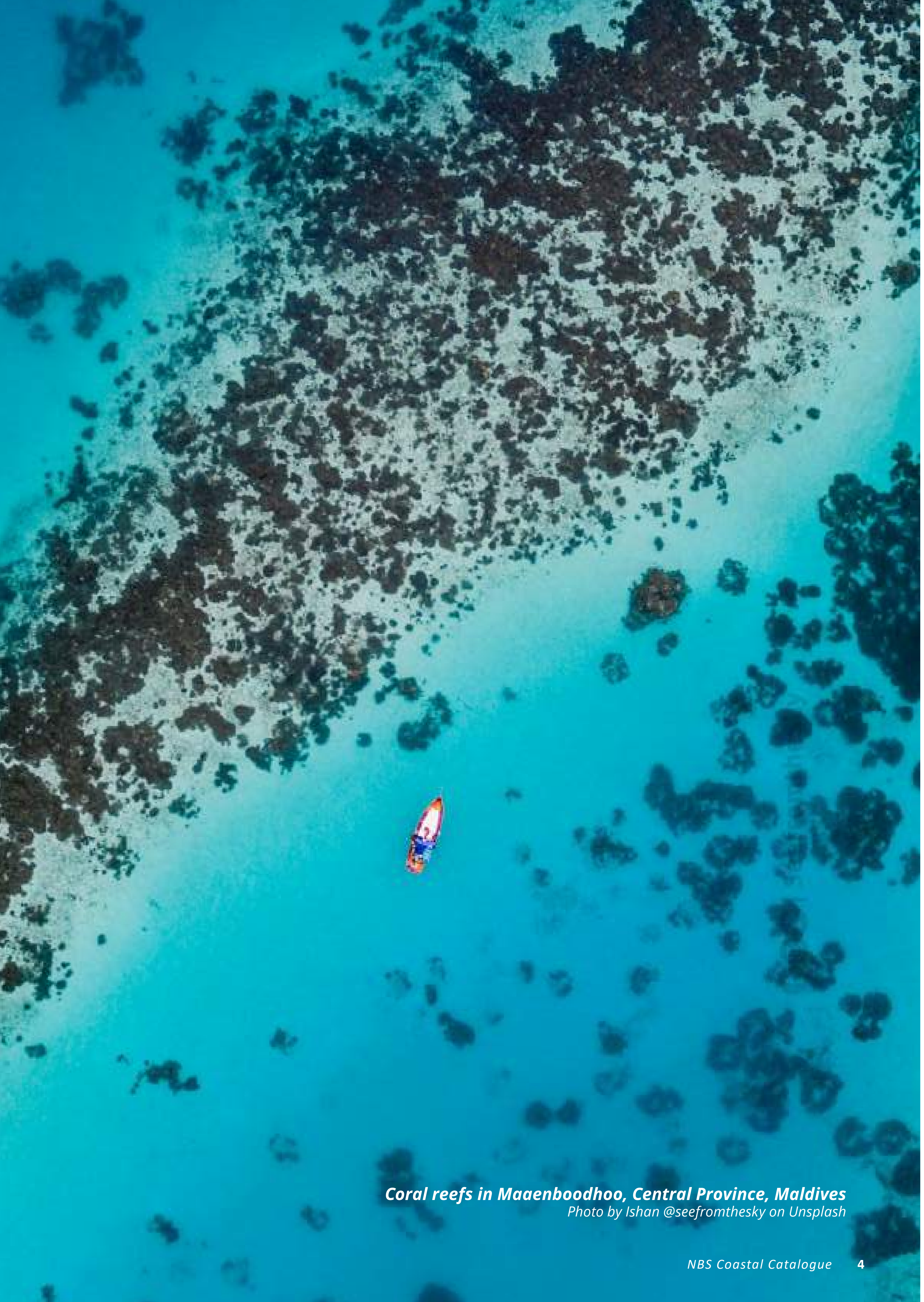

Coral reefs in Maaenboodhoo, Central Province, Maldives
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The Catalogue was developed in collaboration with Felixx Landscape Architects and Planners and Resilient Coast Ltd. Hope Steele edited the Catalogue.

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St. Brelade, Jersey, Channel Islands, United States
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Foreword

Coastal communities are on the front line of climate risk. Rising sea levels, intensifying storms, and accelerating erosion are placing rapidly growing coastal zones under increasing pressure—areas where people, infrastructure, economic activity, and biodiversity-rich ecosystems are highly concentrated. Today, approximately 11 percent of the world's population lives in low-lying coastal areas directly exposed to these hazards. As vital centers of commerce and governance, these zones are both engines of growth and areas of heightened vulnerability—particularly where development has weakened coastal ecosystems and natural systems that once provided protection and services to people and economies. This reality underscores the urgent need to integrate nature-based solutions into coastal resilience planning and investment.

Key global frameworks—including the Sendai Framework for Disaster Risk Reduction, the Paris Agreement, the Sustainable Development Goals, and the Kunming-Montreal Global Biodiversity Framework—recognize the central role of nature-based solutions in advancing resilience and sustainable development, while protecting biodiversity and restoring ecosystem services. In other words, nature-based solutions are not just about managing risk; they represent an opportunity agenda.

For the millions of families and households who rely on nature to sustain their livelihoods, these investments help them to build a ladder out of poverty and to transform natural capital into jobs and income. In coastal contexts, these approaches not only reduce risk, but also generate tangible benefits for people—creating jobs in restoration, stewardship, and nature-based tourism; strengthening food and nutrition security through healthy fisheries; and protecting the homes and assets of the communities most exposed to coastal hazards.

The World Bank Group is scaling up its support for nature-based solutions in coastal resilience. Since 2012, more than US$3 billion has been committed to projects with nature-based components, with a steady increase in operations in recent years. Yet as demand from clients continues to grow, a key challenge remains: translating this momentum into well-designed, bankable, and scalable investments. Practitioners and decision-makers need clearer guidance, grounded in operational experience, on what works, where, and under what conditions.

This Catalogue of Nature-Based Solutions for Coastal Resilience responds to that need. It brings together practical knowledge to support the identification and design of coastal protection strategies that work with and build on nature—across different shoreline types, ecological settings, and development contexts. While no single resource can capture the full diversity of the world's coastlines or the ingenuity of the communities that steward them, this Catalogue is guided by a clear principle: invest in the natural systems that already protect us; restore those that have been degraded; and thoughtfully combine nature-based and engineered measures where risks are highest and space is limited. Such an integrated approach can strengthen resilience while enabling people, economies, biodiversity, and ecosystems to thrive together, often providing more sustainable and cost-effective protection than conventional gray infrastructure alone.

This work reflects a strong collaboration between the World Bank's Global Program on Nature-Based Solutions for Climate Resilience and Felixx Landscape Architects and Planners, with support from the Global Facility for Disaster Reduction and Recovery, the government of Japan, and the World Bank's Global Program for the Blue Economy PROBLUE. It builds on existing knowledge and advances it through practical frameworks, clear visuals, and operational tools—including the Nature-Based Solutions Opportunity Scan—to help identify and prioritize investment opportunities.

We encourage practitioners, policy makers, and partners to use this Catalogue as a platform for action: to inform dialogue, guide feasibility work, and shape investment decisions. Its value will ultimately be measured by how it is applied—adapted to local contexts, strengthened through implementation, and enriched by shared experience. The challenges facing coastal communities are significant, but so too is our collective ability to address them when knowledge, finance, and action are aligned with the power of nature.

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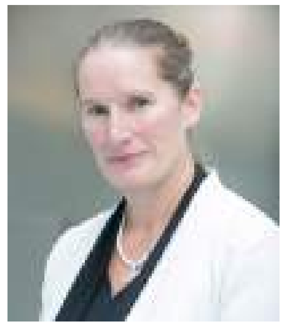

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Red Sea
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Chapter 01

Introduction

Coastal zones are among the most at-risk regions in the world, challenged by the combined pressures of natural hazards, dense populations, and concentrated economic activity in low-lying areas. Coastal hazards include tropical cyclones, extratropical storms, and tsunamis (Kron 2013). Among them, tropical cyclones cause the highest losses among all natural hazards, which have been estimated at US$112 billion per year (UNDRR 2025) and can reduce economic growth in the affected country for more than a decade (Berlemann and Wenzel 2016; Berlemann and Wenzel 2018; Hsiang and Jina 2014; Krichene et al. 2021; Krichene et al. 2023). Land subsidence and the loss of ecosystems are also increasing risks in many coastlines worldwide.

Evidence that climate change and sea-level rise are increasing the impact of coastal hazards is abundant. Tropical cyclones are projected to increase by over 35 percent with sea-level rise and climate change by mid-century (UNDRR 2025). The rise of sea level and other growing coastal hazards will increase risks and aggravate flooding, erosion, and impacts on infrastructure and people in the future (Griggs and Reguero 2021). Sea-level rise will also expose places currently inhabited by tens of millions of people to annual flooding by mid-century (Kulp and Strauss 2019; McMichael et al. 2020; Neumann et al. 2015) and could ultimately inundate areas where between 190 and 630 million people reside by the end of the century (Kulp and Strauss 2019). Rising sea levels and storm changes are also resulting in more powerful waves, increased flooding, and a greater potential for rapid erosion of beaches, cliffs, and coastlines (Hanley et al. 2014; Pang et al. 2023; Reguero et al. 2019; Zhang et al. 2004).

Globally, the vulnerability to coastal hazards falls unevenly, reflecting both the pace of population and economic growth along certain coasts and disparities in coastal protection across countries. The effects of coastal hazards compound with the increasing concentration of infrastructure, economic activities, and people on the coast (Kumar and Taylor 2015; Neumann et al. 2015; Pielke et al. 2008; Reguero et al. 2015). Coastal zones are exhibiting higher growth rates than inland areas (Carrera et al. 2023; Cosby et al. 2024). While the costs of coastal hazards will increase for all countries, low-income countries—including small island developing states (SIDS)—may suffer may suffer far greater consequences while at the same time having fewer resources to prevent disasters and support recovery (UNDRR 2025).

In many coastlines, development has also damaged and degraded coastal ecosystems that provide many services, including coastal protection, nature-based tourism, and habitat for species (Beck et al. 2022; Duarte 2009; Duarte et al. 2020; Narayan et al. 2016; Nichols et al. 2019; Reguero et al. 2018; Worm et al. 2006). Coastal ecosystems such as mangroves, salt marshes, seagrass meadows, coral reefs, dunes, and beaches are among the most productive and valuable ecosystems on Earth. Located at the interface between land and sea, they support a wide range of ecological processes that result in essential benefits to communities. They support biodiversity by providing habitats, nursery grounds, and feeding areas, and many underpin local fisheries and food security. They also support jobs, tourism opportunities and recreation, aesthetic and cultural values, and blue carbon capture and storage (Barbier et al. 2008, 2011; Martínez et al. 2007; Spalding et al. 2017). When coastal cities, ports, resorts, and other infrastructures remove dunes to build by the sea, clear mangrove forests for aquaculture or tourism, cause salt marshes to be landfilled or coral reefs to be damaged, not only can waves and storm surges reach further inland, increasing damages and costs (Beck et al. 2018; Menéndez et al. 2020; Narayan et al. 2017; Reguero et al. 2021), but it also undermines the other essential services ecosystems. From the rapid retreat of mangroves in Southeast Asia to coral reef degradation in the Caribbean and the Pacific, evidence abounds regarding how the removal of nature's first line of defense magnifies the impact of every storm surge and high tide while stripping away the many benefits healthy coastal ecosystems deliver (Burke et al. 2011; Menéndez et al. 2018; Richards and Friess 2016).

Traditional coastal protection has largely depended on "hard" engineering structures (or "gray" infrastructure), which often involve environmental trade-offs and impacts (Angnuureng et al. 2025; Rangel-Buitrago et al. 2018). However, these measures are increasingly challenged by escalating coastal hazards, cost increases (Borsje et al. 2011; Temmerman et al. 2013; van Hespen et al. 2023; Whelchel et al. 2018), and the loss of biodiversity and ecosystem services. Furthermore, not all communities have the financial capacity to protect their shorelines with gray infrastructure. In many coastlines, nature-based solutions (NBS) such as the restoration of dunes, reefs, mangrove forests, and salt marshes can provide a sustainable, cost-effective alternative for coastal protection while delivering economic opportunities and jobs as they sustain tourism and fisheries (Haasnoot et al. 2021; Maes and Jacobs 2017; Morris et al. 2018; Singhvi et al. 2022; Sutton-Grier et al. 2015; Temmerman et al. 2013).

NBS defined broadly as "actions to protect, manage, and restore ecosystems to address societal challenges while delivering benefits for people and biodiversity" (UNEP 2022), can involve various approaches along coastlines. Examples include restoring mangrove and salt marsh belts, rebuilding sand dunes, rehabilitating coral and oyster reefs, and expanding seagrass meadows. Multiple definitions of NBS for climate resilience are used across a wide range of organizations advancing and applying these approaches. *Related concepts include building with nature, engineering with nature, natural flood management, and green infrastructure,* among others, but what unites these concepts is an emphasis on conserving, restoring, and engineering natural systems to benefit both people and the ecosystems they depend on (Bridges et al. 2021). In short, NBS for coastal resilience can be considered a subset of NBS that focuses on addressing risks and building climate resilience in coastal landscapes.

However, NBS are not universally applicable, nor should they be considered the only solution. Site conditions, exposure levels, land-use constraints, ecological settings, and other key factors may impact their performance and feasibility locally. Therefore, local strategies should consider a spectrum of solutions (Figure 1.1) that leverage nature-based as well as engineered defenses to balance risk reduction, adaptability, sustainability, and cost feasibility (Norris et al. 2025; Singhvi et al. 2022; Sutton-Grier et al. 2015). In many cases, resilience and economically efficient strategies require combinations of green and gray measures.

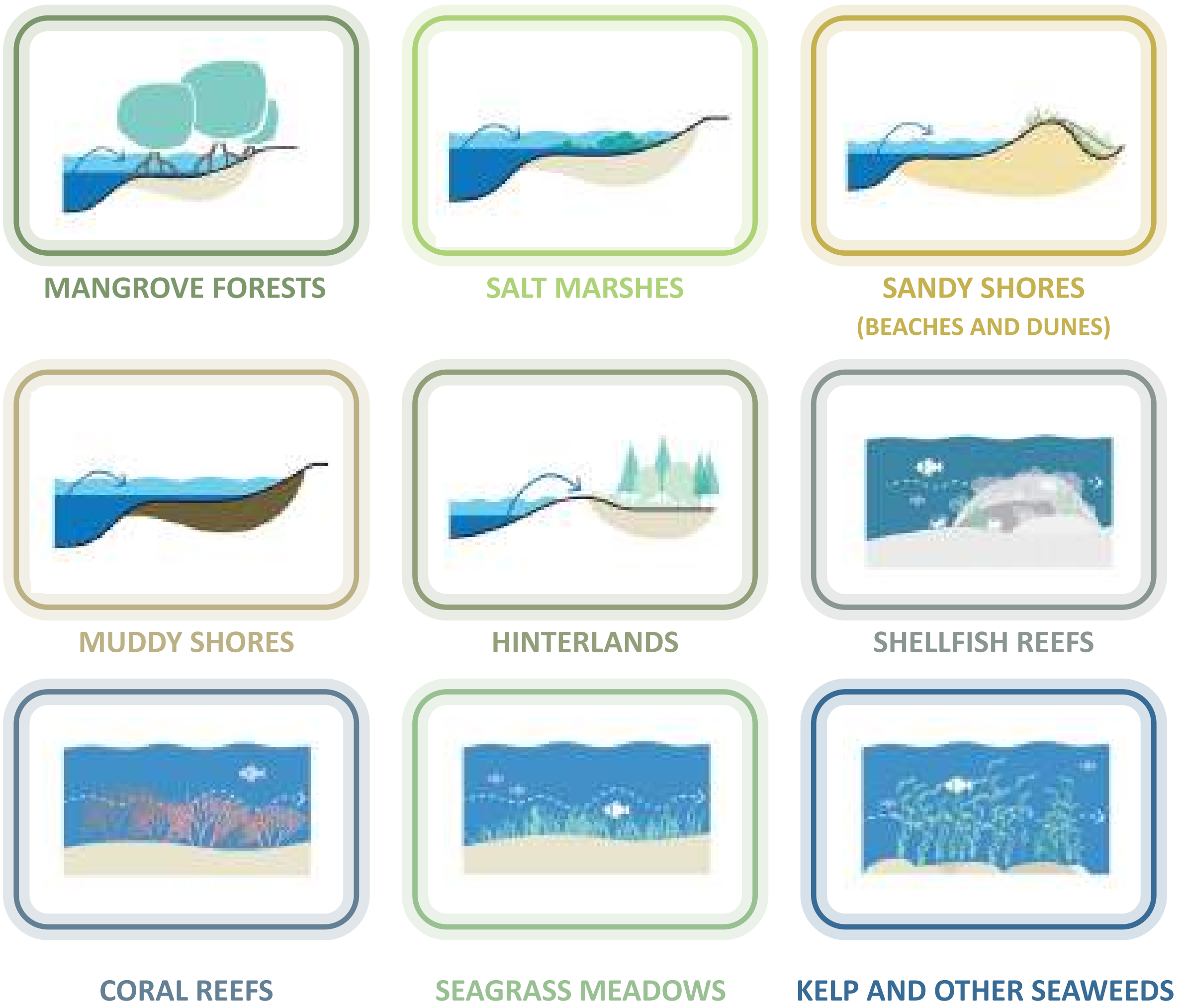
This coastal NBS catalogue is designed to support the identification of investment opportunities and the integration of NBS into coastal risk management and planning. It consolidates and builds on information from key resources, including the *International Guidelines on Natural and Nature-Based Features for Flood Risk Management* (Bridges et al. 2021), the Adapta Blues Catalogue (Adapta Blues 2023), the World Bank's *Catalogue of Nature-Based Solutions for Urban Resilience* (World Bank 2021) and its guidelines for assessing benefits and costs of NBS (van Zanten et al. 2023), among other documents.

Figure 1.1: NBS families in the coastal landscape

Source: Original figure for this publication.

The catalogue organizes coastal NBS into nine overarching typologies or "families": muddy shores, sandy shores (beaches and dunes), hinterlands, coral reefs, shellfish reefs, mangrove forests, salt marshes, seagrass meadows, and kelp and other seaweeds (Figure 1.2). Each family plays a distinct role in reducing climate-related risks, such as attenuating waves, stabilizing sediments, or creating space for floodwaters, while providing valuable co-benefits such as carbon storage, biodiversity, and contributions to nature-based tourism. For each NBS family, the catalogue presents practical guidance to inform planning and investment decisions. This includes descriptions of the key benefits, costs, visual sketches, and case examples to illustrate application; considerations for screening site suitability; and key design and maintenance principles. In a concise, accessible format, the catalogue aims to provide policy makers, planners, and stakeholders with tools needed to identify, prioritize, and integrate coastal NBS into climate and disaster risk management strategies.

Figure 1.2: The coastal NBS families



Source: Original figure for this publication.

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Long Point Light Station, Provincetown, Massachusetts, United States
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Malaysia
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Chapter 02

Integrating Nature-Based Solutions for Coastal Resilience in Investments and Policy

The coastal landscape is an interconnected system where natural processes and human activities are closely linked, where actions in one element can have effects on others. Coastal hydrodynamics and biological processes regulate sediment transport, buffer wave energy, and support biodiversity, while the built environment, such as ports, structures, settlements, and other built infrastructure, can also modify shoreline dynamics and influence ecosystems and drive coastal change. Coastlines also depend on their watersheds and keep close relationships and dependencies with the hinterland. Therefore, the management of coastal zones needs to consider the interactions between land and sea, natural systems and human activities, and multiple sectors and levels of governance.

An example of integrated management is the ridge-to-reef approach, which recognizes land-sea dependence in the coastal system. It links human activities and natural processes in upland areas ("ridge") with downstream coastal and marine ecosystems ("reef"). This framework recognizes that actions such as deforestation, agriculture, and pollution in high-altitude regions directly impact the health of marine environments (Fitzpatrick and Giovas 2021). Similarly, coastal structures can have effects on longshore sediment transport or present impacts beyond their built footprint (Dugan et al. 2008; Rangel-Buitrago et al. 2018). Other characteristics of the coastal landscape may also limit the capacity to leverage nature-based solutions (NBS). For example, in coastal cities with dense development or competing land uses, the space available for large-scale NBS can often be a limiting factor. This makes it essential to identify where these measures can be most effective.

To help identify the opportunity space for coastal NBS, this chapter outlines six core principles for the identification and integration of NBS for coastal resilience across all NBS families in the catalogue. These principles can help guide investment decisions; ensure that selected measures are technically sound; and inform economically viable, socially acceptable, and ecologically sustainable solutions.

2.1 Define the Problem, Assess Net Benefits and Development Goals

The starting point for identifying potential investments in coastal NBS is a clear understanding of the problem to be addressed and the goals and benefits the intervention is expected to deliver. This requires, first, conducting a risk-based assessment to determine what climate-related hazards and impacts (such as flooding, erosion, or saline intrusion) pose the greatest risks to people, infrastructure, and ecosystems. In parallel, it is important to define the full range of desired outcomes and benefits. Detailed guidance is provided in van Zanten et al. (2023).

One of the main characteristics of NBS is that they offer the capacity to deliver multiple benefits in addition to coastal protection. NBS also sit at the intersection of the biodiversity and climate agendas as healthy ecosystems can help address climate mitigation, climate adaptation, and disaster risk reduction, while simultaneously conserving biodiversity. While hazard reduction can be the primary objective of a project, many NBS can also offer tourism opportunities, create jobs, contribute to biodiversity, improve water quality, sequester carbon, and sustain livelihoods (Figure 2.1; see also van Zanten et al. 2025). Articulating these comprehensive sets of benefits from NBS and their alignments with climate and biodiversity strategies can ensure that the measures selected align with both climate resilience and broader development goals. Besides the benefits, key cost components should be assessed for each NBS intervention, including implementation cost, operations and maintenance cost, and other relevant cost components such as the opportunity cost of land and transaction costs.

2.2 Assess Site-Suitability Considerations

After the identification of the problem and desired outcomes, a critical factor is to determine whether the site conditions can support NBS families and interventions. Site suitability depends on factors such as hydrodynamics (e.g., wave energy, tidal range, current velocity, storm exposure), geomorphology, and sediment dynamics (e.g., shoreline slope, substrate type, and sediment supply), water quality (e.g., turbidity, salinity, and pollution levels), and connectivity with adjacent habitats. These factors influence whether an NBS can establish, persist, and deliver its intended protective function and benefits over time. Incorporating environmental changes and future climate conditions (such as sea-level rise or changes in temperature and storm intensity) can help ensure that the selected solution remains viable in the future.

Figure 2.1: The multiple benefits of salt marshes on a qualitative scale

Source: Original figure for this publication.

2.3 Integrate NBS and Gray Infrastructure Using a System-Based Approach

Adopting a system-based approach to coastal resilience planning and investment is one of the most effective ways to deliver solutions that are cost-efficient, sustainable, and long-lasting. By viewing the coast as an interconnected system, planners can design interventions that deliver multiple benefits for both people and nature. This approach recognizes interactions between natural processes, habitats, and built infrastructure; as well as the fact that shoreline dynamics and ecosystem functions often extend beyond a single site or jurisdiction. Because actions in one location can affect conditions elsewhere along the coast, a systems perspective helps ensure that measures are strategically sited and designed to work together rather than in isolation, resulting in a more resilient and sustainable coastal landscape.

Accordingly, NBS and gray infrastructure should not be treated as mutually exclusive alternatives. In some cases, NBS such as mangroves, reefs, dunes, and marshes can enhance the performance and longevity of engineered structures and serve as effective components of risk management strategies (e.g., Taylor-Burns et al. 2025). Conversely, gray infrastructure, including levees, revetments, or surge barriers, may be necessary where hazard intensity or space constraints exceed the protective capacity of NBS alone. By strategically sequencing and positioning these measures across offshore, nearshore, backshore, and hinterland zones, planners can create layered defense systems that increase reliability and adaptability under changing climate conditions (e.g., Reguero et al. 2018). Integrating NBS and gray measures within a coastal systems framework also supports the maintenance of natural processes: aligning interventions with sediment pathways, tidal exchanges, and habitat connectivity can sustain or even enhance protective functions over time while preserving the ecological integrity of the broader coastal landscape.

2.4 Assess Where to Protect, Manage, or Restore, or Where to Construct Hybrid Solutions

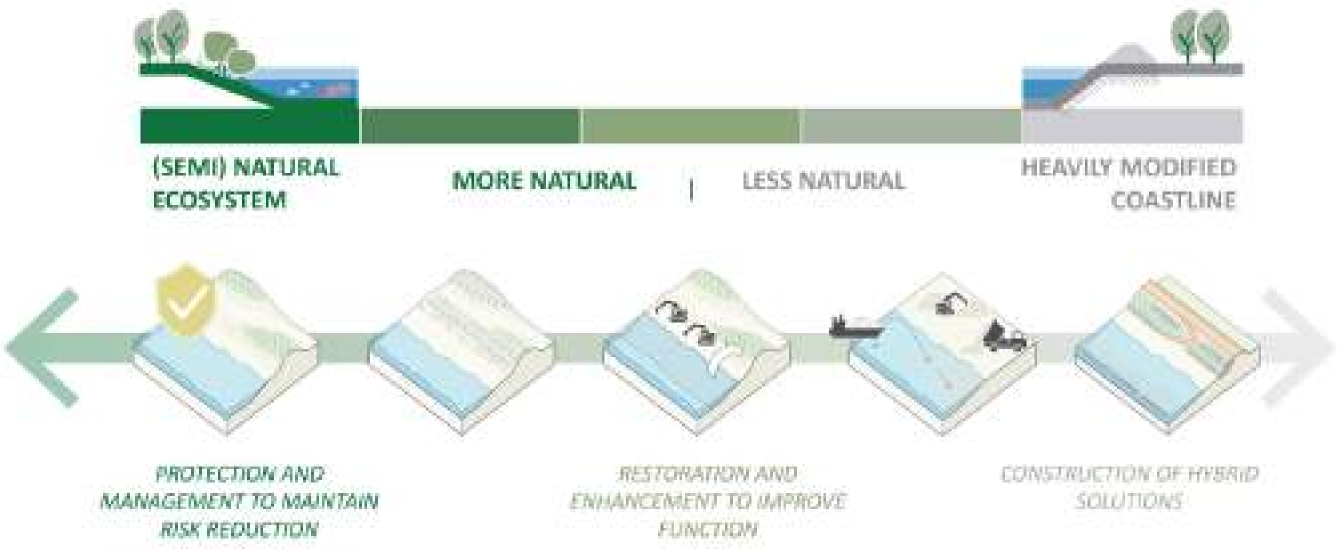
NBS may also involve different degrees of intervention and management actions. This guides organizes the various NBS options into three major strategies for every family type (Figure 2.2):

- **Protection:** On natural or near-natural coastlines with well-functioning ecosystems, such as intact mangroves, healthy coral reefs, or undisturbed dune systems, the focus should be on management and conservation approaches so they can maintain their coastal protection services as natural infrastructure systems (see, e.g., Reguero et al. 2021). Maintaining these habitats through effective protection, sustainable use, and regular monitoring preserves their ability to reduce risk while continuing to deliver co-benefits such as carbon storage, habitat provision, and support for local livelihoods.

- **Restoration and Enhancement:** Where natural systems are degraded but ecologically recoverable, restoration and enhancement strategies can help gain back some of the lost functions and services. Examples include stabilizing dunes through vegetation planting, nourishing beaches to rebuild their buffering capacity, and rehabilitating coral reefs and shellfish beds to reduce wave energy. Such actions can strengthen both the protective function and the wider ecological and economic benefits these habitats provide.

- **Hybrid Solutions:** In heavily modified or densely developed areas, the optimal approach may involve hybrid solutions, which refer to the integration of hard engineering and natural processes. Examples include living shorelines that incorporate vegetation into revetment designs, submerged breakwaters that encourage reef growth, and dunes that are reinforced with structures. These solutions can provide robust protection where hazard levels or space constraints limit the feasibility of other NBS.

Figure 2.2: Continuum of coastal resilience solutions harnessing natural processes



Source: Adapted from Bridges et al. 2021.

While protection relates to valuing and managing existing ecosystems for their risk reduction benefits and co-benefits, restoration, enhancement, and hybrid solutions can be considered to manage existing and future coastal risk. In practice, the prioritization and adequacy of these strategies will depend on local physical settings, socioeconomic factors, risk management decisions, and other considerations. However, the continuum of solutions (Figure 2.2) refers to the idea that coastal protection and adaptation options exist along a spectrum, rather than binary choices. By applying this continuum-based approach, planners and decision-makers can match interventions to local context, ensuring that each investment maximizes protective value while sustaining or enhancing the natural assets of the coastal system.

2.5 Leverage the Scalability and Adaptive Capacity of NBS for Coastal Resilience

One of the defining strengths of NBS is their ability to adapt to changing environmental conditions while continuing to deliver protective and co-benefits over time. Unlike static gray infrastructure, many coastal ecosystems can grow, regenerate, and adjust naturally in response to sea-level rise, shifting sediment patterns, or evolving storm regimes—provided that the conditions for their health and function are maintained. Salt marshes and mangroves, for example, can accrete sediment and migrate inland as seas rise, preserving their capacity to attenuate waves and store carbon.
NBS are also inherently scalable: they can be implemented incrementally, from small community-led projects to large regional programs, and expanded or connected over time to build broader resilience networks. This flexibility allows investments to be matched to available resources, urgent needs, and long-term adaptation pathways. By protecting

space for natural migration, maintaining sediment supply, and connecting habitat patches, planners can ensure that coastal NBS continue to perform under future climate scenarios. Leveraging this adaptive and scalable capacity means not only designing for current risk levels but also enabling ecosystems to evolve and remain effective in protecting communities and infrastructure for decades to come.

2.6 Adopt an Interdisciplinary and Cross-Sectoral Approach

Designing and implementing NBS requires close collaboration across communities, disciplines, sectors, and governance levels. It also requires integrating community needs from the onseet in the design and implementation. From the earliest stages of problem identification and concept design through implementation, operation, and long-term maintenance, effective solutions require coordinated efforts from a diverse set of actors. These include local communities, agencies with responsibilities on coastal zone management; national and local governments; ministries responsible for environment, infrastructure, and fisheries; public utilities; meteorological and planning institutions; civil society organizations; nongovernmental organizations; research centers; and the private sector.

Integrating NBS into coastal resilience strategies demands an approach that links risk management, land-use planning, and climate change adaptation. Early integration of community needs through sustained community engagement and close coordination with relevant institutions will also ensure solutions are co-designed and effectively implemented. They will also require interdisciplinary teams that may include coastal planners, landscape architects, engineers, ecologists, economists, and local stakeholders, to work together to deliver solutions that address multiple objectives and trade-offs. Interdisciplinary and cross-sectoral collaboration is especially important in rapidly urbanizing coastal areas, where space constraints and competing land uses increase the need to optimize the spatial and environmental footprint of interventions. NBS projects also offer an opportunity to catalyze collaboration across traditionally siloed sectors. By fostering joint planning between agencies and disciplines, they can help shift from fragmented, project-by-project interventions toward a systems-planning approach that aligns resilience objectives, optimizes available resources, and maximizes co-benefits. Tools such as the MDB Common Principles for Tracking Nature Finance can further support this interdisciplinary and cross-sectoral approach by providing a shared framework for identifying and tracking nature-positive investments (Multilateral Development Banks 2025).

Figure 2.3: Overview of the indicative costs and benefits of NBS families per unit area.

Protection costs *include estimates of land opportunity costs and the management expenditures required to conserve these systems. For example, hinterland NBS are often suitable for alternative development and therefore tend to entail higher opportunity costs. In coastal and marine contexts, the protection of ecosystems such as coral reefs can also be associated with high costs, as it requires effective upstream wastewater treatment and sediment management to maintain appropriate water quality.*

Restoration and enhancement costs *are characterized across NBS families by describing the proportionality of capital expenditures (CAPEX), associated with one-time investments such as restoring a shellfish reef, and operational expenditures (OPEX), which involve recurring costs (e.g., periodic nourishment of beaches and muddy shores).*

Benefit provision *is expressed on a qualitative scale ranging from none to low, medium, and high.*

Low *Medium* *High*

Source: Original figure for this publication.

Berck, Côte d'Opale, France
Photo by Benjamin Chambon on Unsplash

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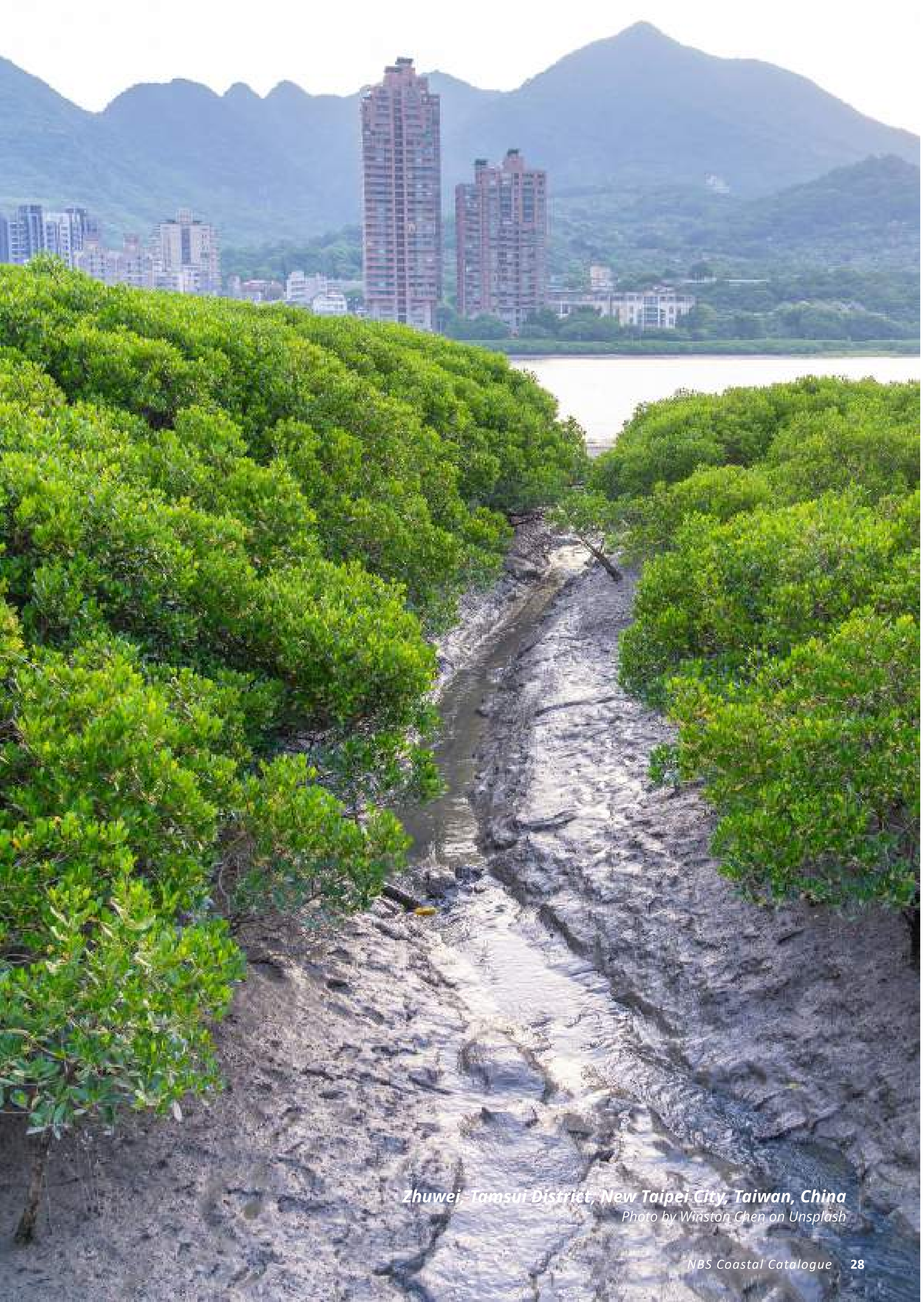


Zhuwei, Tamsui District, New Taipei City, Taiwan, China
Photo by Winston Chen on Unsplash

Chapter 03

THE CATALOGUE

3.1 Reader's Guide

The Catalogue consists of nine chapters, one for each coastal nature-based solutions (NBS) family; these are further split into three types of interventions. This chapter guides the reader through the different sections in each NBS family chapter by explaining the nature of the information included in each section. This can help the reader take the first step to assess possible locations for NBS. Each NBS family chapter consists of the following sections:

- Facts and figures
- Suitability considerations
- NBS interventions
- Benefits
- Costs
- Guidelines and resources
- NBS in practice: Case studies

FACTS AND FIGURES

Description: This provides generic background information about the NBS family and includes key definitions.
Coastal risk reduction benefits: Here is information about the flood and erosion reduction benefits.
Co-benefits and ecosystem threats: This paragraph describes the co-benefits of NBS family and common threats and causes of degradation.
Interventions: This paragraph sets forth the approaches that can be taken. The possibilities include:

- Protection of existing NBS
- Restoration and enhancement of NBS
- Hybrid interventions.

SUITABILITY CONSIDERATIONS

This section describes considerations of location and environmental suitability to help determine whether an NBS can be suitable for a particular coastal setting. Suitability considerations that are relevant for the feasibility and implementation of the NBS are dependent on the NBS family and may differ between interventions. Examples of suitability conditions are Climate, Hydrodynamics, Salinity, Water Quality, and Soil Conditions. This section identifies and describes these factors, but does not provide guidance on how to achieve or modify them.


Location and Climate


Soil


Hydrodynamics

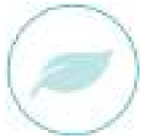

Slope

Salinity


Wave Exposure, Current Velocity, and Wind Velocity


Sedimentation Rate


Turbidity and Water Quality


Natural Regeneration


Sediment Size

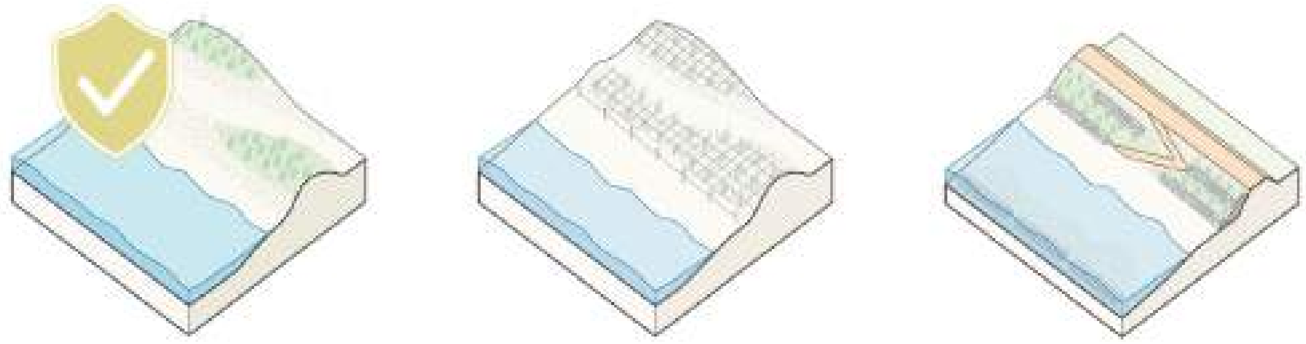
Suitability considerations icons

NBS INTERVENTIONS

Protection measures
This section provides information on conservation and threats to ecosystems related to the NBS family. Information provided on protective measures includes their general effectiveness as well as possible policy instruments/mechanisms.

Restoration and enhancement measures
This section focuses on actions to restore or rehabilitate a partially degraded ecosystem, restore a destroyed ecosystem, and/or enhance ecosystems that are healthy. Some examples of actions include hydrological restoration, nourishment, and planting.

Hybrid interventions
This section focuses on the integration of ecosystems with traditional (gray) coastal infrastructure, such as levees. Hybrid interventions may include the restoration of salt marshes or mangrove ecosystems in combination with embankments. The section also discusses the effectiveness of these approaches and provides guidance on their design.

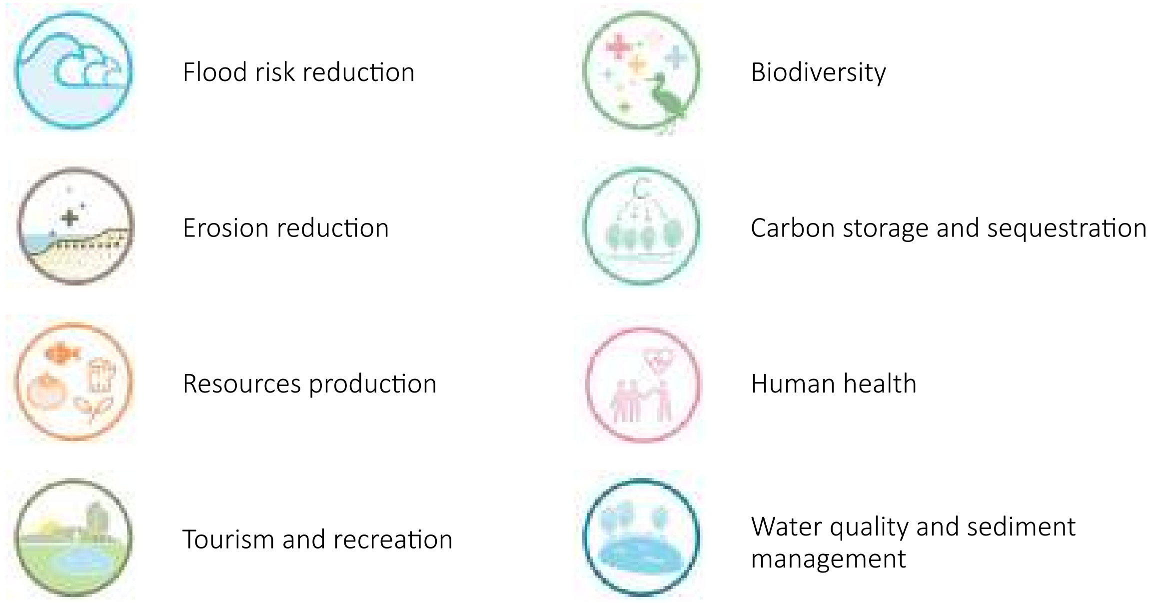


Examples of protection measures, restoration and enhancement measures, and hybrid interventions for sandy shores (beaches and dunes).

BENEFITS

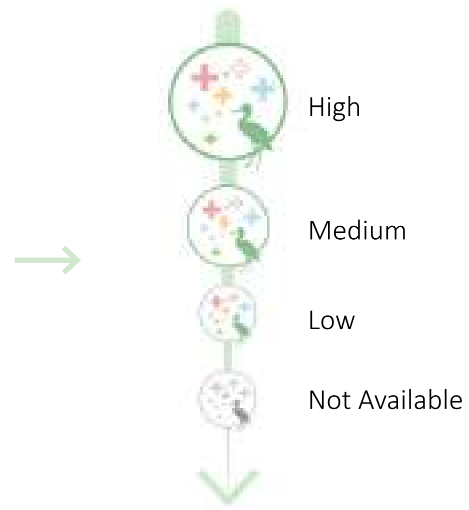
This section describes social, economic, and environmental benefits of the NBS family.

Each NBS family chapter contains a list of selected benefits that the project could deliver. Where data are available, quantified examples of benefits are provided. The benefits considered are:



Benefits icons

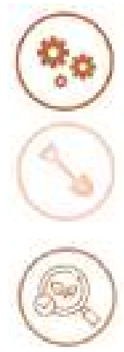
NBS Benefits Chart



Valuation method

COSTS

This section describes the cost considerations for different NBS interventions and provides international unit cost examples. Costs are expressed in standard units (e.g., per hectare or per cubic meter) and in US dollars.

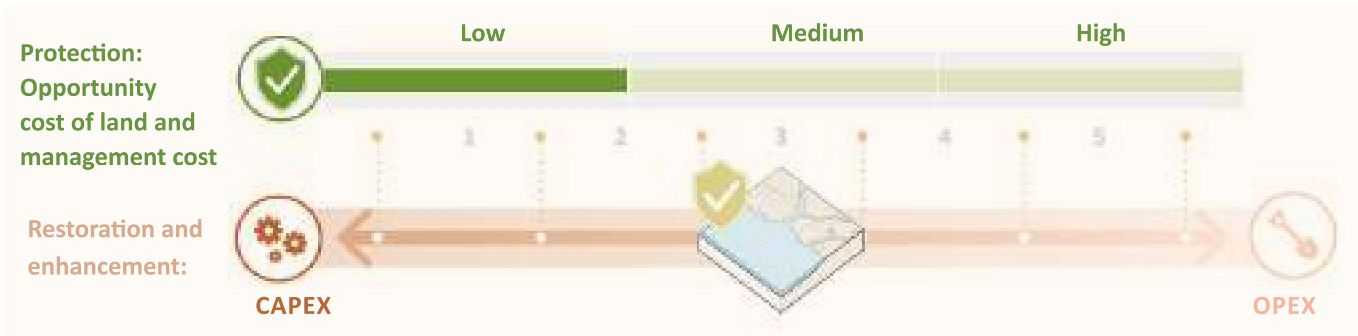


Implementation costs: These are costs related to protection measures, restoration or enhancement measures, and hybrid interventions. This includes construction and implementation costs.

Operations and maintenance costs: These costs cover operations and maintenance costs for the selected interventions.

Other cost considerations: Other cost considerations, such as land costs—including strategic development, planning, and upfront purchase—are described.

Lastly, a qualitative cost comparison between the different interventions is included.



CAPEX: Implementation costs
OPEX: Operations and maintenance costs

Valuation method

GUIDELINES AND RESOURCES

This section points the reader to further information regarding the NBS family in guidance manuals, handbooks, manuals, and key articles.

NBS IN PRACTICE: CASE STUDIES

This section provides case studies of NBS along with lessons learned and guidance for successful implementation and maintenance. Each case study comprises an image, project name, year, location, a brief description, size, benefits, costs (where available), challenges, lessons learned, and source.

3.2

Coastal NBS Families

Clicking on an NBS family will take you directly to the corresponding chapter.

MUDDY SHORES

SANDY SHORES
(BEACHES AND DUNES)

HINTERLANDS

CORAL REEFS

SHELLFISH REEFS

MANGROVE FORESTS

SALT MARSHES

SEAGRASS MEADOWS

KELP AND OTHER SEAWEEDS

MUDDY SHORES

Norddeich, Norden, Germany
Photo by Andreas Kretschmer on Unsplash

FACTS AND FIGURES

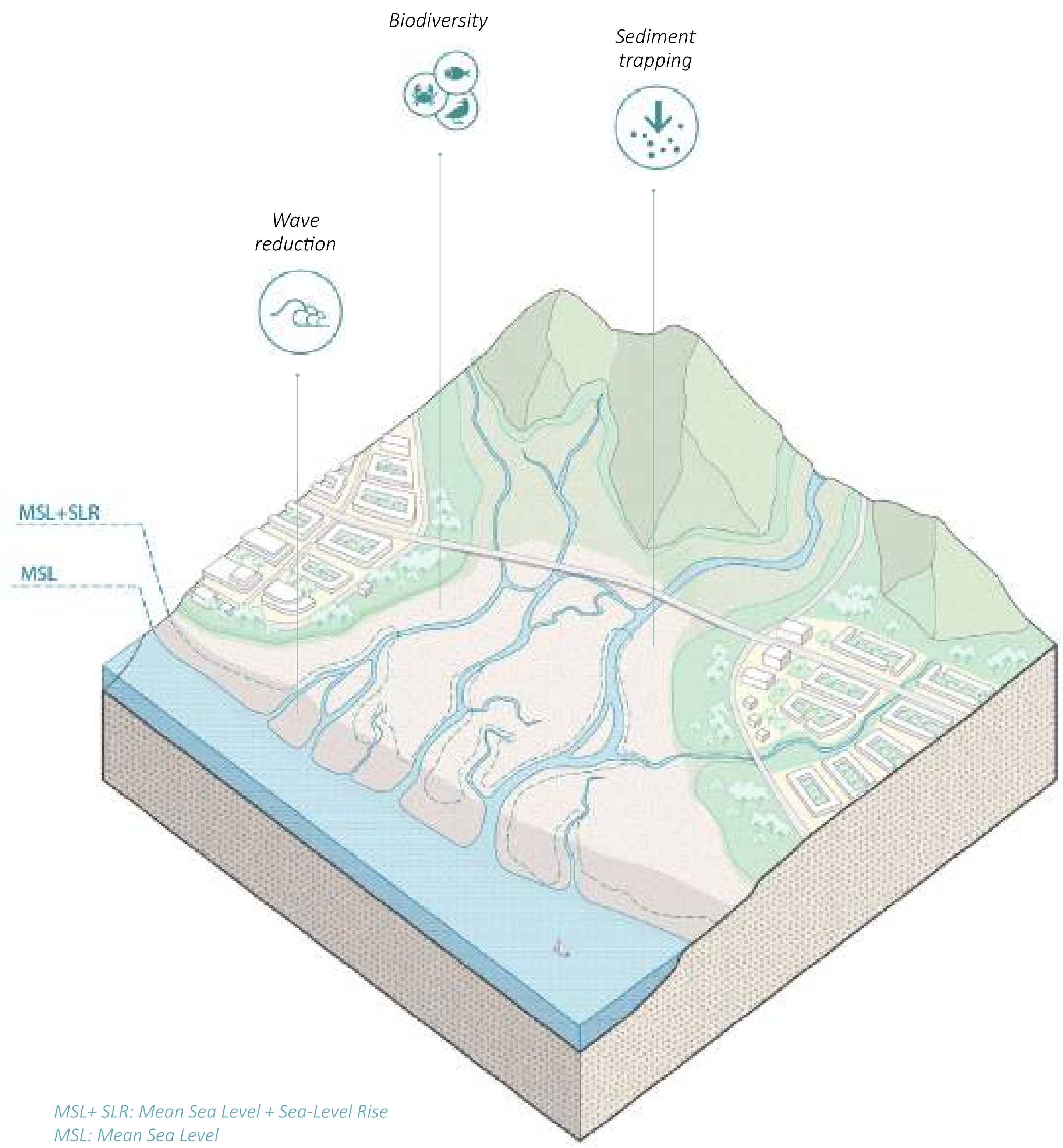
Muddy shorelines (mud-dominated coasts) can include mudflats, tidal flats, and mudbanks. These coastal environments typically form where rivers widen and their flow velocity decreases as they near the ocean, allowing fine-grained sediments (silts and clays) to settle and form low-lying coastal plains (e.g., estuaries). The muddy shoreline profile typically covers the area where tidal and wave-induced flows interact with the shoreline; their morphology is mainly shaped by tides and waves and the availability and characteristics of sediment. Over time, muddy shores reach a dynamic equilibrium, adjusting their morphology to balance the wave and tidal conditions (Friedrichs 2011). Features such as barrier islands, rocky outcrops, and sand banks (including features such as cheniers) can also contribute to the development of muddy shorelines, creating low-energy zones where fine-grained sediment can accumulate and settle.

These environments can increase sediment deposition and stabilize the shoreline. The extent that these ecosystems can provide flood protection depends on the physical and ecological structure of the muddy shores. For instance, in their bare scenario (without vegetation), coastal flood protection stems from their broad, low-gradient profile. These typically start from beaches or vegetated areas in the upper tidal zone to expansive tidal flats containing fine particles (of less than 63 micrometers in diameter) such as silt and clay in the middle to lower zones, and can include sandy lower flats (with particles ranging from 63 micrometers to 2 millimeters) in the lowest part of the profile (Wentworth 1922). These undulating shorelines dissipate wave energy and decrease incoming flow velocities, enhancing sediment deposition. Vegetation, such as mangroves, can establish on muddy shorelines from mean sea-level to highest spring tide (Alongi 2009); in this vegetated scenario, ecosystems such as salt marshes (Salt Marshes chapter) and mangrove forests (Mangrove Forests chapter) amplify the flood defense function of muddy coasts. Mudflats can also change in response to variations of environmental conditions, such as changes in precipitation patterns (linked to runoff) that alter the sediment supply to the coastal system (Ralston and Stacey 2007). Vegetation helps trap sediments, supports vertical land accretion, and significantly increases resistance to wave action and storm surges.

Muddy shores also provide a wide array of ecological benefits and livelihood support. These tidally dominated systems are regularly flushed by both riverine and marine waters, which bring nutrients that sustain diverse biological communities. While they often lack macroalgae and vegetation, mudflats are highly fertile as a result of high organic loads and host biofilms, microalgae (seaweed), and marsh species at the fringes. A wide variety of species thrive in healthy expansive muddy shore habitats, including filter feeders and other invertebrates such as worms, shellfish, and snails. They are therefore important feeding and resting areas for wildlife, including migratory shorebirds—with some estuaries hosting up to 200,000 birds during migration (Burger and Olla 1984). Their productive habitats support fisheries, contribute to carbon storage, and offer recreational, cultural, and economic value.

Several of these shorelines are therefore also recognized under the Ramsar Convention for their international importance. However, pressures such as land reclamation, water pollution and contamination of sediment, coastal development (e.g., buildings and infrastructure), disrupted sediment transport, and climate change–induced sea-level rise are degrading these systems, leading to problems such as shoreline erosion and loss of biodiversity.

Nature-based solution (NBS) interventions in these types of shorelines can be implemented to either protect existing muddy shorelines or enhance or restore degraded areas. Protecting existing muddy shorelines preserves their multifunctional role in, for example, reducing coastal flooding and erosion, enhancing biodiversity, and sustaining local livelihoods (such as fisheries). Muddy shores can also be used in combination with hard structures such as levees (hybrid interventions).



Visualizing the processes and benefits of muddy shorelines.

SUITABILITY CONSIDERATIONS

To deliver benefits such as flood protection and biodiversity enhancement, muddy shores must be located in areas where conditions allow them to remain stable and functional.

Location and climate: Muddy shores can form across various latitudes but are more prevalent in temperate and tropical regions where wave energy is low to moderate. These conditions allow fine sediments, such as silts and clays, to settle and accumulate. The underlying geological settings—such as the presence of erodible bedrock or nearby sediment-rich river systems—also play a significant role in determining where muddy shores can form. Local meteorological events and low-pressure surges impact the wave-induced erosion rate of muddy shores and soft cliffs (bluffs).

Hydrodynamics: Muddy deposits are found across a wide range of tidal environments; however, macrotidal conditions (tidal ranges exceeding 4 meters) particularly favor the extensive development of mudflats (Healy 2005). In estuarine regions, the mixing of fresh and saltwater generates estuarine currents, which play a crucial role in transporting sediments toward the estuary's head (Healy et al. 2002). Muddy coasts are typically found in sheltered areas protected from wave action, such as estuaries, bays, or lagoons, where mild hydrodynamic conditions promote the deposition of fine sediment. The tidal range will dictate the extent to which the mudflats exist upstream and their width along the shoreline. Tidal and riverine currents are responsible for erosion and the accretion of muddy shores, redistributing sediments. Wind-generated wave energy may form across open water or propagate into the area from the open ocean. These waves act to remobilize the soft sediments, which are then transported in tide- or wave-induced currents.

Salinity: Muddy shores are not constrained by specific salinity thresholds but are often associated with estuarine environments, where substantial freshwater and sediment discharge can be found. This suggests that salinity levels in these areas are typically lower than those in wave-dominated, sandy regions. Estuarine environments, which are dynamic mixing areas for riverine and marine waters, are associated with a range of salinity gradients throughout the estuary and over time (e.g., gradient changes caused by extreme events such as floods and droughts) (Feher et al. 2023). This plays an important role for the presence of biota, for the types of habitats, and for the biogeochemical processes in the estuary (Cloern et al. 2017).

Sedimentation rate: Muddy coasts are found across most continents. Sixty percent of them are located in tropical zones, primarily because of the substantial sediment loads delivered by tropical rivers (Hulskamp et al. 2023). The most prominent muddy coastal systems are situated in China, Indonesia, and the Indian subcontinent—regions that collectively receive 70 percent of the global sediment load (Hulskamp et al. 2023). Several factors drive the high sediment concentrations in these areas, including large catchment sizes, high sediment erodibility, steep terrain, seismic activity (which causes soil instability), and episodic or monsoonal weather events. Fine sediment contributions can also result from the reworking of offshore deposits and cliff erosion (Healy et al. 2002).

Soil: Muddy shores are typically found in coastal areas with abundant fine sediment supply, consisting of particles smaller than 63 micrometers in diameter, including silts (4–63 micrometers) and clays (less than 4 micrometers). These coasts also often contain organic matter, such as vegetation or marine detritus, and may feature deposits of sand (63 micrometers to 2 millimeters) and shells, such as cheniers (Healy 2005). The characteristics of soils in muddy shore ecosystems are heavily influenced by the local geology. Parent materials derived from marine sediments, alluvial deposits, or eroded soft rock contribute to the high clay and silt content typical of these environments. These fine-grained soils often have low permeability and high organic matter accumulation, affecting nutrient cycling, plant colonization, and stability. The mineral composition and grain size of the soil also impact erosion resistance and vegetation presence. Within tidal flats, the lower to subtidal zones exposed to greater wave energy generally display sandy or silty-sand characteristics. In contrast, central zones, extending up to the mean high-water mark, often exhibit the highest accumulation of fine sediments such as mud that contains large clay content (Healy et al. 2002). These depositions are typically cohesive and more resistant against erosion than noncohesive sandy soils.

Slope: Muddy shores tend to form in gently sloping areas where tidal waters can inundate and recede over large areas, allowing sediment to settle and accumulate under low-flow conditions. Mudflat slopes often vary between 0.5:1000 and 1:1000 (Healy 2005). Tidal flats in morphodynamic equilibrium under tidal currents have a convex-up profile, while tidal flats under waves produce a concave-up equilibrium profile (Friedrichs 2011).

Quanzhou, Fujian, China
Photo by lastmayday on Unsplash

NBS INTERVENTIONS

PROTECTION MEASURES

The long-term dynamic equilibrium of muddy shorelines and the causes of mudflat degradation need to be characterized to facilitate successful conservation.

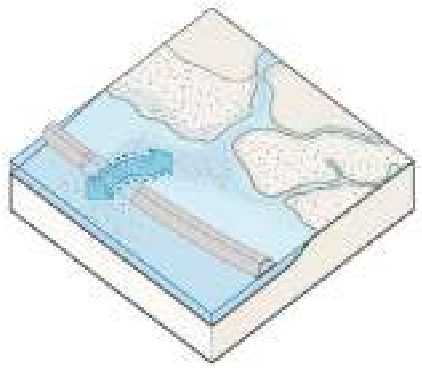
Muddy coasts can naturally recover from erosion by accumulating sediment during periods of high sediment supply and low wave activity. However, over longer timeframes, changes in the extent and stability of muddy shores will depend on the sea-level rise, changes in storm frequency, and sediment supply, which may impact their natural regeneration potential.

Muddy shores can be protected by sustaining natural flows and sediment transport; controlling pollution and improvement of wastewater management to reduce contaminant inflow; establishing buffer zones to limit urban encroachment; and enforcing sustainable coastal development practices (such as limiting hard infrastructure in intertidal zones) to avoid coastal squeeze. These protection measures can be complemented with policy and governance measures of catchment areas and coastal areas, public education, and community involvement to promote the ecological significance of mudflats and ensure long-term conservation.

RESTORATION AND ENHANCEMENT MEASURES

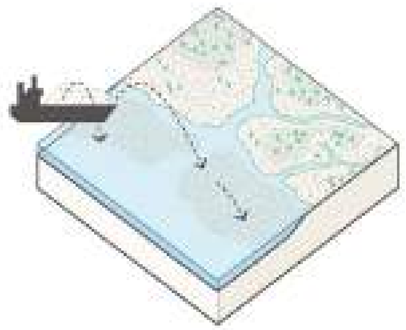
Hydrological restoration

The loss of mudflats can be mitigated through various techniques that address the causes of degradation. Lack of sediment input, for instance, may stem from both natural processes (e.g., seasonal fluctuations) and human activities (e.g., land-use change or upstream damming). Hence it is essential to understand the system's long-term dynamic equilibrium and carefully define the baseline against which restoration is measured (Jolivet et al. 2022). Where mudflat degradation is linked to human activity, restoration can involve removing hard structures that interrupt hydrological connections. An example is restoring tidal flow by reconnecting tidal creeks or restoring freshwater input.



Managed realignment

Managed realignment is a restoration approach that involves intentionally breaching or removing coastal defenses to allow tidal flow to inundate previously reclaimed land. This process facilitates the natural development of intertidal habitats such as mudflats (and often salt marshes too) by restoring tidal hydrodynamics and sediment deposition. It important to begin monitoring ecological development and sedimentation rates early to support adaptive management (French 2006). Effective managed realignment requires strategic site selection and careful designing to regulate changes in estuarine water levels, thereby avoiding adverse flooding effects on surrounding land (Pontee 2015).

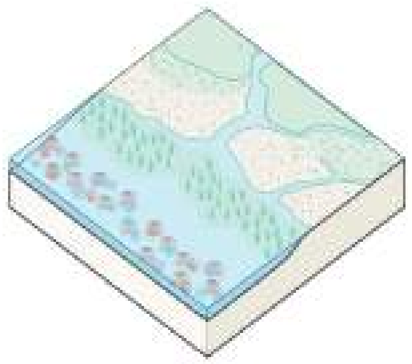


Mudflat augmentation

Mudflat augmentation is the placement of fine-grained sediment (such as silts and clays) to increase the surface elevation of mudflats in order to, for instance, reduce the impact of sea-level rise. This can be done either indirectly, by restoring watershed connectivity and sediment flows to encourage natural deposition over time, or directly, by mechanically placing dredged sediment onto mudflat surfaces.

Although nourished mudflats typically adjust to local conditions within the first year, ongoing erosion may require periodic replenishment (van der Werf et al. 2015). One of the key challenges lies in the logistics of delivering sufficient sediment volumes across large, flat, and often inaccessible areas for vessels. In these cases, the frequency of interventions and ecological damage can be reduced with a "mud-motor" concept. This concept utilizes large-scale nourishment areas of sediment to provide sustained sediment supply over several years (Baptist et al. 2019). While these techniques can support land elevation gain and are often used in conjunction with salt marsh (Salt Marshes chapter) or mangrove restoration (Mangrove Forests chapter), their effectiveness depends on site-specific conditions.

Maintaining sediment is often a challenge, particularly in dynamic environments with high wave energy or tidal currents that can quickly redistribute the material. Successful augmentation requires careful sediment selection (to match grain size and consolidation behavior) as well as hydrodynamic modeling. It may also require containment structures (such as brushwood fences) to promote sedimentation processes until the added sediment integrates naturally into the system. In addition, stimulating surface micro-topography formation can enhance biogeochemical functioning by creating conditions that support redox-driven "hot spots" of high microbial activity that largely influences the biogeochemical processes, essential for nutrient cycling and long-term soil development (Diamond et al. 2020; Frei et al. 2012). Overall, stimulating the microtopography enhances ecological diversity and productivity of the ecosystem.



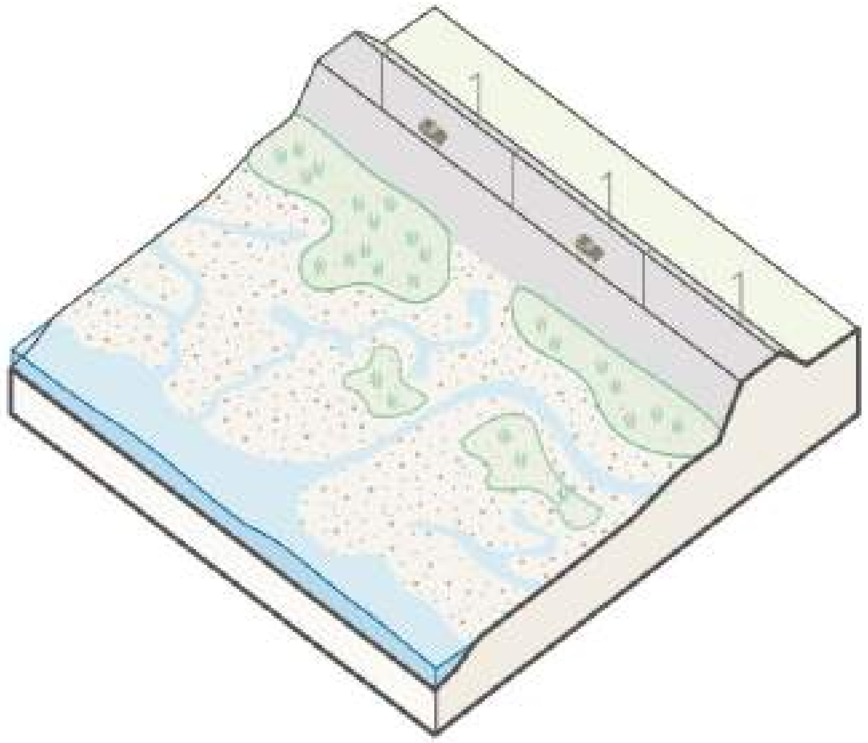
Connectivity and multiple lines of defense

Mudflats can be bound by flats or low-lying features below low tide (Dyer et al. 2000) and vegetation (such as mangroves and salt marshes) in the intertidal zone. These features and vegetation are often interconnected and support each other. In addition, submerged structures and reefs can dissipate energy, enabling sediment to accumulate, vegetation to colonize, and ecosystems to establish. The presence of submerged and emerged vegetation can stabilize the seabed and enhance sediment deposition (Ondiviela et al. 2014; USACE 2021). The flood protection benefits of mudflats can be enhanced by maintaining healthy ecosystems.

HYBRID INTERVENTIONS

Muddy shores can be integrated in the design of coastal structures such as levees and embankments to reduce hydraulic loads and increase flood protection. This requires adequate sediment and available space in front of embankments. The required surface areas are often extensive, as small-scale interventions may be insufficient to significantly reduce hydraulic loads or promote stable sediment accumulation, given that sediment transport processes generally occur at large spatial scales. However, coastal structures can disturb the sediment balance (Winterwerp et al. 2014). Minimizing the reflecting waves from these hard structures (e.g., through mildly sloping levees) can facilitate the development of muddy forefronts.

Coastal structures should also provide sufficient room for muddy shoreline dynamics, as well as guaranteeing the integrity of the structures in the periods of mudflat retreat. This can be achieved by monitoring the dynamics of local natural systems and complementing field measurements with modeling studies, so that the dynamics of the system can be characterized and considered in project designs. Moreover, integrating protection measures and/or restoration interventions into broader coastal management plans and climate adaptation strategies supports the long-term functionality and resilience of muddy shorelines across the full life cycle of coastal defense systems.



Le Mont-Saint-Michel,France
Photo by paws_and_prints on Unsplash

BENEFITS

Flood risk reduction: Mudflats act as natural buffers against extreme flood events by dissipating wave energy and reducing wave height before it reaches the shoreline (Best et al. 2022). Wide, shallow, and expanding mudflats favor the establishment of aquatic vegetation such as seagrasses, mangroves, and salt marshes (see the Seagrass Meadows, Mangrove Forests, and Salt Marshes chapters), which further enhance the wave energy dissipation (Möller and Spencer 2002; van Bijsterveldt et al. 2023). Furthermore, associated natural features, such as oyster beds (Shellfish Reefs chapter), can enhance the overall effect on wave attenuation and sediment deposition.

Erosion reduction: Mudflats can quickly recover after storms and can thereby contribute to shoreline resilience (van der Wegen et al. 2019). Vegetation on the mudflats can further enhance the role of mudflats in stabilizing coastlines and reducing erosion (Möller et al. 2014; van Bijsterveldt et al. 2023).

Tourism and recreation: Mudflats attract tourists and nature enthusiasts interested in birdwatching, observing wildlife, and experiencing unique coastal ecosystems. Mudflat landscapes provide tranquil settings for recreational activities such as walking or fishing, enhancing visitor experiences and promoting environmental awareness (Beninger 2019; Schmäing and Grotjohann 2024).

Culture and social interactions: Mudflats serve as gathering places for communities engaged in traditional fishing, clam digging, and harvesting marine resources, thus fostering social cohesion and cultural identity (Beninger 2019). These areas also provide venues for educational programs and community events that raise awareness about coastal conservation and sustainability (Parr et al. 2012), opportunities for scientific research and citizen science initiatives, and engagement opportunities for residents in environmental monitoring and conservation efforts (Hart et al. 2022).

Carbon storage and sequestration: Unvegetated mudflats are often overlooked when it comes to carbon storage (James et al. 2024). They can capture and store significant amounts of carbon under the right conditions—for instance, in environments with high mud content, mild hydrodynamic conditions, and low redox environments. In the Persian Gulf, for instance, mudflats have been found to sequester up to 85 metric tons of organic carbon per hectare (Elsayed et al. 2025).

Biodiversity: Mudflats support diverse and specialized ecosystems that host a wide range of species, including migratory birds, fish nurseries, and benthic organisms (Beninger 2018). Moreover, mudflats play a vital role in nutrient cycling and maintaining ecological balance in coastal ecosystems, making them essential for global biodiversity conservation efforts.

The multiple benefits of muddy shores on a qualitative scale

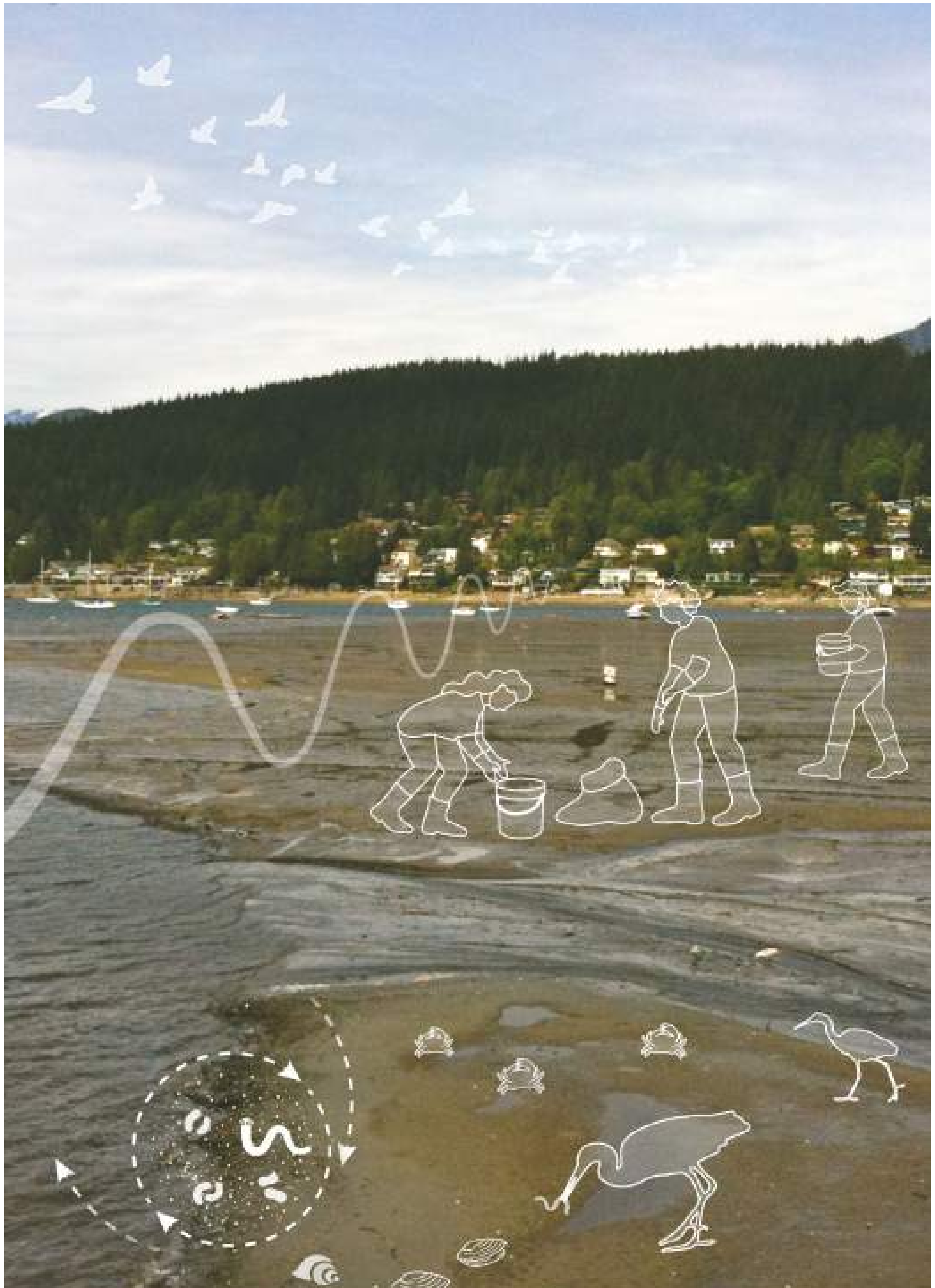


Illustration inspired by the photo of mudflats by Mezzoblue on Flickr.

COSTS

Implementation costs

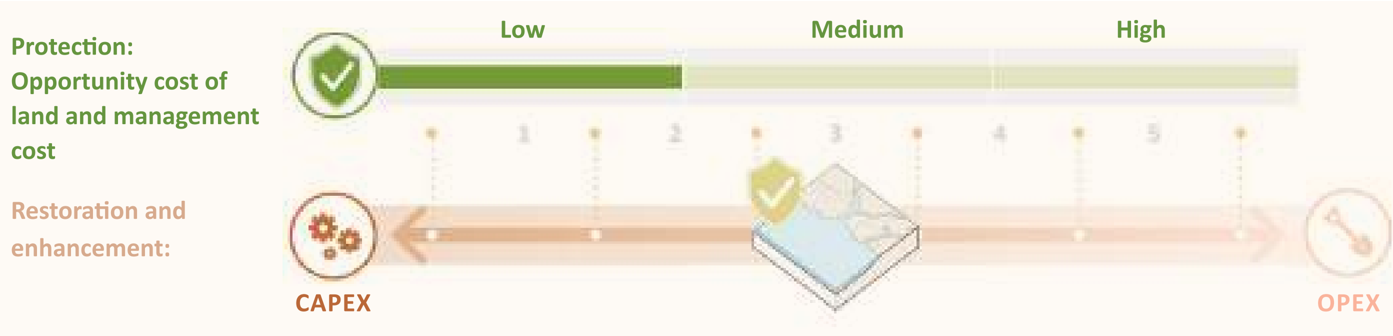
Protecting tidal flats can maintain their ability to protect coastal areas from flooding and erosion. Protection may be sufficient in areas with low erosion rates and sufficient mudflat presence. In areas of high erosion, or where mudflat accretion is necessary, mud nourishment or reef restoration (if required) can be implemented. Mud nourishment involves dredging mud from areas such as harbors and depositing it on existing mudflats. Reef restoration includes transplanting and installing artificial structures, among other techniques. In some cases, there may also be a need to construct sheltering structures—such as brushwood dams, permeable groins, or breakwaters—to reduce hydrodynamic energy and create conditions that promote sediment deposition. The cost of constructing permeable groins can be US$16–US$160 per meter, based on data from Demak, Indonesia; Thailand; and Viet Nam (Winterwerp et al. 2020). Furthermore, restoration projects that include mud nourishments can range from €5 to €15 per cubic meter (van Rijn 2019), while a mega nourishment project such as the mud motor in Friesland (the Netherlands) costs in total €1.3 million (Naturally Resilient Communities, n.d.). Costs associated with mudflat restoration will depend on the dredging and placement strategy (e.g., pumping), local cost of labor, machinery needs, transportation restrictions, sediment supply sources, and cost of materials.

Operations & maintenance costs

Maintenance activities of nourishment projects include recurring dredging and mud deposition. The associated costs depend on the frequency of nourishment, the amount of material required, and the local rate of coastal erosion. Broader maintenance efforts may also involve embankment or levee maintenance, fencing and sign-posting, and vegetation management. In cases where sheltering structures—such as brushwood dams, permeable fences, or breakwaters—are used to promote sedimentation, ongoing maintenance is required to ensure their structural integrity and effectiveness. This may involve costs related to long-term monitoring of the sedimentation rate, removing debris, and replacing damaged components. The maintenance costs for these fences are approximately US$20–US$80 per meter per year (Winterwerp et al. 2020).

Other cost considerations

Access to or ownership of land in coastal intertidal areas is required for the protection and restoration of muddy coastlines. Land ownership may be public or private. The area required for mudflat protection and/or restoration is large, which increases its associated costs and makes engagement and collaboration with multiple landowners and stakeholders necessary. Examples of land-related costs include land acquisition costs, land use costs (e.g., payments to landowners), land protection costs (including managing and controlling access), community resettlement costs, and construction and implementation costs (tactical design solutions).



CAPEX: Implementation costs
OPEX: Operations and maintenance costs

GUIDELINES AND RESOURCES

The resources listed provide guidance for designing standard levees, hybrid interventions, and restoring muddy coastlines, supporting their assessment, planning, and implementation as nature-based solutions. They also include information on creating suitable conditions for muddy shores, as well as guidance on monitoring approaches.

Levee design guidelines
CIRIA (Construction Industry Research and Information Association). 2013. *The International Levee Handbook*. London: CIRIA. https://www.ciria.org/CIRIA/Resources/Free_publications/I_L_H/ILH_resources.aspx

Hybrid infrastructure designs
Piercy, C. D., Pontee, N., Narayan, S., Davis, J., and Meckley, T. 2021. Coastal Wetlands and Tidal Flats. In *International Guidelines on Natural and Nature-Based Features for Flood Risk Management:* Chapter 10 Coastal Wetlands and Tidal Flats, edited by Bridges, T. S., J. K. King, J. D. Simm, M. W. Beck, G. Collins, Q. Lodder, and R. K. Mohan. Vicksburg, MS: U.S. Army Engineer Research and Development Center, chapter 10. https://issuu.com/poweroferdc/docs/nnbf-guidelines-2021/442?fr=sZTFiNjQyNjA2NDQ

Restoration guidelines
EcoShape Resources. 2021. Technical Guidelines Series to Restore Eroding Tropical Muddy Coasts: Technical Guidelines #1 "'Building with Nature Approach"; Technical Guidelines #2 "Systems Understanding"; Technical Guidelines #3 "Permeable Structures"; Technical Guidelines #4 "Associated Mangrove Aquaculture Farms"; Technical Guidelines #5 "Building Sustainable Aquaculture through Coastal Field Schools." https://www.wetlands.org/technical-guidelines-released-for-restoring-eroding-tropical-coastlines/

In addition, the Nature-Based Solutions Opportunity Scan (NBSOS) is a tool that helps identify NBS investment opportunities, providing information on NBS types, suitable locations, costs, and coastal protection benefits and co-benefits. It supports decision-makers in integrating NBS into planning, and investment strategies for both urban and coastal areas.

MUDDY SHORES CASE STUDIES

PROJECT #1
Managed Realignment for Mudflat Creation at Paull Holme Strays, Humber Estuary, United Kingdom (2003)

PROJECT #2
Wallasea Island Wild Coast Project Case Study, United Kingdom (2006)

PROJECT #3
Kruibeke-Controlled Flood Area, Belgium (1994–2024)

PROJECT #4
Mudflat Restoration with T-Shaped Structures, Viet Nam

PROJECT #5
Mud Motor for Salt Marsh Development, the Netherlands (2016–18)

Massachusetts, United States
Photo by LXS Photography on Unsplash

PROJECT #1
Managed Realignment for Mudflat Creation at Paull Holme Strays, Humber Estuary, United Kingdom (2003)

Photo by Paull Holme Strays.
Source: Gómez, A., November 5, 2012. Wild at Hull: Paull Holme.
https://wildathull.blogspot.com/2012/11/paull-holme-strays.html

Location

Humber Estuary, England, United Kingdom

Approach

Managed realignment

Size

***80 hectares** (**45 hectares** mudflat and **35 hectares** salt marsh)*

Cost

***US$9.6 million.** Monitoring costs of approximately **US$97,000** for years 1 through 5 and approximately **US$45,000** for years 6 to 10.*

Description

The managed realignment at Paull Holme Strays involved breaching sea walls to create new intertidal habitats on former agricultural land. The project aimed to compensate for the loss of intertidal mudflats due to development activities in the Humber estuary. Initiated in 2003, the site encompasses 45 hectares of mudflat and 35 hectares of salt marsh. Within two years, estuarine species began colonizing the site, though organism abundance remained lower than in adjacent natural habitats. The project serves as a short-term solution for habitat loss, with challenges in sustaining mudflats due to rapid accretion and elevation changes.

Benefits

- *Created 80 hectares of new intertidal habitat, including mudflats and salt marsh, supporting biodiversity.*
- *Coastal flood risk was reduced by allowing natural tidal flooding, reducing the need for artificial barriers.*
- *Promoted biogeochemical cycling, sediment dynamics, and trophic interactions essential for estuarine ecosystems.*

Biodiversity enhancement

Flood risk reduction

Challenges

- *Rapid sediment accretion has led to the unintended development of salt marsh rather than sustained mudflats.*
- *The abundance of organisms remains significantly lower than in natural mudflats even after two years.*
- *Differing tidal elevations across the site have resulted in uneven habitat development, complicating the goal of mudflat creation.*

Lessons learned

- *Managed realignment can quickly create new habitats but may not sustain the intended ecological function over time.*
- *The success of realignment projects heavily depends on local physical and biological conditions, such as tidal elevation and sedimentation rates.*
- *Ongoing, long-term monitoring is essential to understand the development and sustainability of restored habitats.*

Source (references)

Manson, S. and Pinnington, N. 2012. 'Paull Holme Strays Managed Realignment' (Humbar estuary). Measure analysis in the framework of the Interreg IVB project TIDE. *Measure 31*. https://www.tide-toolbox.eu/measures/paull_holme_strays_managed_realignment/

Mazik, K., Musk, W., Dawes, O., Solyanko, K., Brown, S., Mander, L. and Elliot, M. 2010. Managed realignment as compensation for the loss of intertidal mudflat: A short term solution to a long term problem? *Estuarine, Coastal and Shelf Science* 90(1)11–20. https://doi.org/10.1016/j.ecss.2010.07.009

PROJECT #2
Wallasea Island Wild Coast Project Case Study, United Kingdom (2006)

Jubilee Marsh 4 days after breaching – July 2015.
Source: Tyas, C. 2023. Royal Society of the Protection of Birds (RSPB). Panorama solutions. Wallasea Island Wild Coast Project – A landmark conservation and engineering scheme. https://panorama.solutions/en/solution/wallasea-island-wild-coast-project-landmark-conservation-and-engineering-scheme

Location

Essex Coast, United Kingdom

Approach

Managed realignment

Size

***108 hectares** of intertidal habitat were created (**85 hectares** of mudflat and **23 hectares** of salt marsh habitats).*

Cost

*Approximately **US$9.7 million**.*

Description

The Wallasea Island Wild Coast Project was a managed realignment initiative aimed at creating mudflats and salt marshes. The project involved breaching the seawall and allowing the land to flood, transforming arable farmland into a diverse wetland habitat. This effort was designed to combat the loss of intertidal habitats due to climate change and coastal squeeze, while also providing flood protection and enhancing biodiversity.

Benefits

- *Initial accretion rates of 10 centimeters—50 percent from external sediments and 50 percent from redistributed, local sediments—helped stabilize the environment, promoting mudflat formation. This in turn contributed to coastal flood risk and erosion reduction.*
- *The ecosystem appeared to be thriving, as there was rapid colonization of benthic invertebrates, with densities of between 10,000 and 20,000 organisms per square meter.*
- *Waterbird populations grew, supporting up to 12,000 individuals annually, enhancing the site's conservation value.*
- *Salt marsh coverage increased from 1 percent to nearly 100 percent within four years, demonstrating rapid habitat establishment and success.*

Challenges

- *Balancing flood risk management with ecological goals requires complex engineering and stakeholder coordination.*
- *Addressing community concerns demanded extensive public engagement and transparency throughout the project.*
- *Managing the large-scale realignment introduced logistical and environmental challenges, complicating implementation.*

Lessons learned

- *Early and consistent stakeholder engagement fosters community support and project success.*
- *Integration of ecological considerations into engineering design enhances biodiversity and project outcomes.*
- *Flexibility in design and execution allows the adaptation to unforeseen challenges and improves resilience.*

Source (references)

Wallasea Wetland Creation Project. Submission for RSPB/CIWEM Living Wetlands Award 2007. 20 November 2006. https://www.ecoshape.org/app/uploads/sites/2/2020/05/SubmissionforRSPBCIWEMLivingWetlands-Award2007.pdf

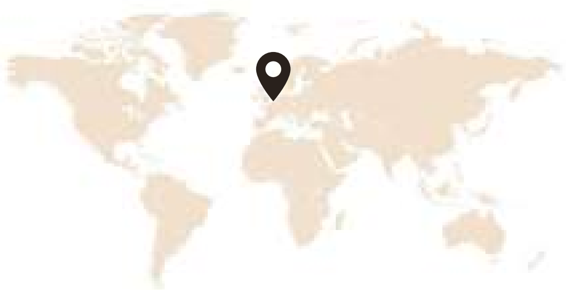
Wright, A., Townend, I., and Scott, C. 2010. *RSPB Wallasea Island wild coast project – Lessons for designing managed realignment sites*. 44th Defra Flood and Coastal Management Conference, Teleford, United Kingdom, June 30–July 2, 2010. https://eprints.hrwallingford.com/735/1/HRPP418_RSPB_Wallasea_Island_wild_coast_project_-_Lessons_for_designing_managed_realignment_sites.pdf

PROJECT #3
Kruibeke-Controlled Flood Area, Belgium (1994–2024)

Controlled flood area Bovenzanden during storm tide Benjamin in 2025. Photo by Thomas Bruyninckx.
Source: Sigma Plan: Polders of Kruibeke. https://www.sigmaplan.be/en/projects/polders-kruibeke#:~:text=The%20Polders%20of%20Kruibeke%20now,include%20the%20beavers%20and%20otters

Location

Scheldt Estuary, Belgium



Approach

Managed realignment

Size

***300 hectares** of mudflats.*

Cost

€100 million

Description

The embankments of the polders (levees, embankments) of Kruibeke were lowered to create an area where storm water could be stored during extreme events, and where tidal mudflats and marshes could be restored. Several weirs were installed so that tidal waters could also flow behind the lowered levees during normal conditions. New levees were built further inland to ensure the protection of nearby communities. Overall, the project created 300 hectares of tidal mudflats and marshes, 150 hectares of grassland bird habitat, and 150 hectares of forests and creeks at the area behind the overflow levee.

Benefits

- *Flood risk reduction, not only for the town of Kruibeke, but also for upstream towns along the Scheldt Estuary.*
- *The creation of natural habitats for diverse species, hence increasing biodiversity.*
- *Recreation and tourism opportunities for birdwatching, cycling, and hiking.*

Biodiversity enhancement | *Flood risk reduction* | *Tourism and recreation*

Challenges

- *Stakeholder opposition presented a challenge that required a lengthy period of communication and relationship building.*
- *Legal issues with land expropriation were another challenge.*
- *Pipeline rerouting and other infrastructural issues were also difficult.*

Lessons learned

- *Community engagement aids project acceptance.*
- *Combining flood protection with ecological restoration enhances project value.*
- *Integrated flood and nature-based approaches are more sustainable long term than traditional flood defense systems.*

Source (references)

Climate ADAPT Case Studies: Kruibeke Bazel Rupelmonde (Belgium): A controlled flood area for flood safety and nature protection. https://climate-adapt.eea.europa.eu/en/metadata/case-studies/kruibeke-bazel-rupelmonde-belgium-a-controlled-flood-area-for-flood-safety-and-nature-protection

Sigma Plan: Polders of Kruibeke: https://www.sigmaplan.be/en/projects/polders-kruibeke#:~:text=The%20Polders%20of%20Kruibeke%20now,include%20the%20beavers%20and%20otters

PROJECT #4
Mudflat Restoration with T-Shaped Structures, Viet Nam

Wave dampening effect of bamboo T-fences, Ca Mau Province, Viet Nam. Photo by R. Sorgenfrei.
Source: Schmitt, K. and Albers, T. 2023. Mangroves and ecosystem-based coastal protection in the Mekong River Delta, Vietnam. In O. B. B. Yllano (Ed.), Mangrove Biology, Ecosystem, and Conservation. IntechOpen. https://doi.org/10.5772/intechopen.110820

Location

Viet Nam (Lower Mekong Delta, including Soc Trang, Bac Lieu, and Ca Mau provinces)

Approach

Mudflat restoration measure

Size

***10,000 meters** (the total length of T-fences installed).*

Cost

Cost was not explicitly mentioned, but since the structures use local bamboo materials, they offer a low-cost alternative to concrete.

Description

The "T-Fence" project in Viet Nam's Lower Mekong Delta focuses on mitigating coastal erosion using permeable bamboo fences. These fences reduce wave energy, promote sediment deposition, and create conditions conducive to mangrove regeneration. Covering areas prone to erosion, such as Soc Trang and Bac Lieu provinces, the project employs sustainable, cost-effective bamboo designs. Initial implementations include 7,500 meters of fencing on the east coast and 2,500 meters on the west. Monitoring shows effective sedimentation and natural mangrove regrowth in restored areas, ensuring long-term protection of levees (embankments) and coastal zones.

Benefits

- *Fences decrease wave height by up to 80 percent, minimizing erosion threats to coastal levees. By reducing waves, structures promote sediment deposition (up to 17 centimeters in 7 months), stabilizing floodplains for mangrove regrowth and minimizing erosion threats to coastal levees.*

Coastal erosion reduction

Challenges

- *Shipworms severely weaken bamboo, requiring chemical treatment or alternative materials.*
- *Regular inspections and repairs are essential, especially in highly exposed areas, which results in high maintenance needs.*

Lessons learned

- *Fence design must reflect site-specific hydrodynamic and morphodynamic conditions.*
- *Long-term success depends on protecting mangroves from human and natural impacts post-restoration.*
- *Ongoing evaluations ensure sedimentation and fence stability, avoiding project setbacks.*
- *Combining bamboo fences with concrete or other reinforcements enhances resilience in high-energy locations.*

Source (references)

Dinh, S., Albers, T., and Schmitt, K. 2013. *Shoreline Management Guidelines Coastal Protection in the Lower Mekong Delta*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, https://www.researchgate.net/publication/315637641_Shoreline_Management_Guidelines_Coastal_Protection_in_the_Lower_Mekong_Delta

PROJECT #5
Mud Motor for Salt Marsh Development, the Netherlands (2016–18)

Tidal flat near Koehoal. Photo by EcoShape.
Source: EcoShape. No date. Re-use of dredged sediment – Mud Motor. https://www.ecoshape.org/en/cases/re-use-of-dredged-sediment-mud-motor-in-port-of-harlingen-koehoal-nl/

Location

Koehoal, Friesland, the Netherlands (Port of Harlingen)

Approach

Mudflat augmentation (restoration measure)

Size

*A total of **470,516 cubic meters** of fine-grained sediment was deposited over two winter seasons.*

Cost

€1.3 million

Description

The Mud Motor project is a pilot initiative that explores the beneficial use of dredged sediment to stimulate mud flat and salt marsh development in the Wadden Sea. Annually, approximately 1.3 million cubic meters of fine sediment are dredged from the Port of Harlingen to maintain navigability. Instead of traditional offshore disposal, this project strategically deposits the dredged material in a designated area north of the port. Natural tidal currents then transport the sediment toward the Koehoal salt marshes, promoting their growth and stability. This approach aims to enhance coastal resilience, reduce maintenance dredging needs, and improve ecological conditions.

Benefits

- *Contributes to flood risk reduction and thereby reduces maintenance cost of the levee by sustaining the foreshores.*
- *The salt marsh stabilizes and accumulates sediment in the area.*
- *The salt marsh development increases biodiversity and reduces turbidity in the area.*

Biodiversity enhancement | *Flood risk reduction* | *Coastal erosion reduction*

Challenges

- *Sediment transport varies because of varying environmental conditions (wind, waves, tide, and freshwater discharge) and complex sediment dynamics.*
- *Minimizing the ecological disturbances (such as turbidity) was challenging.*
- *There are uncertainties (such as the horizontal expansion of the marsh) in the long-term development of marsh elevation.*

Lessons learned

- *Careful and strategic sediment management is needed.*
- *The force and direction of the wind and the freshwater-induced circulation are important factors in determining the mud motor dynamics.*
- *The waves lead to erosion at the study site and perennial vegetation on the salt marsh stabilizes marsh growth.*
- *Significant mud was transferred into the tidal gully.*
- *Accurate monitoring is essential to capture the efficiency of the mud motor.*

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Büsum, Germany
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SANDY SHORES (BEACHES AND DUNES)

Quinns Rocks, Australia
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FACTS AND FIGURES

A beach is a dynamic coastal landform found along the edges of oceans, seas, lakes, or rivers, which is composed of loose particles such as sand, gravel, pebbles, or cobblestones. Beach systems—which are shaped and deposited by the continuous action of waves, tides, and currents—play a vital role in coastal protection, acting as a buffer against flooding and erosion.

Beaches are typically divided into three zones: the backshore, which lies above the high tide line and is only affected during storms; the foreshore, located between the high and low tide lines and regularly washed by waves; and the nearshore, the shallow offshore area where waves begin to break. Sand—often made of quartz, shell fragments, or volcanic minerals—is the most common sediment, although pebble or shingle beaches are found in high-energy wave environments.

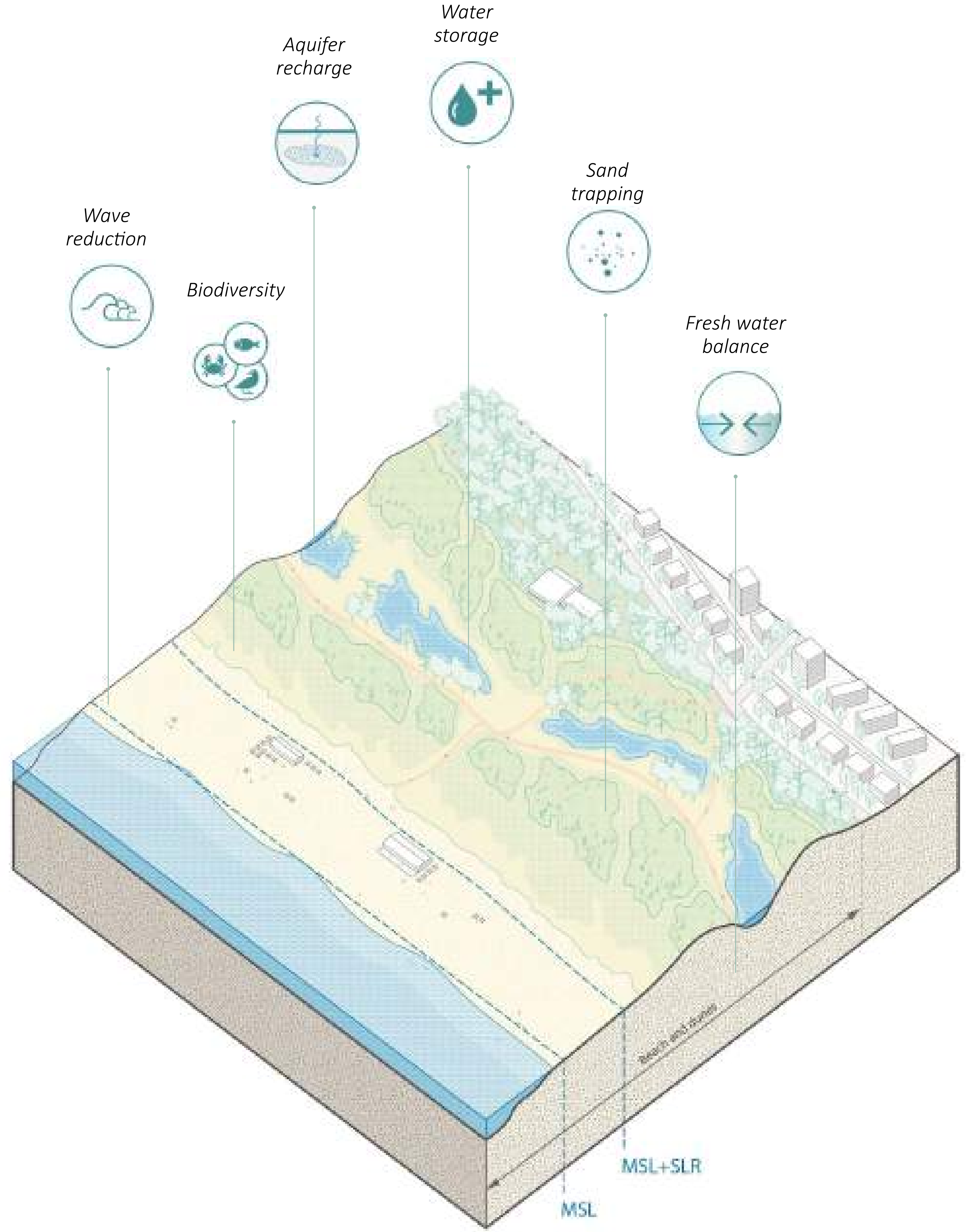
These coastal systems are not static; they change over time (during storms, seasons, and years) as a result of natural forces and human activities. In general, beaches and dunes undergo erosion during extreme events but recover during calmer conditions. Storms can erode beaches and dunes, transporting sediment offshore and forming sandbars that help dissipate wave energy. After storms, calmer conditions allow sediment to return, rebuilding the beach. Similarly, dunes, which are sand ridges formed by wind, also erode during storms but recover through wind-driven sand deposition and vegetation growth, which stabilizes the sediment (Silva et al. 2016; Suanez et al. 2012). Despite their vulnerability to storms, dunes recover through sediment redistribution and plant regrowth, contributing to the long-term resilience of sandy shores. Dunes and beaches are closely connected and work together to shape and protect the shoreline (Hanley et al. 2014). Furthermore, their cyclical pattern of disturbance and recovery is crucial for preserving the protective function of beaches and dunes against coastal hazards.

Waves, tides, and storm surges are key drivers of sediment transport that shape the width, elevation, and sediment composition of a sandy beach environment (Hanley et al. 2014; Komar and Inman 1970; Wright and Short 1984). Sediment transport occurs through cross-shore movement (toward or away from the shore) and longshore movement (along the coast), driven by waves, tides, and currents. Sediment can be moved as bedload (along the seafloor) or suspended load (within the water column). Dunes depend on nearby beach sediment and are influenced by the same transport processes.

A key concept in understanding beach dynamics is the sediment budget, which tracks the balance of sediment gains and losses within a defined coastal area or "cell" (Inman 2005; Rosati 2005). Sources of sediment include longshore transport from adjacent areas, river input, and erosion of nearby land. Sinks include sediment loss to adjacent compartments, dredging, mining, erosion, and submarine canyon transport. When sediment losses exceed inputs, beaches erode and retreat. Both natural and human activities can alter sediment budgets by impacting the sources of sediment, extracting sediment from the system, modifying natural flows, or intercepting and modifying sediment transport with structures.

Maintaining a balanced sediment budget is essential for beach stability and coastal protection. The resilience of sandy shores depends on the interplay between erosive events and recovery periods. Dunes are especially important in this system, forming when wind carries dry sand inland, where it accumulates and is stabilized by vegetation. Over time, dunes can grow into complex systems, provided there is enough sediment, wind, and space.

However, beach and dune systems have significant pressures from urbanization, infrastructure development, sand mining, coastal structures and disruption of sediment dynamics, and coastal squeeze (Defeo et al. 2009). These factors can compromise the natural resilience and recovery cycles of beaches and dunes and, consequently, compromise their coastal protection services. To address these challenges, nature-based solutions must strike a balance between economic



MSL+ SLR: Mean Sea Level + Sea-Level Rise
MSL: Mean Sea Level

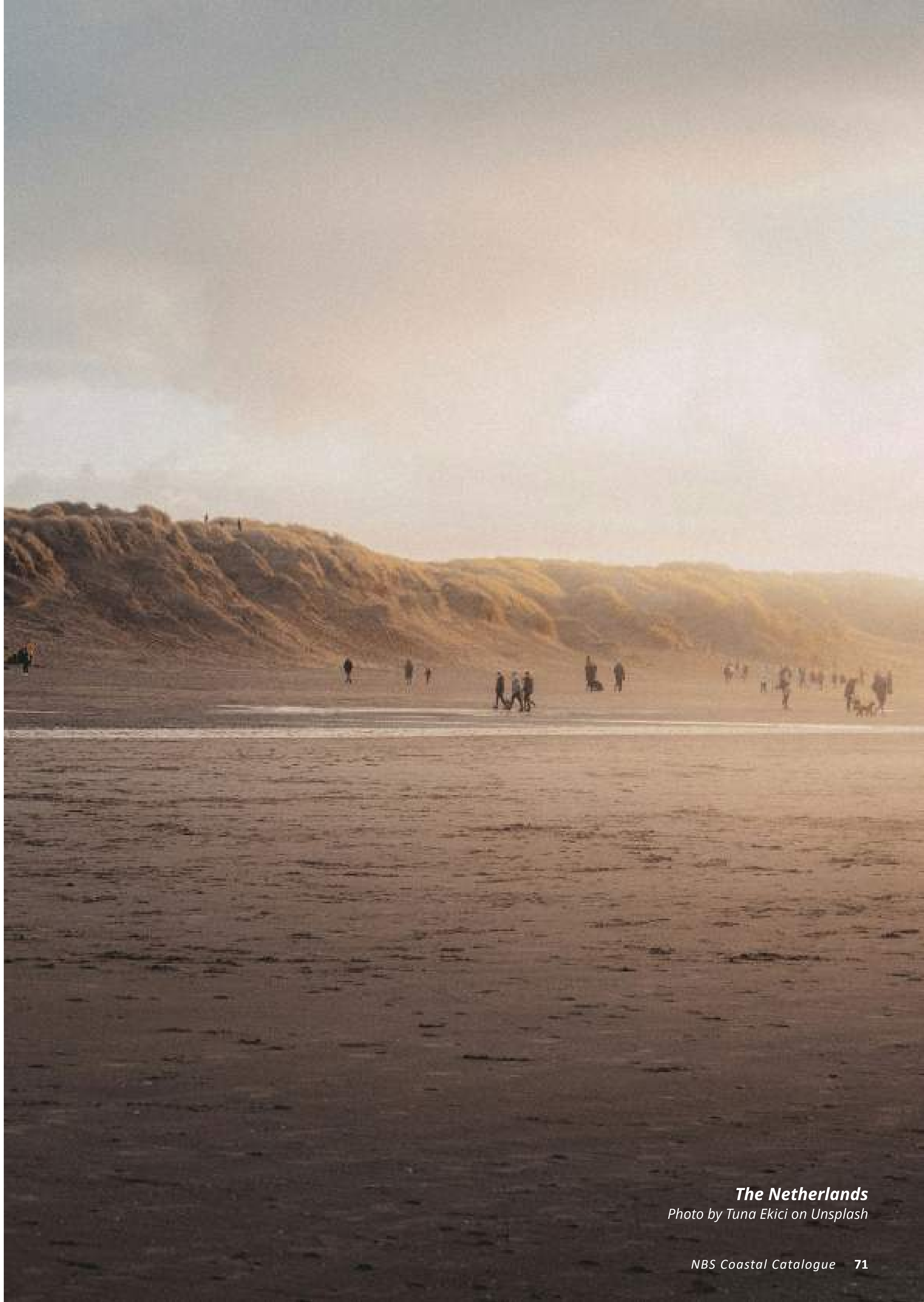
Visualizing the processes and benefits of sandy shorelines.

growth and the preservation of coastal processes. Sustainable coastal management involves aligning development goals with the need to maintain sediment flows and beach-dune integrity. Ignoring these natural processes can lead to long-term risks for both built infrastructure and ecological systems. Effective and lasting interventions also require a multidisciplinary approach, combining expertise from engineering, coastal geomorphology, ecology, and governance (Morris et al. 2020; Singhvi et al. 2022; Sutton-Grier et al. 2018). An integrated perspective can ensure that beach and dune management strategies are not only technically sound and cost-efficient but also environmentally sustainable and socially responsible.

Hard engineering solutions, such as seawalls, groins, and breakwaters, have traditionally been employed to counteract coastal erosion (Griggs et al. 2019; Martin et al. 2005). While these structures can provide short-term relief for infrastructure and property, mounting evidence underscores their potential to disrupt natural sediment flows, exacerbate erosion downstream, and reduce the long-term adaptive capacity of shorelines (Dugan et al. 2008; Griggs 2005; Rangel-Buitrago et al. 2015; Stancheva et al. 2011). As a result, there has been a paradigm shift toward "soft engineering" and nature-based solutions (NBS) such as beach nourishment, the restoration of dunes, and other strategies that mimic natural behaviors, such as stabilization techniques with native vegetation or incorporating large woody debris (Hanson et al. 2002; Johnston et al. 2023; Nordstrom et al. 2011; van der Meulen et al. 2023).

Beaches and dune systems are of high ecological and socioeconomic importance as they offer habitats, recreational and tourism opportunities, and cultural and aesthetic value; they can also act as carbon sinks. Beach areas play a crucial role in the growth and prosperity of many coastal regions across several sectors such as tourism, employment, property values, ecosystem services, and coastal protection. For example, beach tourism constitutes a substantial share of the global travel industry, generating billions of dollars annually. Moreover, tourism and "sun and sea" recreational activities can generate socioeconomic impacts even away from the coastline (Houston 2024; Marzetti Dall'aste Brandolini 2006; Stronge 2005). The tourism and hospitality sectors supported by beaches are also major sources of employment (Houston 2013, 2024).

Because beaches and dunes are inherently dynamic systems, it is crucial that their design accounts for both historical drivers of change and a projection of future scenarios, specifically considering the impacts of socioeconomic development and climate change. Sea-level rise and potential alterations in the frequency and intensity of storms could significantly influence present coastal dynamics and resilience. Restoring beach and dune systems requires understanding the past, present, and possible future physical system dynamics (sediment budgets, associated hydrodynamics, sediment dynamics, and interactions with ecological systems), which are critical for determining the scale and feasibility of a given project (Brayshaw and Lemckert 2012; Lodder et al. 2021; Smith et al. 2012). Nature-based adaptation approaches in sandy shores can involve different strategies, discussed below.



The Netherlands
Photo by Tuna Ekici on Unsplash

SUITABILITY CONSIDERATIONS

To make sure that beaches and dunes are healthy and resilient against environmental changes, a range of conditions must be taken into account when determining the site of the NBS. These site suitability considerations apply to all types of NBS, including protection, restoration and enhancement, and hybrid interventions.

Location and climate: Sandy coastlines vary globally based on climate, environment, and geomorphology (Luijendijk et al. 2018). Often densely developed for tourism and real estate, beaches are dynamic landforms with shifting boundaries. Their size depends on slope, sediment supply, tides, and wave energy (Wright and Short 1984), with dunes forming as small ridges within the system.

Hydrology / Hydrodynamics: Sand transport in the coastal zone is mainly driven by waves. However, this only holds within a zone of limited cross-shore width. The strip along the coast where sand transport is mainly driven by waves is called the *active coastal zone*. Therefore, beaches span from the depth of closure, which the seaward limit where waves affect morphodynamic processes within a specific timescale, to the highest elevation reached by waves, which constitutes the transition to the dune system.

Hydrodynamic processes and the relative contributions of different mechanisms to sediment transport and morphologic change differ as functions of beach state depending on whether the surf zone and beach are reflective, dissipative, or in an intermediate state (Wright and Short 1984). Conditions of persistently high wave energy combined with abundant and/or fine-grained sediment results in maintaining highly dissipative states, which exhibit very low mobility. Relatively low mobility is also associated with persistently low-steepness waves acting on coarse-grained beach sediments when the modal beach state is reflective. The greatest degree of mobility is associated with intermediate but highly changeable wave conditions, medium-grained sediment, and a modest or meager sediment supply. Under such conditions, the beach and surf zone tend to alternate among the intermediate states and to exhibit well-developed bar trough and rhythmic topographies (Wright and Short 1984). In general, large tidal ranges produce flatter beach sections, often resulting in the formation of terraces (Masselink and Short 1993). Hence, the hydrodynamic conditions help define suitable zones for NBS interventions, as they can be a key driver shaping coastal morphodynamics.

Sediment transport: Although beach areas naturally change with seasons and between years, a shoreline where sediment budgets are maintained over time ensure that short-term erosion—such as the temporary and rapid loss of beach or dune material over hours to days from a storm—does not lead to long-term or chronic erosion, which occurs gradually over years or decades. Long- and cross-shore sediment rates and processes are central to understanding the underlying causes of erosion and planning of effective solutions for sandy shores. Suitability criteria for identifying effective solutions include understanding historic causes of shoreline change, the availability of sediment sources, adequate grain sizes, strategic consideration of placement areas, ecological impacts, and long-term durability.

Sediment size: Beaches are formed with coarse particles ranging in diameter from 63 microns to 2 millimeters, which can be biogenic sediments (erosion products of marine deposits or framework-building organisms such as coral reefs) or clastic sediments (weathering products of rock fragments). Dune sand properties are similar to those of beach sand, as dunes are supplied by beach sand, but sorting by wind and waves can create spatial variations in grain size across the beach and dune system.

Slope: Typical elements in a sandy beach and dune system suitable for an NBS intervention may include long-shore bars or a reef system, beach cusps, and dunes. *Dissipative beaches* present surf zones 300–500 meters wide, shore normal bars and troughs, low-slopes (0–2 degrees), wide beach faces, and fine sand. *Reflective beaches* are characterized by steeper narrow beach faces and slopes (5–10 degrees), coarser sediment of even pebbles, a narrow surf zone; they often present cusps on the upper part (Wright and Short 1984). Dunes have a better chance of developing over an extensive area with gentle slopes and where wind processes can accumulate sediment (Barman et al. 2016).

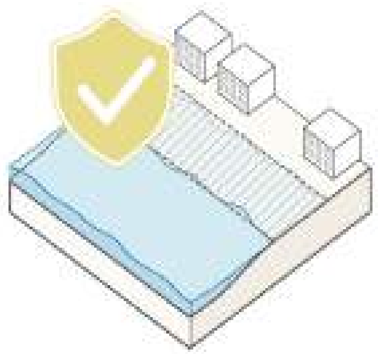
Hvide Sande, Denmark
Photo by Jo Filmmaker on Unsplash

NBS INTERVENTIONS

PROTECTION MEASURES

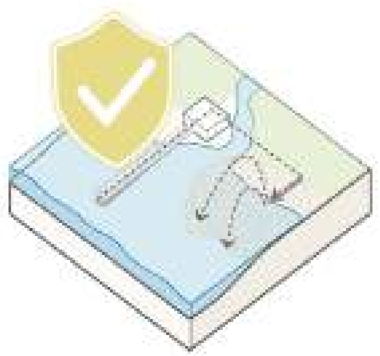
Beach management

The natural coastal protection offered by beaches and dunes can be maintained with effective management strategies that ensure the natural processes that shape sandy shores are safeguarded. Techniques include installing fences to prevent trampling, organizing beach access, creating designated paths to minimize vegetation damage on dunes, and placing informative signs to educate visitors about the importance of these ecosystems. Also construction in areas that impede the exchange of sediments across- and along-shore should be avoided (Eichmanns et al. 2021; Johnston et al. 2023; Staudt et al. 2021). Such interventions can not only maintain physical beach integrity but also support biodiversity and enhance the natural resilience of the beaches.



Setback zones

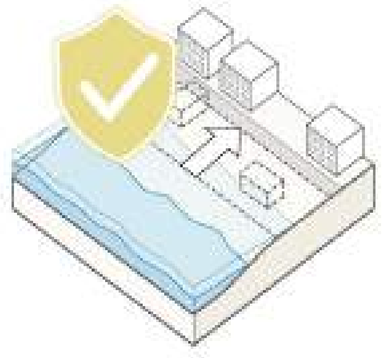
At the governance level, the enforcement of zoning laws and setback regulations serves to limit pressures on the natural processes of the shoreline. Coastal setbacks and other forms of development limits on the active parts of the beach and dune systems are an effective way to ensure sandy shores' stability and functions in the longer term. A *coastal setback zone* is a buffer area where certain or all types of development are prohibited or restricted. A setback zone is usually defined by a specific distance from the shoreline, where the shoreline is often defined by the highest water mark or permanent vegetation line. The main functions of the coastal setback zone are to provide protection from coastal flooding and erosion and to support coastal uses and economic activities, to provide shoreline access, and to maintain the natural processes of the beach (Williams et al. 2018).



Restoring sediment balances and natural processes

Restoring sediment transport processes can also be an effective way to protect and restore sandy shorelines. This type of strategy aims to maintain the sediment budget's equilibrium. The main goal is to achieve a balance between the inputs (gains) and outputs (losses) of sand in a coastal system such as a beach, dune, or shoreline (Clayton 1980). The successful management of sandy beaches to restore and sustain sand budgets (e.g., via nourishment), depends on the kind of mitigation undertaken, local beach characteristics, and the source of "borrowed" sediment (Hanley et al. 2014).

Sand bypassing, for example, is the process of restoring natural sediment transport, often with engineered interventions, that was interrupted by artificial structures or sand deficits (e.g., sand mining). These types of sediment management solutions can be critical for coastal erosion control, navigation safety, and shoreline stability. Techniques can involve improving existing structures or removing sediment barriers, such as groins, to allow for natural sediment transport. The redistribution of sediment can be also achieved by mechanical means (e.g., dredging and pumping); by ongoing sediment bypassing with pumps and pipelines (Brayshaw and Lemckert 2012); and through channels, artificial inlets, sand trapping, and relocation strategies.



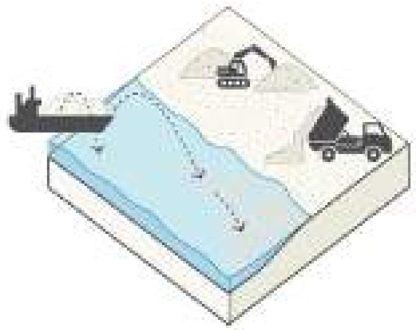
Managed retreat and realignment

Managed retreat and realignment is a coastal management strategy that allows the shoreline to move inland to deal with sea-level rise and coastal erosion. It often refers to the purposeful, coordinated movement of people and buildings away from risks.

Managed retreat can often be combined with setback zones. Hard coastal structures disrupt natural shoreline processes (such as tidal exchange) and can exacerbate erosion and flooding (Brayshaw and Lemckert 2012; Rangel-Buitrago et al. 2017).

Other similar strategies refer to regulated tidal exchange and depoldering or removing levees or groins, which are often used in managed realignment strategies. Instead of using hard structures such as seawalls or groins, managed realignment approaches allow the shoreline to readapt and coastal habitats to retreat, creating buffer spaces from coastal hazards (Rangel-Buitrago et al. 2017). Removing and/or retreating structures and buildings can also restore natural dynamics and lower long-term costs while offering environmental and recreational benefits. By removing these obstacles, managed realignment strategies can accommodate future changes in the shoreline. However, the viability of managed realignment strategies depends on factors such as land use, property ownership, and available space.

RESTORATION AND ENHANCEMENT MEASURES



Nourishments

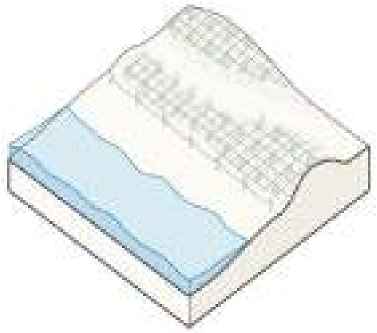
Beach nourishment can provide resilient coastal protection and recovery from storms (Houston 2022). Beach nourishment techniques involve the addition of sediment to coastal areas to expand beach width and/or raise the elevation of the shoreline by supplementing sand, which can be subsequently redistributed by natural coastal processes including wave action, currents, and wind. However, nourishment solutions can also have ecological impacts, and their design and planning should consider how to minimize ecological impacts by restoring habitat and ecological values (de Schipper et al. 2021). Effective nourishment strategies require a thorough understanding of site-specific factors such as wave climate, water-level fluctuations, and wind dynamics to enhance performance and longevity.

Nourishments can be constructed using various sediment types and sizes that can be placed on the above-water beach profile or submerged (nearshore) beach profile. In general, there are three main types of beach nourishment. They differ in where along the shore profile sediment is deposited: on the beach, the shoreface, or the dune (Speybroeck et al. 2006). Beach and dune nourishments require the sediment to be tilled after the nourishment has taken place, For the shoreface nourishment, it is only necessary for the dredger to deposit the sediment in the nearshore zone. Sediment size is also a central part of nourishment design. Nourishments that use coarser-grained sand are expected to create and maintain steeper and wider beach zones, whereas sediment that is finer than the native sand can stimulate dune growth through wind-blown transport but can be more quickly (and even permanently) washed offshore by waves (de Schipper et al. 2021). Therefore, the design and implementation of nourishment projects must account for the inherent variability of sandy coastal systems, which are subject to cycles of erosion and accretion.

Beach nourishment design should also consider combining with other solutions, including structures, revegetation programs, and dune restoration strategies. While nourishment solutions can help address sediment deficits temporarily, mitigating the underlying drivers of coastal erosion is essential to ensure sustainable outcomes; otherwise, these interventions may require repeated maintenance and reapplication (Griggs and Reguero 2021; Houston 2013, 2024).

Headlands and modified breakwaters for shoreline stability

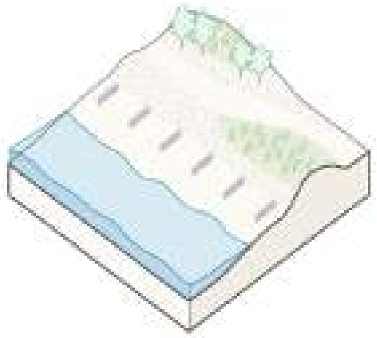
Shoreline structures such as groins and breakwaters interrupt the natural movement of sediments and can often lead to downstream erosion. These impacts can be mitigated through designs that are more permeable to sediment transport such as artificial headlands or reefs, or by optimizing and/or removing structure to enhance sediment bypassing and reduce downstream erosion (Hoggart et al. 2015; Rangel-Buitrago et al. 2017).



Dune restoration

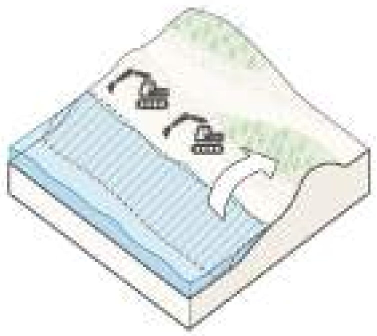
Dune restoration involves repairing or rebuilding sand dunes to enhance their ability to protect the coastline and support environmental goals (Antunes do Carmo et al. 2010). This strategy may involve both natural recovery methods and active human intervention to stabilize and rebuild dune systems that have been damaged by erosion, storms, or human activity. Dune restoration and management involve techniques to stabilize sand (Borsje et al. 2011) include installing sand fences and geotextiles to reduce wind erosion, nourishing sand, and constructing boardwalks to limit foot traffic damage (Gracia et al. 2018; Moreno-Casasola et al. 2008). Techniques for dune restoration include (Coastal Restoration Trust 2011; Denning et al. 2024; IHCantabria 2007; NSW 2001):

- **Sand fencing:** This involves installing wooden or plastic sand fences to capture wind-blown sand and facilitate the accumulation and initiation of dune formation.
- **Vegetation planting and stabilization:** This involves planting native dune vegetation—such as marram grass (*Ammophila arenaria*) or sand couch (*Elytrigia juncea*)—with root systems that can help enhance dune stability. The presence of this vegetation encourages additional sand accretion by trapping airborne particles (White et al. 2024).
- **Sand nourishment:** This involves mechanically placing sand onto eroded or diminished dunes to restore their height and volume. Sand nourishment is often integrated with vegetation planting and sand fencing to optimize dune rehabilitation and long-term persistence.



Other dune stabilization techniques

The natural balance of beach-dune processes can be disrupted by factors such as grazing, beach traffic, construction projects, vegetation loss, and groundwater extraction, leading to dune degradation and reduced coastal protection during extreme events. Vegetation loss can also increase inland sand drift, affecting coastal zones. Dune stabilization techniques aim to reduce dune degradation and may involve revegetation, protecting native vegetation, limiting access over the dune, and using aeolian sand traps to enhance sediment stability. Planting dune grasses, thatching with plant debris, and installing fencing along the seaward face help reduce erosion, mitigate wave and wind impacts, and prevent shoreline retreat.

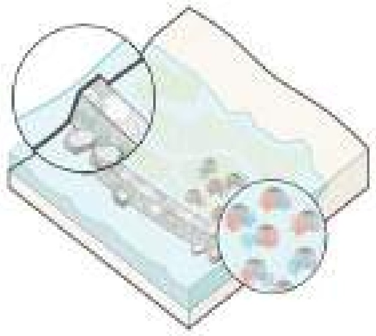


Beach scraping

Beach scraping refers to the process of mechanically removing a layer of sand from the foreshore and transferring it to the backshore. Beach berms are often formed during summer wave conditions; beach scraping involves the artificial relocation of course materials in the beach berm toward the backshore to strengthen the upper part of the beach profile and the dune systems (Bruun 1983). Beach scraping is different from beach nourishment: while nourishment involves sand being imported from outside the active coastal zone, beach scraping aims to redistribute the sand within the active coastal system. When the scraped sand is placed on the dune or applied to the dune foot, it helps reinforce the dune protection function. Beach scraping can be viewed as mimicking the natural recovery of the beach profile after storm erosion. This method may be adequate in areas exposed to seasonal erosion or acute storm events. The ecological impacts of incidental beach scraping are generally minor. However, beach scraping does not contribute to the overall stability of the beach profile.

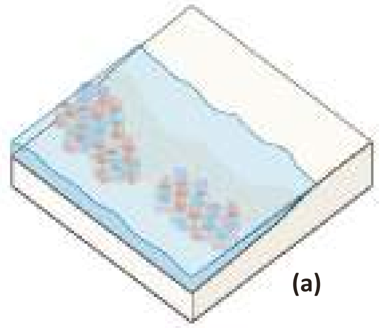
HYBRID INTERVENTIONS

On chronically eroding shorelines, coastal armoring structures can contribute to the degradation of the beach and dune systems both directly in front of and adjacent to these structures, which reduces recreational opportunities and diminishes the natural protective functions provided by beaches and dunes. However, coastal managers often use armoring to protect upland developments by reducing direct wave impact. This inherent conflict between preserving beach and dune systems and safeguarding upland infrastructure can be addressed through innovative designs and soft engineering approaches (Cooper and Mckenna 2008; Pilkey and Cooper 2012). On sandy coastlines, sand nourishment can be combined with other solutions, such as multifunctional levees and boardwalks, to provide additional flood protection and reduce wave impact on coastal structures (Terchunian 1988). For example, the use of groins and submerged/emerged breakwaters have been traditionally used with beach nourishment to help stabilize coastlines and mitigate erosion. Groins are shore-perpendicular structures that trap sand, while detached breakwaters are shore-parallel structures that reduce wave energy and create "shadow zones" for sediment retention. Other examples of hybrid interventions are perched beaches, where a submerged breakwater enhances sediment accumulation on a previously existing natural beach, and artificial pocket beaches, developed between two shore-normal structures (such as groins and breakwaters) (González et al. 2010). Some of the most comment hybrid interventions are described below:

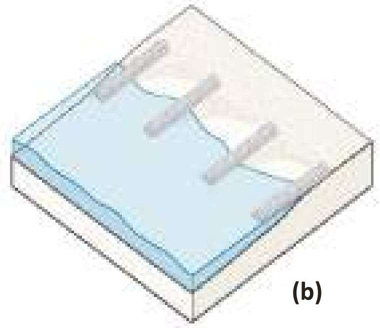


Perched beaches

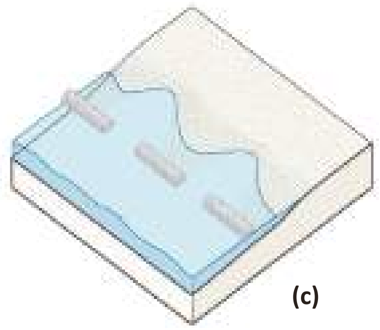
Natural perched beaches are a common feature of cliff coasts fronted by a shore platform (Gallop et al. 2012). They generally consist of coarse material (sand, pebbles, and even boulders) resulting from local cliff erosion. Similar to these natural forms, artificial perched beaches can be designed with an artificial sill, generally consisting of rubble mound structures (Gallop et al. 2011; González et al. 1999). A perched beach provides a wider beach at locations where the natural beach has become too narrow and low as a result of erosion of the *coastal profile*. The perched beach concept is often used in situations where the coastline has been fixed with a hard structure (such as a seawall or revetment) that has accelerated the erosion of the natural beach. Restoring an equilibrium *coastal profile* requires sand fill (artificial nourishment) of the subtidal beach down to the *closure depth*. The required amount of sand depends on the mean grain size and can be very large if the sand available for beach fill is of the same quality as or slightly finer than the natural sand. A submerged sill to support the lower part of the beach profile considerably reduces the amount of sand needed for nourishing the beach. The perched beach concept applies to exposed or moderately exposed shorelines with perpendicular or near-perpendicular wave incidence at locations with a steep and eroded coastal profile.



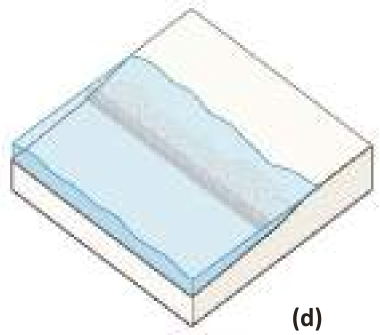
(a)



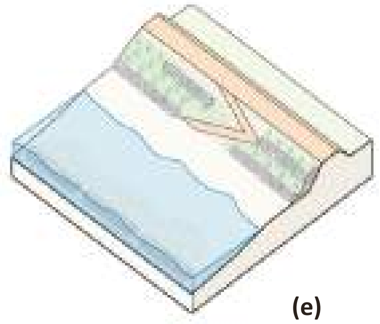
(b)



(c)



(d)



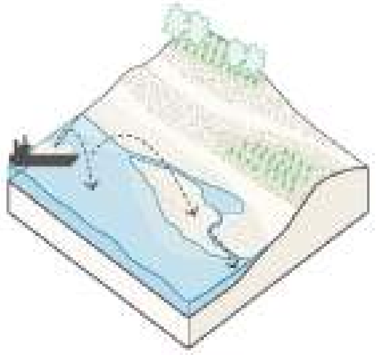
(e)

Erosion control structures

Shoreline erosion control structures such as groins and detached breakwaters, beach nourishment, or a combination of structures and sediment addition are the most common responses to beach erosion. The selection of the appropriate technique requires taking into consideration the physical and economic conditions (e.g., wave climate or quarries), the social environment (e.g., aesthetic rules or tourism), and the environmental impact of construction and service (e.g., material footprint, reversibility, or pollution):

- **Submerged coastal structures (a)** are frequently regarded as an effective way to provide beach protection while mitigating the negative impacts—such as loss of beach amenity and diminished aesthetic value—commonly associated with traditional coastal defenses like detached breakwaters and groins (Ranasinghe and Turner 2006). Submerged structures involve artificial reefs, implemented as submerged artificial features, and frequently serve as multipurpose low-crested structures. The deployment of these reefs involves introducing a hard substrate into a predominantly soft-bottom environment, thereby inducing changes to both the abiotic and biotic characteristics of the habitat.
- **Groins (b),** normally perpendicular to the shoreline, block (part of) the littoral drift and trap sand on their upstream side. Groins can have various shapes and they can be emerged, sloping, or submerged; they can also be single or deployed in groups; and they are normally built as rubble mound structures, but they can also be constructed with other materials, such as concrete units and timber. Groins can also be designed as permeable structures to allow certain sediment bypassing (Torres-Freyermuth et al. 2020).
- **Detached breakwaters (c),** which represent a principal category of shoreline erosion control measures, are most often installed parallel to the shoreline, functioning to dissipate incoming wave energy before it reaches the coast.
- **Low-crested structures (d)** are a type of breakwater that present a low or submerged crest that facilitates partial wave transmission over the structure. Notably, increasing the crest freeboard amplifies the aesthetic intrusion and further reduces the transmission of wave energy to the beach.
- **Innovative hybrid infrastructure solutions (e)** can combine these traditional approaches with natural and built features—for example, in areas where there is little space to implement natural approaches alone (van Slobbe et al. 2013; Sutton-Grier et al. 2015; Waryszak et al. 2021).

Mega nourishment strategies



Conventional beach nourishment projects for erosion control typically have a lifespan of several years, after which re-nourishment is required. Each intervention, however, may disrupt the local ecosystem due to the repeated disturbance. Mega-nourishment strategies represent a distinct approach that is characterized by the placement of sand volumes various times greater than traditional nourishment solutions in a single, strategically selected location. This method enables sustained sediment dispersion and long-shore transport by waves and wind over decades, thereby reducing the frequency of direct human intervention and minimizing ecological disturbance. Deployed at this larger scale, mega-nourishment can promote dune formation, support the establishment of new ecological habitats, and enhance the recreational value of the coastal zone. Beach mega-nourishment projects are often installed in combination with other natural and engineered systems (Brown et al. 2016). An emerged, concentrated nourishment along a sandy shore, whereby part of the nourishment is dry, can also provide space for recreation, water sports, and beach lovers. In addition, new dunes and vegetation could develop, increasing the area's environmental value (Brière et al. 2018; Herman et al. 2021).

Reinforced and artificial dunes

The role of the coastal dune system as a natural barrier against coastal inundation has long been recognized. Artificial dunes, specifically designed for coastal protection, can also serve to protect from flooding and erosion by creating sand buffers in the backshore (Magliocca et al. 2011; Matias et al. 2005). Reinforced dunes are a type of engineered sand dunes that combine natural dune features with artificial reinforcements—such as geotextiles, sand-filled containers, or buried seawalls—to enhance their ability to resist erosion, withstand storm impacts, and protect coastal infrastructure (Allan et al. 2003; Antunes do Carmo et al. 2009). They are a hybrid solution between nature-based coastal defenses and traditional hard infrastructure (Odériz et al. 2020).

Natural dune growth can also be enhanced in these dunes through sediment addition or traps, offering environmentally sound, flexible coastal defense.

The Gold Coast, Australia
Photo by City of Gold Coast on Unsplash

BENEFITS

Flood risk reduction: Sandy coastlines and dunes play a vital role in protecting coastal areas from storms and flooding. By dissipating wave energy and providing vertical elevation, they reduce the risk and impact of inundation. Additionally, these dynamic landforms can help mitigate climate change effects by trapping sediment and naturally adjusting their shape and height to keep pace with sea-level rise and shifting environmental conditions.

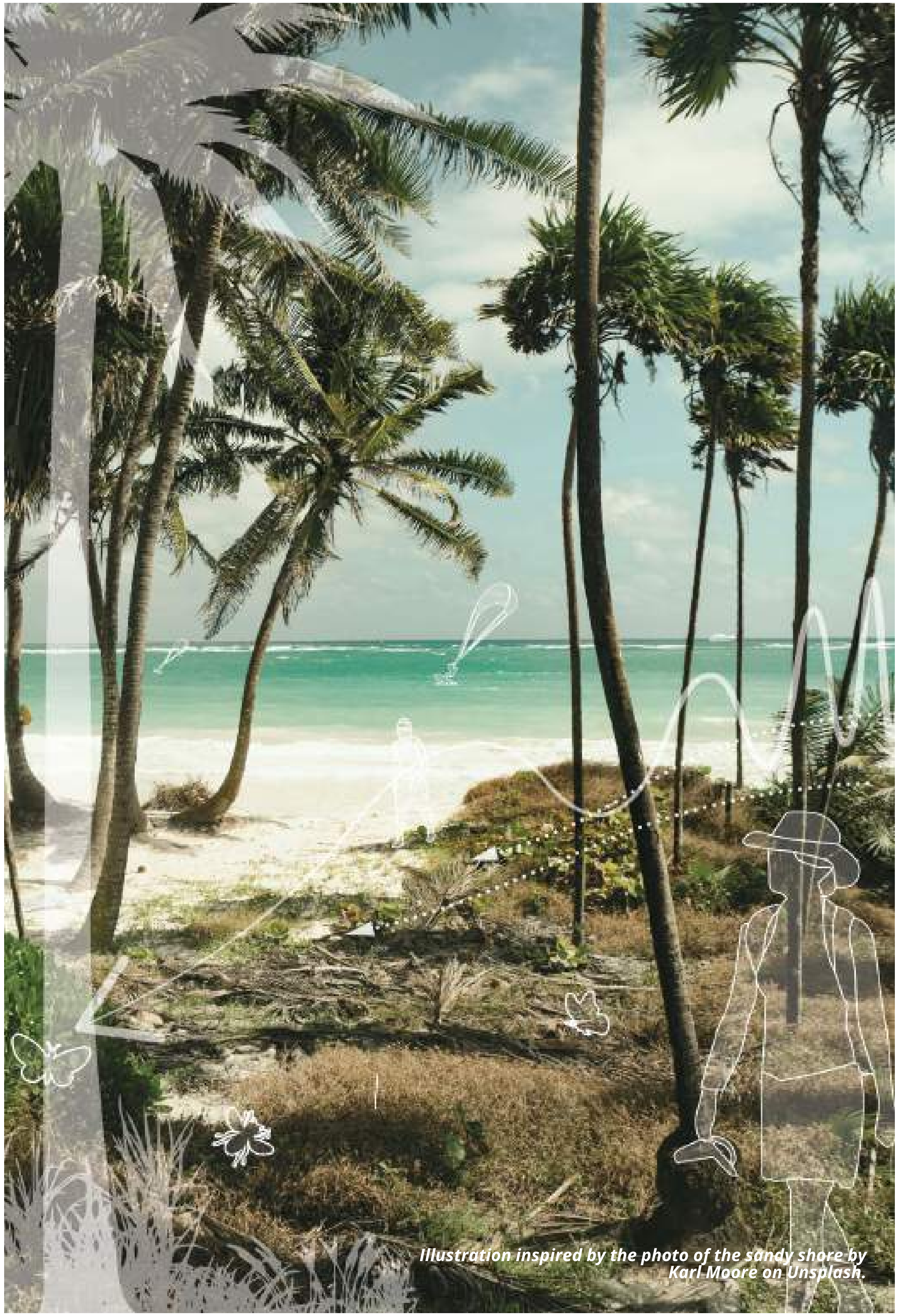
Erosion reduction: A well-maintained beach can reduce erosion and protect the hinterland from loss of land. Dunes also buffer storm erosion and help the beach recover by naturally nourishing the shoreline during extreme events, serving as reserves of sand. Furthermore, vegetation in dunes help prevent erosion and beaches to recover from the impact of storms (Silva et al. 2016) while also helping to trap and store sand that allows dunes to grow and create additional storm protection (Cunniff and Schwartz 2015).

Tourism and recreation: The tourism and recreation value of beaches is among the most significant economic benefits that coastal zones offer. This value stems from the ability of beaches to attract visitors, generate spending, create jobs, and support local and national economies. Sandy shores offer large economic value in coastal regions through tourism and recreation opportunities such as surfing, scuba diving, boating, fishing, swimming, walking, and sunbathing. For example, in Europe, coastal tourism in 2022 generated €238 billion in turnover and €82 billion in gross value added, and it generated employment for over 2.5 million people in coastal regions (European Commission 2025). Moreover, in four Mediterranean countries—Spain, Italy, France, and Greece—coastal tourism accounts for over 70 percent of the tourism sector's economic output. In the United States, there are 1.4 billion visits to US beaches annually that generate an economic output of US$520 billion, with US beach tourists generating annually about US$3,000 in economic output, US$1,400 in direct spending, and US$200 in taxes for every US$1 spent on nourishment (Houston 2024).

Beaches and dunes are a source of aesthetic appreciation—a visual amenity with effects on house prices (Benson et al. 1998; Fraser and Spencer 1998), as well as inspiration for scientific research, cultural production, and art. They are also sites of cultural, social, and educational importance, and represent local cultural and environmental heritage (Nehren et al. 2016; Pérez-Maqueo et al. 2013).

Social Interaction: Coastal environments positively influence social aspects of human well-being. Scenic coastal zones create a strong sense of place, forging a meaningful relationship between people and their surroundings (Jorgensen and Stedman 2006), which helps build social cohesion and deliver multiple public health benefits (Shamai 1991).

The multiple benefits of sandy shores and beaches on a qualitative scale



COSTS

Implementation costs

Protecting vulnerable beaches and dunes can maintain their ability to protect coastal areas from flooding and erosion, along with providing other benefits such as tourism and recreation. Protection measures may be sufficient in areas with low erosion rates and sufficient beach or dune presence. In areas of high erosion, restoration measures, such as nourishment, can be implemented.

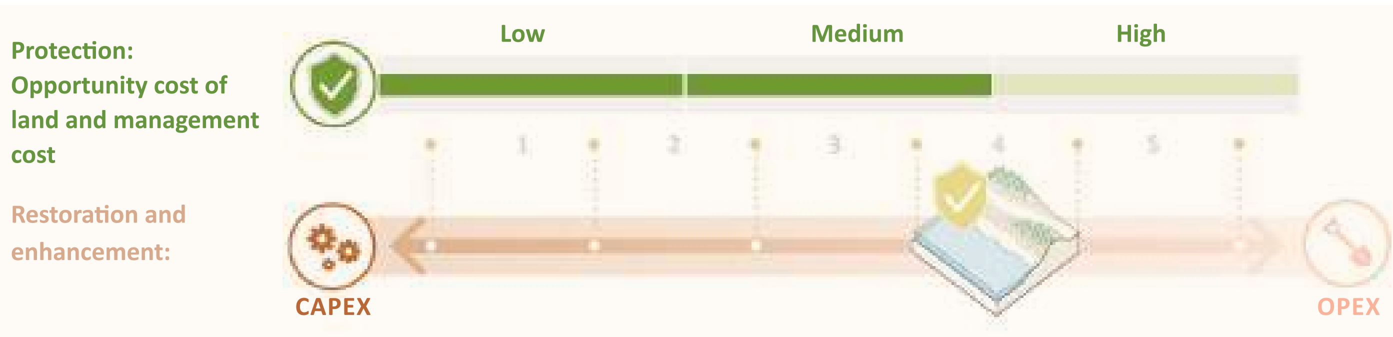
Beach nourishment projects, which involve adding sand to beaches, can range in cost from US$1 to US$4 million per mile of shoreline. These costs encompass infrastructure and the variable expense of acquiring sand. Estimates can fall between US$3 and US$15 per cubic meter when local dredge sites are available, but this can vary (Qiu et al. 2020). For example, a summary of cost for the first beach nourishment campaign for Sydney's beaches for a total of 12 million cubic meters included the cost of dredging and nourishment of US$230 million, the unit cost per cubic meter of sand of US$19 per cubic meter, and related project costs (including impact assessment and consultation) of US$70 million for a total of US$300 million. The total unit cost per cubic meter of sand was US$25. Subsequent campaigns cost US$120 million (Sydney Coastal Councils Group, n.d.). Costs associated with beach nourishment and dune restoration will also depend on local labor, machinery, transportation, and material (e.g., sand) costs.

Operations & maintenance costs

Maintenance costs of beach nourishment and dune restoration are driven by activities such as recurring dredging and sand deposition on these coastal areas and replanting of dune vegetation. The frequency and amount of sand required will depend on coastal erosion rates at the project site. Operations and maintenance costs, for instance for beach nourishment, can have a range between US$100 and US$500 per linear foot; this estimate was based on a 50-year project life (Cunniff and Schwartz, 2015).

Other cost considerations

Access to or ownership of land in coastal areas is required for the conservation and restoration of sandy shores. Land ownership may be public or private. The land area required for beach and dune conservation and/or restoration is large, which increases costs associated and makes engagement and collaboration with multiple landowners and stakeholders necessary.



CAPEX: Implementation costs
OPEX: Operations and maintenance costs

GUIDELINES AND RESOURCES

The resources listed provide guidance for designing traditional shore protection, hybrid interventions, and restoring sandy coastlines, supporting their assessment, planning, and implementation as nature-based solutions. They also include information on creating suitable conditions for sandy shores, as well as guidance on monitoring approaches.

Design guidelines of coastal structures

US ACE (U.S. Army Corps of Engineers). 1984. *Shore Protection Manual Volume 1*. Vicksburg, Mississippi: US ACE. https://usace.contentdm.oclc.org/digital/collection/p16021coll11/id/1934/

Hybrid infrastructure designs

Lodder, Q., Jeuken, C., Reinen-Hamill, R., Burns, O., Ramsdell, R. III, de Vries, J., McFall, B., IJff, S., Maglio, C., and Wilmink, R. 2021. Beaches and Dunes. In *International Guidelines on Natural and Nature Based Features for Flood Risk Management*, edited by Bridges, T. S., J. K. King, J. D. Simm, M. W. Beck, G. Collins, Q. Lodder, and R. K. Mohan. Vicksburg, MS: U.S. Army Engineer Research and Development Center, Chapter 9. https://issuu.com/poweroferdc/docs/nnbf-guidelines-2021/358?fr=sNTZjYzQyNjA2NDI

Sandy shore restoration guides

Adapta Blues. 2023. *Catalogue of Adaptation Measures to the Effects of Climate Change in the Coastline*. https://lifeadaptablues.eu/wp-content/uploads/2023/04/Catalogue_EN.pdf

Morris, R. L., Bishop, M. J., Boon, P., Browne, N. K., Carley, J. T., Fest, B. J., Fraser, M. W., Ghisalberti, M., Kendrick, G. A., Konlechner, T. M., Lovelock, C. E., Lowe, R. J., Rogers, A. A., Simpson, V., Strain, E. M. A., Van Rooijen, A. A., Waters, E., and Swearer, S. E. 2021. *The Australian Guide to Nature-Based Methods for Reducing Risk from Coastal Hazards*. Earth Systems and Climate Change Hub Report No. 26. NESP Earth Systems and Climate Change Hub, Australia. https://nespclimate.com.au/wp-content/uploads/2021/05/Nature-Based-Methods_Final_05052021.pdf

World Bank. 2021. *A Catalogue of Nature-Based Solutions for Urban Resilience*. Washington, DC: World Bank Group. http://hdl.handle.net/10986/36507

In addition, the Nature-Based Solutions Opportunity Scan (NBSOS) is a tool that helps identify NBS investment opportunities, providing information on NBS types, suitable locations, costs, and coastal protection benefits and co-benefits. It supports decision-makers in integrating NBS into planning, and investment strategies for both urban and coastal areas.

SANDY SHORES (BEACHES AND DUNES) CASE STUDIES

PROJECT #1
Rehabilitation Following Diamond Mining in the Pocket Beach Areas, Namibia (2004–05)

PROJECT #2
Dune Restoration Project in Rio Grande do Sul, Brazil (2011–16)

PROJECT #3
Natural Groins, Casamanca River Mouth, Senegal (2018–22)

PROJECT #4
Sand Engine Combined with Structures, Togo-Benin (2022–23)

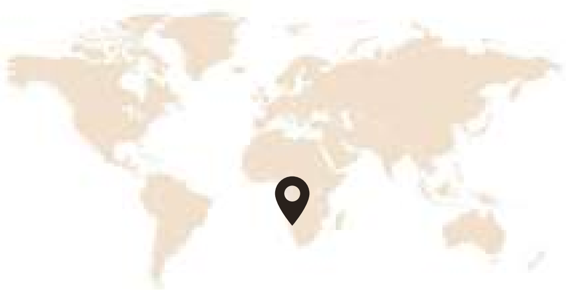
Schiermonnikoog, the Netherlands
Photo by Jonah Geurs on Unsplash

PROJECT #1
Rehabilitation Following Diamond Mining in the Pocket Beach Areas, Namibia (2004–05)

Aerial view of post-mining rehabilitation in pocket beach areas, Namibia (2004–05). Photo by Google Earth.

Location

Sperrgebiet, Namibia



Approach

Restoration and enhancement measures

Size

***0.5 hectares** consisting of 48 experimental plots of 25 x 15 meters each*

Cost

***US$4,955** (low cost)*

Description

This project aimed to rehabilitate dune ecosystems affected by diamond mining. It involved transplanting indigenous plants, assessing substrate types, and using windbreaks to enhance sand accumulation and vegetation growth. The study ran from August 2004 to August 2005, focusing on evaluating the effectiveness of various rehabilitation techniques and spontaneous restoration. Monitoring included growth measurements of transplanted species and natural recolonization by indigenous plants. The results highlighted the importance of managing wind erosion and providing conditions favorable for plant survival and growth.

Benefits

- *Erosion was reduced as a result of increased sand accumulation in areas where windbreak nets were used.*
- *Biodiversity increased, as observed by improved species richness in netted areas, nearly matching undisturbed regions. Plant survival rates were higher in netted areas than in un-netted ones, and there was significant growth of Othonna furcata as a result of effective wind protection and spontaneous recolonization by 75 percent of pre-mining species.*

Biodiversity enhancement

Coastal erosion reduction

Challenges

- *A lack of pre-mining impact assessments hindered initial planning.*
- *Wind erosion risk affected plant survival in unnetted areas.*
- *The high cost of windbreak nets impacted overall budget.*
- *There were limited data on the effectiveness of different substrate types.*
- *Sand deposition varied, affecting the consistency of results.*

Lessons learned

- *Windbreaks significantly enhance sand accumulation and plant survival.*
- *Natural recolonization can restore species richness effectively.*
- *Transplanting native plants requires careful timing and favorable conditions.*
- *Managing environmental factors such as wind and sand is crucial.*
- *Ongoing monitoring is essential for evaluating long-term success.*

Source (reference)

Martínez, M, L., Gallego-Fernández, J. B., and Hesp, P. A., editors. 2013. *Restoration of Coastal Dunes*. Berlin Heidelberg: Springer.

PROJECT #2
Dune Restoration Project in Rio Grande do Sul, Brazil (2011–16)

Aerial view of dune restoration in Rio Grande do Sul, Brazil. Photo by Google Earth.

Location

Osório, Rio Grande do Sul, Brazil

Approach

Restoration and enhancement measures

Size

The restored dune system extends over ***2 kilometers*** *of shoreline.*

Cost

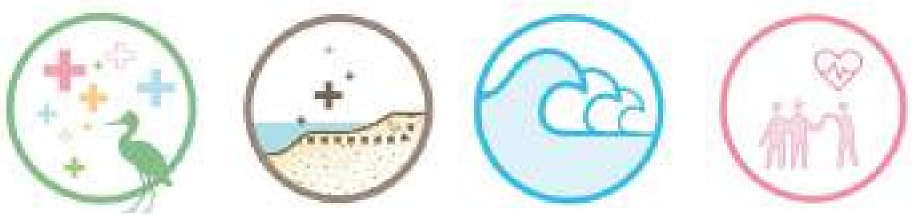
Medium-to-high cost

Description

The Osório Municipality implemented a dune restoration project starting in 2011 to comply with local environmental legislation. The project aimed to restore and increase the width of the dune system to 60 meters following the construction of a housing complex that breached regulations. Key measures included the planned retreat of a road, the stabilization of washout channels, the installation of sand fences, and controlled beach access to protect the dunes. Monitoring surveys over five years (2011–16) revealed that restoration efforts successfully enhanced dune width and stability, improving the area's resilience to coastal erosion.

Benefits

- *Improved dune width and stability, reducing coastal erosion.*
- *Enhanced flood protection against storm surges, safeguarding local infrastructure.*
- *Increased biodiversity with the re-establishment of native pioneer species.*
- *Compliance with environmental regulations, preserving the natural landscape and its social interaction benefits.*



Challenges

- *Sand fences required frequent relocation due to storms, complicating sediment accumulation.*
- *Maintaining washout channels was challenging because of erosion from meandering water flow.*
- *Ensuring long-term stability of washout structures was difficult, with previous failures noted due to wave energy and inadequate design.*

Lessons learned

- *Planned retreat of infrastructure, such as roads, is crucial for successful dune restoration.*
- *Continuous maintenance is necessary for the effectiveness of sand fences and washout channels.*
- *Community involvement and adherence to management plans significantly contribute to the sustainability of restoration efforts.*

Source (reference)

Botero, C. M., Cervantes, O., and Finkl, C. W. 2018. *Beach Management Tools - Concepts, Methodologies and Case Studies*. Coastal Research Library, Volume 24. Springer International AG. https://link.springer.com/book/10.1007/978-3-319-58304-4

PROJECT #3
Natural Groins, Casamanca River Mouth, Senegal (2018–22)

THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP

Community involvement in the construction of natural groins. Photo by Patrick Chevalier.
Source: Coastal NBS in West Africa. Factsheets. *Baseline study West African Case Studies for Coastal Nature Based Solutions*. https://www.hkv.nl/wp-content/uploads/2024/02/AppD-NBS_Factsheets.pdf

Location

Diogué, Casamanca, Senegal

Approach

Restoration and enhancement measure

Size

***8** groins along **1,400 meters** of coastline in Diogué*

Cost

Low-to-medium cost

Description

Permeable groins are used to protect the coastline from erosion while allowing longshore sediment transport. Groins were made of local materials (sticks and palm leaves) and co-designed with the local community.

Benefits

- *Erosion reduction decreased because the groins reduced the wave energy and trapped sediment. The beach width increased by 40 meters from May 2022 to December 2023.*
- *Coastal protection was enhanced as a result.*

Coastal erosion reduction

Challenges

- *Driving the posts can be challenging.*

Lessons learned

- *Maintenance is crucial and can be achieved through community efforts. For this, training is necessary.*

Source (references)

Coastal NBS in West Africa. Factsheets. *Baseline study West African Case Studies for Coastal Nature Based Solutions*. https://www.hkv.nl/wp-content/uploads/2024/02/AppD-NBS_Factsheets.pdf

Erosion Control Experience- Casamance Islands. https://gizc.org/experience-lutte-erosion/

Nature Based Solutions. No date. Fighting Erosion with Nature-Based Solutions. https://www.nature-basedsolutions.com/page/1133/fighting-erosion-with-nature-based-solutions

Sandwatch. No date. Casamance Semi-Permeable Groyne Project. https://www.sandwatchfoundation.org/casamance-groyne-project.html

Chevalier, P. 2022. *Fight against Erosion with Permeable Groynes: Scaling Up the Diogue Experience*. Guide No. 2. https://www.sandwatchfoundation.org/uploads/6/6/9/5/66958447/fighting_erosion_with_permeable_groynes.pdf

PROJECT #4
Sand Engine Combined with Structures, Togo-Benin (2022–23)

Bird's-eye view of the sand motor area combined with structures, Togo–Benin. Photo by Boskalis.
Source: International Association of Dredging Companies. 2024. Sand motor protecting coastal communities in Togo and Benin. *Dredging for Sustainable Infrastructure (DFSI) Magazine*. https://www.iadc-dredging.com/wp-content/uploads/2024/10/DFSI-Magazine-01-Togo-and-Benin-sand-engine-double-pages.pdf

Location

Coastline from Grand Popo, Benin, to Aneho and Agbodrafo,Togo

Approach

Restoration and enhancement measures

Size

***4-kilometer-long** mega nourishment **(6.4 million cubic meters)** and rock groins*

Cost

***US$54 million** (high cost)*

Description

The coastline from Grand Popo in Benin to Aneho and Agbodrago in Togo was experiencing severe coastline retreat, affecting the infrastructure and livelihood of the coastal communities. The project—as part of the West African Coastal Areas (WACA) program—used the concept of a mega nourishment, in combination with groins as a reinforcement strategy, to protect the coastline against erosion.

Benefits

- *A reduction of coastal erosion was gained by strategically placed substantial volumes of sand (mega nourishment) at a location where natural processes by wind, waves, and currents redistribute it along the coastline.*
- *The natural distribution of sediment along the shore was reinforced by the groins, which function as reinforcement systems for this process. Groins also mitigated erosion during extreme events.*

Coastal erosion reduction

Tourism and recreation

Challenges

- *It was challenging to finalize the work within a preferred season to avoid extreme sea conditions.*
- *The community needed to maintain access to their livelihoods (fishing and other daily activities) during the operations.*
- *Obtaining funding was challenging.*

Lessons learned

- *Planning, coordination, and stakeholder engagement were crucial.*
- *This project demonstrated that the sand motor concept can be successfully adapted to new regions to reduce erosion.*

Source (reference)

International Association of Dredging Companies. (2024). Sand motor protecting coastal communities in Togo and Benin. *Dredging for Sustainable Infrastructure (DFSI) Magazine*. https://www.iadc-dredging.com/wp-content/uploads/2024/10/DFSI-Magazine-01-Togo-and-Benin-sand-engine-double-pages.pdf

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HINTERLANDS

The Gold Coast, Australia
Photo by City of Gold Coast on Unsplash

FACTS AND FIGURES

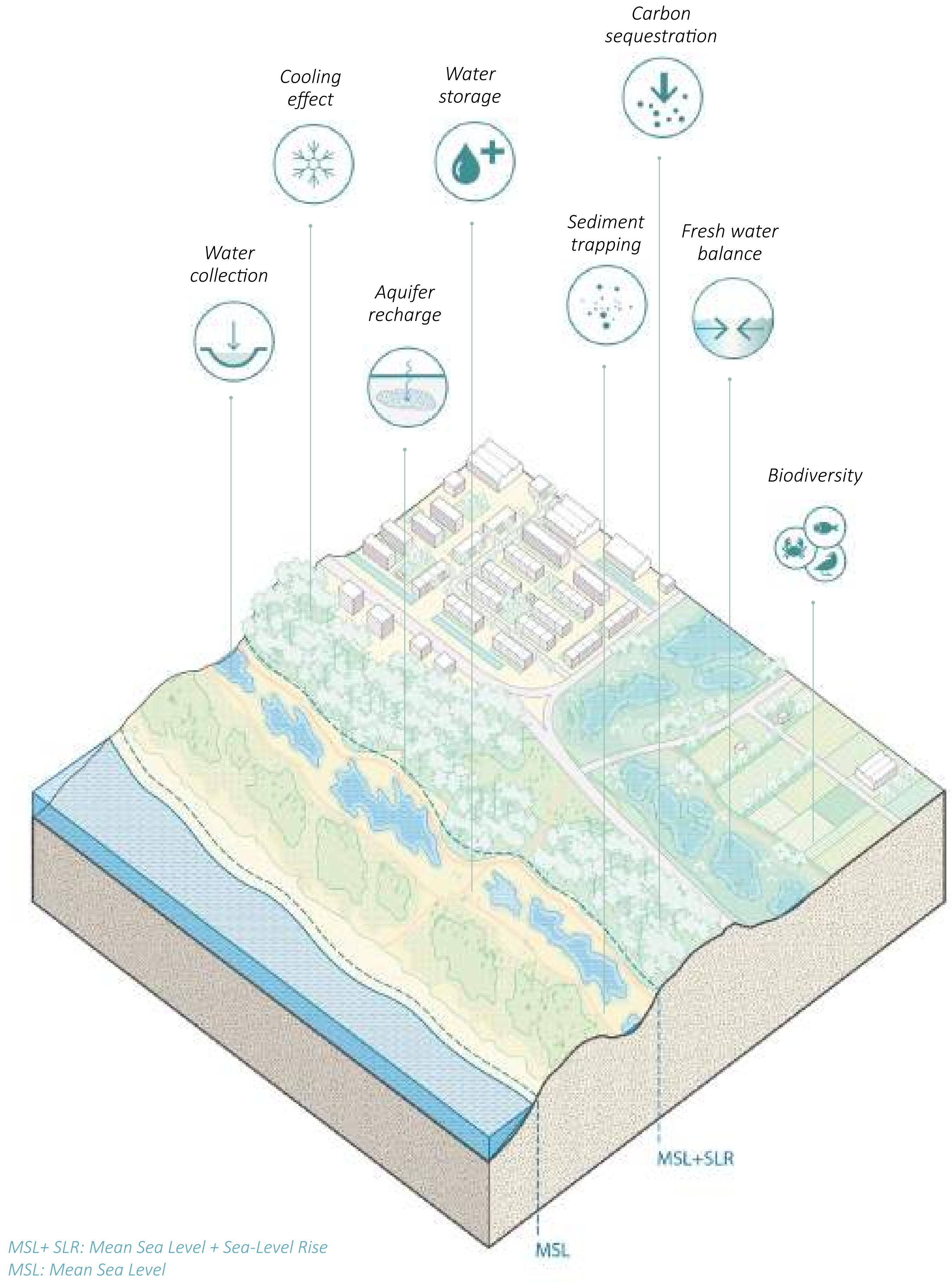
Coastal hinterlands are defined as the landward areas beyond the coastal zone. They include inland grasslands, wetlands, inland sedimentary landforms, and forests and other vegetation that grow in freshwater or brackish environments, inland from the shoreline but still part of the coastal system. They serve as transitional regions between the ocean and inland environments (Mangor and Dronkers 2024) and can include forests, grasslands, wetlands, and stationary dunes. However, the characteristics of the coastal hinterland landforms vary depending on their geographical location, climate, and proximity to the sea (McLachlan and Brown 2006). Unlike salt marshes (see the *Salt Marshes chapter**) and other coastal ecosystems covered in other chapters, hinterland features are not directly influenced by coastal dynamics but play a fundamental role in the preservation of other coastal defenses, ecological functions, and human activities.*

Coastal hinterlands serve as natural buffers, protecting inland areas from coastal hazards, winds (Benazir et al. 2024), and seawater intrusion (Middleton and Boudell 2022). Their vegetation stabilizes soil, reducing erosion and supporting the resilience of adjacent ecosystems such as salt marshes, mangroves, and beach and dune systems. Coastal hinterland areas can play a key role in the hydrological cycle, as they affect rainwater runoff and flooding.

Although coastal hinterlands typically do not provide direct protection against flooding, they contribute to flood safety by enabling other ecosystems and infrastructures to function and adapt. In addition, coastal hinterlands provide other critical ecosystem services such as carbon sequestration and groundwater replenishment (Murray et al. 2019); they also provide habitat for diverse flora and fauna (Lockwood and Maslo 2014), as well as space for agriculture and recreation (Ramsar Convention Secretariat 2016). Furthermore, they serve as ecological corridors linking inland ecosystems to the coast (Balbar and Metaxas 2019; Merenlender et al. 2022) while also sustaining significant human activities, including agriculture, forestry, and tourism (O'Mara 2012).

However, coastal hinterlands are under pressure from climate change impacts such as rising sea levels, extreme weather events, and saltwater intrusion (Ross et al. 2020). For instance, hinterland ecosystems often depend on freshwater and can degrade with excessive exposure to saltwater. Other environmental stressors include urban and industrial expansion, pollution, and overexploitation of water resources (Schneider et al. 2017).

Preserving these hinterlands is essential for coastal resilience strategies because these areas ensure the protection and long-term balance of other shoreline systems. They are also essential to human activities and the ecological integrity of the coastal zone. Nature-based solution (NBS) interventions can aim to protect existing, healthy hinterland ecosystems (protection measures), restore or enhance degrading areas (restoration and enhancement measures), or they can be combined with hard structures such as levees (hybrid interventions).



Visualizing the processes and benefits of hinterlands.

SUITABILITY CONSIDERATIONS

To ensure that hinterland areas can function effectively as resilient NBS, it is important to assess their suitability requirements.

Location and climate: The location and climate of coastal hinterlands influence the suitability of NBS such as forests, wetlands, and grasslands. Temperature, precipitation (Butterfield et al. 2018), and salinity (Zeng et al. 2020) determine which ecosystems can be restored or integrated and how to manage these areas. For example, wetlands require specific moisture and salinity levels to thrive (Barbier 2011a), and forests depend on climate-adapted species for long-term stability. Climate shifts can alter the ability of these ecosystems to function, making careful management and future climate considerations essential for resilience.

Hydrology: The hydrology of coastal hinterlands influences the viability of NBS such as forests, grasslands, and wetlands. Managing groundwater and surface water interactions is crucial for successful interventions (Gedan et al. 2011). Wetlands adapt to fluctuating water levels and periodic inundation (Barbier 2011b), while forests require stable moisture for long-term growth. Preserving natural water dynamics supports flood regulation, habitat restoration, and water quality improvement (Temmerman et al. 2013).

Salinity: Salinity also plays a critical role in coastal hinterlands as it influences which species can establish and thrive. Salt-tolerant species, such as saltbushes, thrive in saline conditions (Adam 2002), whereas freshwater-dependent plants (such as willows) will not succeed in these environments. Coastal forests with salt-adapted species can tolerate salinity up to 2–5 parts per thousand, while grasslands generally thrive below 10 parts per thousand (Eliáš et al. 2013). Beyond these thresholds, seed germination and plant growth decline, influencing species selection, their spatial arrangement, and overall ecosystem functioninsg, and thereby affecting the effectiveness of NBS (Keddy 2010).

Wave exposure, current velocity, and wind velocity: Although not directly exposed to coastal dynamics, coastal forests such as *Casuarina equisetifolia* can withstand short-term flooding and wave exposure during storms (Benazir et al. 2024). Coastal grasslands help buffer wave action but are sensitive to exposure intensity (Temmerman et al. 2013). Wind velocity also affects these ecosystems. Strong winds can damage vegetation and erode soil. Forests and grasslands adapted to wind often have specialized root systems or flexible stems, but areas with persistent winds may require robust species or interventions such as windbreaks (Laurance and Curran 2008).

Soil: Soil conditions are crucial for coastal forest and grassland ecosystems. Well-drained soils, typically sandy or loamy, are needed to support plant growth while avoiding waterlogging that can hinder root development. Coastal forests benefit from nutrient-rich soils that can withstand occasional saltwater exposure, particularly during storm surges (Hanley et al. 2020). Coastal grasslands thrive in soils with good root penetration and moderate organic content (He et al. 2024).

Slope: Slope is key to minimizing soil erosion, especially in areas prone to runoff and flooding. Coastal forests present gentle to moderate slopes (5–15 percent incline), which promote stability, water retention, and nutrient flow (Haaf et al. 2021). Steeper slopes (greater than 15 percent) can increase runoff and erosion and may need interventions such as terracing or erosion control mats to stabilize the soil (Haaf and Dymond 2024). On steep terrain, more resilient species or protective measures may be needed to prevent soil loss. Coastal grasslands perform best on gentle slopes, offering good drainage without waterlogging (Chhabra 2011).

Cliffs of Moher, Ireland
Photo by Anna Hunko on Unsplash

NBS INTERVENTIONS

PROTECTION MEASURES

Protecting coastal hinterlands is important to maintain other coastal ecosystems' health and services such as flood protection, biodiversity, carbon sequestration, and tourism.

Strategies that protect areas, sustainable land use, and actively managing these areas can be effective. Sustainable land-use practices, such as agroforestry, responsible forestry, and sustainable grazing, are crucial for reducing soil erosion, retaining water, and preventing freshwater salinization. These practices can also support biodiversity and increase the natural resilience of coastal hinterlands to climate-related impacts (Ayyam et al. 2019).

Policies aimed at sustainable development help maintain these areas. Such policies support biodiversity and critical ecosystem services, and buffer human-induced pressures while enabling responsible urban and industrial growth.

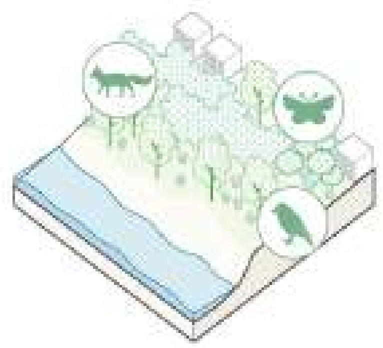
RESTORATION AND ENHANCEMENT MEASURES

Degraded coastal hinterlands can be restored, or healthy areas can be enhanced, through a range of NBS interventions: *Active management*, which involves adaptive strategies and continuous monitoring, can address dynamic threats such as sea-level rise, intensified storms, and shifting land-use patterns. The management of groundwater levels can also be an important part of hinterland preservation and a strategy to prevent saltwater intrusion.

Effective management can focus on promoting natural regeneration: in coastal hinterland forests, natural regeneration can occur through seed dispersal or sprouting from root systems, while grasslands regenerate via seed banks activated by disturbances or vegetative growth from existing plants (López-Barrera et al. 2007). Therefore, ensuring the presence of adequate seed sources, along with proper soil fertility, moisture, and minimal disturbance from human activity or invasive species, are key factors for maintaining these ecosystems (Manning et al. 2006). In areas of abandoned lands (such as brown fields), passive rehabilitation—including natural vegetation growth and phytoremediation, where plants reduce soil contamination—can over time gradually transform into valuable ecosystems (Hunter 2014; O'Connor et al. 2019). Complementary measures, including invasive species control and establishment of buffer zones, ensure long-term sustainability and adaptability to evolving environmental challenges (European Commission 2020).

Hydrological restoration

Hydrological restoration can maintain the ecological integrity of coastal hinterlands, especially in areas affected by human activities or climate change. For instance, hard infrastructure such as dams can hinder freshwater flow, leading to the degradation of riparian wetlands (Schneider et al. 2017). Similarly, hydrological connectivity needs to be considered for preventing and managing saltwater intrusion of coastal aquifers from factors such as overextraction of groundwater, sea-level rise, river discharges, and coastal flooding events. Overall, restoration and hydrological management strategies can increase biodiversity, improve water quality, and enhance the overall resilience of the coastal system (Bullock et al. 2011).



Creating ecological corridors

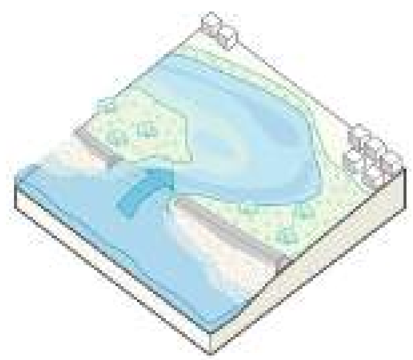
Creating and restoring ecological corridors within coastal hinterlands enhances biodiversity connectivity between inland ecosystems and the coast. These corridors provide safe passage for species, helping to maintain gene flow and enabling species to migrate as environmental conditions change. In addition to supporting biodiversity, these corridors contribute to resilience by linking habitats that provide important ecosystem services such as water filtration and carbon sequestration (Lindenmayer et al. 2006).

Reforestation and afforestation

While *reforestation* restores previously forested areas, *afforestation* introduces forests to regions that were not previously forested; both are vital for stabilizing ecosystems and mitigating climate impacts. Planting native, salt-tolerant, and drought-resistant species specifically adapted to coastal conditions contributes to soil stabilization, erosion prevention, and enhanced carbon sequestration. A strategic approach involves zonation planting, where vegetation is established in zones according to salinity and inundation levels. Upland areas can be reforested with mixed hardwood species to ensure ecosystem functionality. These planting strategies are often complemented by soil stabilization techniques, such as introducing fast-growing pioneers or using grasses, to enhance ground cover, reduce surface erosion, and improve soil structure (Veerkamp et al. 2021).

Creating urban coastal green infrastructure

Creating green infrastructure corridors and projects in the hinterland such as bioretention areas, urban forests, and open green spaces with coastal-adapted species can help manage stormwater, coastal flooding, and erosion, and can provide essential habitat for wildlife (Staddon et al. 2018). Urban coastal green infrastructure can integrate NBS at various scales to enhance community well-being. These interventions can promote ecological health as green infrastructure corridors while offering aesthetic and recreational values to communities. For example, bioretention areas, such as rain gardens and bioswales, capture and absorb rainwater runoff, reducing the pressure on stormwater systems and filtering pollutants before they reach the marine environment (Staddon et al. 2018). Vegetated buffer zones can be established between urban developments and dune ecosystems; these can be formed of grasses, shrubs, and trees and can help provide coastal defense against flooding and erosion (Staddon et al. 2018). Plant roots help stabilize soils and absorb excess water, while the zones act as a transition between the built environment and natural coastal habitats. Green infrastructure strategies, therefore, can enhance urban resilience while contributing to the long-term sustainability of coastal ecosystems.



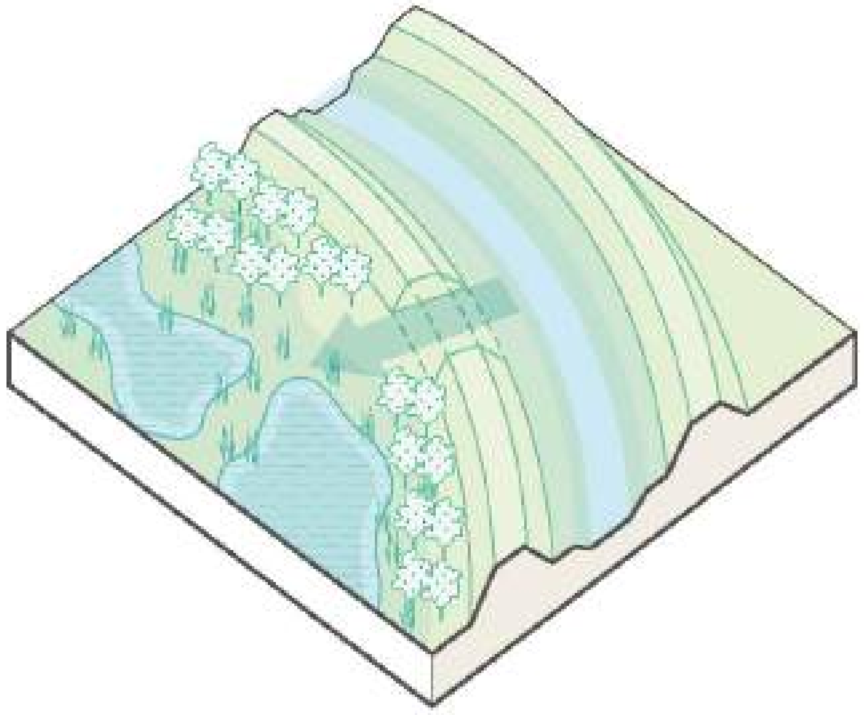
Managed realignment

Managed retreat or *managed realignment* is a coastal management strategy that allows the shoreline to move inland instead of attempting to hold the line. Managed realignment can allow natural processes to reshape coastal areas and enhance the natural ability of coastal ecosystems to mitigate storm impacts (Temmerman et al. 2013). At the same time, coastal ecosystems can be facilitated to expand seaward to form a new line of defense. This approach typically involves removing or adjusting existing defenses and allowing the coastline to evolve naturally, often through the restoration of wetlands and intertidal zones.

HYBRID INTERVENTIONS

Habitat protection or restoration can complement hard infrastructure such as levees. Reforestation in coastal hinterlands near hard infrastructure such as dikes can stabilize soil, prevent erosion, and add ecological resilience, contributing to both flood defense and ecosystem restoration. For example, in some instances, pine forest behind levees has been shown to be effective in reducing tsunami flow and debris (Pasha and Tanaka 2016). Furthermore, buffer zones and floodplain zoning complement hard infrastructure by ensuring that protected areas are open for natural processes (Sakijege et al. 2012). Such synergistic effects contribute to making coastal areas more adaptable to climate change.

The dimensions required for combining hard infrastructure and coastal hinterland interventions will vary depending on the available space, specific coastal conditions, ecosystem characteristics, and flood risk. It is essential to tailor these dimensions to detailed, site-specific assessments that consider local wave heights, storm surges, land availability, and ecological functions needed for successful integration. For instance, buffer zones behind hard infrastructure such as dikes or seawalls may need a range of 50–100 meters, depending on the specific goals (e.g., habitat creation, water retention, or erosion control) and vegetation type. The area should be large enough to allow for natural processes such as sediment accumulation, plant growth, and hydrological functions (Temmerman et al. 2013).



Aiguablava, Begur, Spain
Photo by Guillermo Bresciano on Unsplash

BENEFITS

Flood risk reduction: Coastal hinterlands, including forests, wetlands, and grasslands, reduce flood risks by absorbing excess water, slowing runoff, and lowering peak flow during storms. Wetlands enhance water retention, while grasslands improve infiltration. Furthermore, coastal forests can reduce wave energy and are shown to reduce the impact of extreme tsunami events (Chang and Mori 2021).

Erosion reduction: Flow velocities are reduced within hinterland ecosystems such as freshwater wetlands; these reduced velocities lead to high sedimentation rates. Furthermore, the roots in these areas can help trap sediment, prevent erosion, and help build land in the coastal zone (Mitsch et al. 2014). Similarly, coastal forests—such as casuarina and pine—stabilize sandy soil and prevent erosion through their deep and extensive root systems (Synopsis IAS 2023).

Resources production: Hinterlands support local economies through sustainable agriculture, forestry, and grazing. Practices such as crop rotation and agroforestry maintain soil fertility and prevent erosion (O'Mara 2012). Coastal forests provide timber and non-timber products, ensuring long-term productivity without degrading resources (Gracia et al. 2005). Furthermore, research on the impacts of cattle on coastal dune forest restoration indicates that cattle grazing influences vegetation structure and composition and may hamper restoration (Mpanza et al. 2009.

Tourism and recreation: Hinterlands attract ecotourism through activities such as hiking, wildlife watching, and photography, providing benefits to local communities while helping to conserve habitats (Ramsar Convention Secretariat 2016). These areas also offer access to protected coastal reserves, increasing their recreational value, with dune-forest reserves are ideal for birdwatching and coastal grasslands support rare plant species (Kusler 2006).

Water quality and sediment management: Coastal hinterlands, including wetlands, forests, and grasslands, improve water quality and manage sediment. Vegetation traps pollutants, and wetlands remove nitrogen and phosphorus, while forests and grasslands stabilize soils and reduce erosion. Studies show sediment load reductions of 50 percent to 90 percent, depending on vegetation type (Valente et al. 2021).

Carbon storage and sequestration: Coastal ecosystems, including forests, grasslands, and wetlands, are vital for carbon sequestration. Coastal forests could capture 5–10 metric tons of CO_2 per hectare annually, with *Casuarina equisetifolia* forests sequestering up to an average of 9.1 tons in tropical regions (Ravi et al. 2025); restored coastal grasslands sequester 3–5 tons of CO_2 per hectare annually (Richards et al. 2024).

Biodiversity: Coastal hinterlands (including forests, grasslands, and wetlands) are biodiversity hotspots. Coastal forests shelter terrestrial and avian species, while grasslands support pollinators and grazing wildlife. These ecosystems act as corridors for species movement, offering services such as pollination, pest control, and genetic diversity preservation (Lockwood and Maslo 2014). Coastal grasslands can significantly contribute to biodiversity, with pollination and pest control services (Mpanza et al. 2009).

The multiple benefits of hinterlands on a qualitative scale

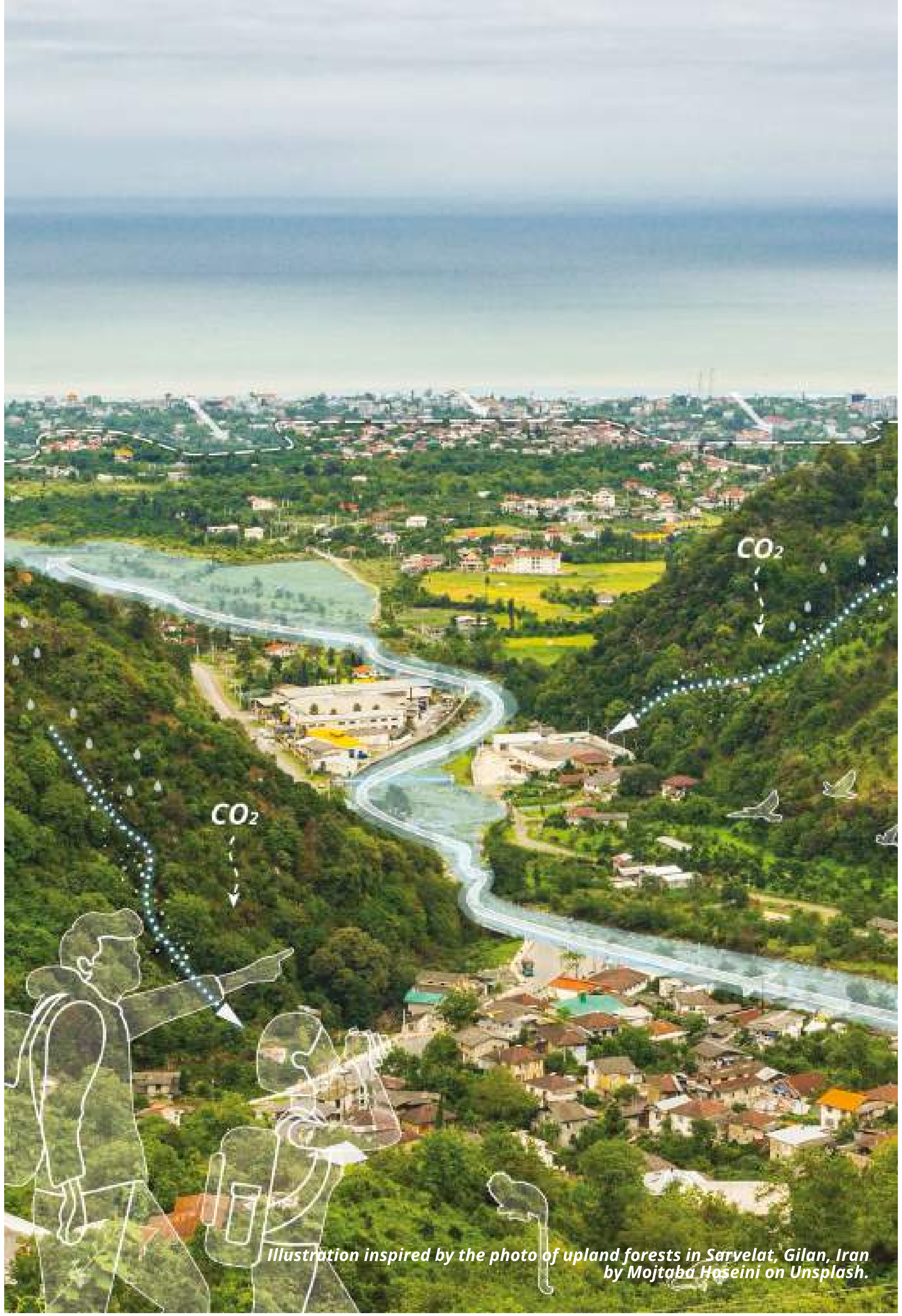


Illustration inspired by the photo of upland forests in Sarvelat, Gilan, Iran by Mojtaba Hoseini on Unsplash.

COSTS

Implementation costs

Protection and restoration costs vary by habitat and region. Forest protection costs can vary from US$5 to US$10 per hectare per year (excluding opportunity costs of land) (Sathaye et al. 2001), and natural regeneration is on the order of US$9 per hectare per year in countries such as Brazil, India, and Indonesia (Raihan and Said 2022). Key expenses for forest restoration include planting and vegetation restoration (native species acquisition, site preparation, and planting), infrastructure rehabilitation (tidal gates, drainage, and sediment traps), and monitoring (Thom 2000). To convert land to forest (afforestation) can cost approximately US$723 per hectare in Malaysia, while it can be up to US$12,000 per hectare in China because Malaysia has relatively lower labor costs and better growing conditions (Raihan and Said 2022). The cost of planting can be on the order of US$150–US$500 per hectare (Sathaye et al. 2001).

The cost-effectiveness of integrating coastal hinterlands with hard infrastructure depends on local context, including risk levels, available space, and community involvement. While traditional hard infrastructure requires significant upfront investment in construction and maintenance, NBS such as wetland restoration may have lower initial costs but generally require larger areas (van Zelst et al. 2021). Establishing a woodland forest (in front of a levee) costs approximately €6,000, considering material, planting, and transportation costs (de Vries and Dekker 2009).

Operations & maintenance costs

Sustaining restored ecosystems requires ongoing management, including monitoring, invasive species control, and hydrological adjustments. Maintenance costs vary by ecosystem, with grasslands needing less upkeep than coastal forests. Coastal forests might also require frequent pruning, depending on the chosen forest management strategy. For instance, a first estimate of pruning costs for a planted willow woodland in front of a levee in the Netherlands was on the order of €2000 per two years (de Vries and Dekker 2009). Erosion-prone areas demand continuous investment in protective measures. Regular monitoring of biodiversity, water quality, and habitat health ensures long-term success (Thom 2000). Involving local communities in the management of these interventions can improve engagement and can lead to lower maintenance costs. For example, in Japan, communities played an important role in post-tsunami restoration of pine forests (NPO Watari Green Belt Project, n.d.).

Other cost considerations

Restoration projects should consider land tenure: public land can ensure long-term stability but generally involves more regulations and permits, whereas private land allows more flexibility regarding these requirements, though it involves complex negotiations and coordination. Land acquisition costs may include costs related to land use (e.g., payments to landowners), community resettlement, and land protection costs (e.g., controlling access). Large-scale restoration will also require collaboration among governments, communities, and conservation groups to align policies, funding, and goals (Chape et al. 2005).

CAPEX: Implementation costs
OPEX: Operations and maintenance costs

GUIDELINES AND RESOURCES

The resources listed provide guidance for designing and restoring coastal hinterlands, supporting their assessment, planning, and implementation as nature-based solutions. They also include information on creating suitable conditions for coastal hinterlands, as well as guidance on monitoring approaches.

Design guidelines:
Bryant, M., Allan, P. and Kebbell, S. 2017. A settlers' guide: Designing for resilience in the hinterlands. Buildings, 7(1):23. https://doi.org/10.3390/buildings7010023

Coastal hinterland restoration guides
Barlow, B., Andreu, M., Asaro, C., Maggard, A. and Auel, J. 2021. Pine forest landowners guide. General Technical Report (1 of 23 volumes). Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station, 260:1–36. https://doi.org/10.2737/SRS-GTR-260n

Chan, H. T. and Baba, S. 2009. Manual on Guidelines for Rehabilitation of Coastal Forests Damaged by Natural Hazards in the Asia-Pacific Region. International Society for Mangrove Ecosystems (ISME) and International Tropical Timber Organization (ITTO), 66 pp. https://www.unisdr.org/files/13225_ISMEManualoncoastalforestrehabilita.pdf

Holst, L., Rozsa, R., Benoit, L., Jacobson, S. and Rilling, C. L. 2003. Long Island Sound Habitat Restoration Initiative: Technical Support for Coastal Habitat Restoration. https://lispartnership.org/wp-content/uploads/2010/03/LIS.Manual.pdf

In addition, the Nature-Based Solutions Opportunity Scan (NBSOS) is a tool that helps identify NBS investment opportunities, providing information on NBS types, suitable locations, costs, and coastal protection benefits and co-benefits. It supports decision-makers in integrating NBS into planning, and investment strategies for both urban and coastal areas.

HINTERLANDS CASE STUDIES

PROJECT #1
Casuarina Coastal Reserve, Darwin, Australia (2004–10)

PROJECT #2
Restoration of Coastal Grasslands – Sodwana Bay, South Africa (ongoing since the early 2000s)

PROJECT #3
Pineta di Alberese Restoration, Tuscany, Italy (primarily 1990s)

PROJECT #4
Coastal Pine Forest, Japan (Ongoing)

Yakushima Island, Yakushima, Kagoshima, Japan
Photo by Daria Oss on Unsplash

PROJECT #1
Casuarina Coastal Reserve, Darwin, Australia (2004–10)

Bird's-eye view of coastal forest in Darwin, Australia. Photo by Lucid on Unsplash.

Location

Darwin, Northern Territory, Australia

Approach

Restoration

Size

*Approximately **1,361 hectares***

Cost

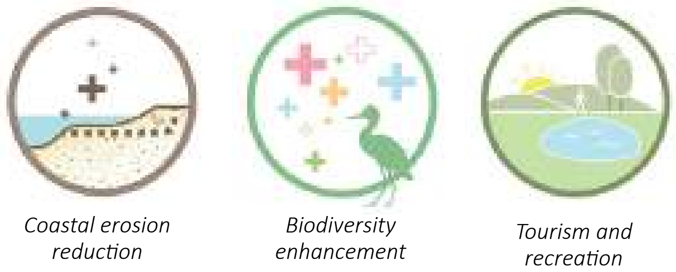
The group operates primarily through community volunteer efforts, government support, and grants. Costs include materials for native plantings, tools for invasive species removal, and periodic maintenance efforts such as controlled burns.

Description

The Casuarina Coastal Reserve features a mix of monsoonal rainforests, coastal dune ecosystems, and coastal woodlands. It provides critical habitats for migratory shorebirds, native flora, and fauna. Restoration efforts led by the Casuarina Coastal Reserve Landcare Group have focused on re-establishing native vegetation and combating invasive species such as gamba grass. Key initiatives include replanting the degraded beach block area with native species and restoring the Moth Block to support endangered Atlas Moth populations.

Benefits

- *Reduced erosion by stabilizing dunes and coastal soils.*
- *Increased biodiversity by supporting native species, including rare and endangered ones such as the Atlas Moth.*
- *Supported tourism and recreation by attracting visitors for birdwatching, hiking, and beach activities.*
- *Supported community engagement by providing an avenue for local participation in environmental restoration.*



Challenges

- *Ongoing efforts are required to control invasive species (weeds such as gamba grass).*
- *Adjacent urban development leads to habitat fragmentation and risks such as fire.*
- *Volunteer-based operations sometimes struggle with resource constraints.*

Lessons learned

- *Volunteer efforts significantly enhance restoration and awareness, highlighting the importance of community involvement.*
- *Effective management of invasive species and fire risks is essential to include in long-term maintenance plan.*
- *Partnering with local governments and organizations maximizes impact.*

Source (references)

Landcare Australia. No date. Coastcare https://landcareaustralia.org.au/news/casuarina-coastal-reserve-landcare-group/

PROJECT #2
Restoration of Coastal Grasslands – Sodwana Bay, South Africa (ongoing since the early 2000s)

THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP

Aerial view of coastal grasslands in Sodwana Bay, South Africa. Photo by Google Earth.

Location

Sodwana Bay, KwaZulu-Natal, South Africa

Approach

Restoration

Size

Approximately ***1,200 hectares***

Cost

Part of broader park redevelopment initiatives costing around ***120 million South African rand (~US$7 million)*** *for multiple sections, including ecological restoration and visitor facility upgrades.*

Description

The coastal grasslands of Sodwana Bay, part of the iSimangaliso Wetland Park (a UNESCO World Heritage Site), are critical habitats for biodiversity and ecosystem services. These grasslands were degraded due to overgrazing, tourism development, and invasive plant species. Restoration efforts included the reintroduction of native grass species, removal of invasive alien plants (such as Chromolaena odorata*), and improved management practices. Controlled burns were used to mimic natural fire regimes and stimulate grass growth. The restoration program was carried out by iSimangaliso Authority in collaboration with local communities, emphasizing sustainable land management and ecological rehabilitation.*

Benefits

- *Flood reduction: the grasslands play a role in absorbing excess water, reducing flood risks in adjacent areas.*
- *Restoration supports endemic species such as the blue swallow* (Hirundo atrocaerulea) *and other grassland-dependent flora and fauna, increasing the area's biodiversity.*
- *Restored grasslands help capture carbon, contributing to climate change mitigation.*
- *Increased ecological integrity has boosted eco-tourism activities such as bird watching and nature tours, generating revenue for local communities, supporting tourism and livelihoods.*
- *Restored landscapes reconnect communities with their natural heritage and support sustainable resource harvesting.*

Flood risk reduction | *Biodiversity enhancement* | *Carbon sequestration* | *Tourism and recreation*

Challenges

- *Continuous efforts are required to prevent the return of invasive plants.*
- *Initial reluctance from communities because of a limited understanding of long-term restoration benefits required extensive awareness campaigns.*
- *Securing consistent funding for long-term monitoring and maintenance remains a challenge.*

Lessons learned

- *A collaborative approach by engaging local communities ensures the sustainability of restoration efforts.*
- *Combining traditional ecological knowledge with scientific methods improves outcomes.*
- *Ecosystem-based planning by factoring in natural processes such as fire regimes enhances restoration success.*

Source (references)

iSimangaliso Wetland Park. 2025. . https://isimangaliso.com/index.php?option=com_zoo&task=item&item_id=764&Itemid=1294&lang=en

South African History Online. 2023. Sodwana Bay National Park. South African History Online. https://sahistory.org.za/place/sodwana-bay-national-park

PROJECT #3
Pineta di Alberese Restoration, Tuscany, Italy (primarily 1990s)

Parco naturale della Maremma [Maremma Regional Park]. Photo by Francesco Mocellin.
Source: Wikipedia. https://it.wikipedia.org/wiki/Parco_naturale_della_Maremma#/media/File:Panorama_dalla_torre_Torre_di_Castelmarino.jpg

Location

Maremma Regional Park in Tuscany

Approach

Restoration

Size

600 hectares *along the Tyrrhenian coastline*

Cost

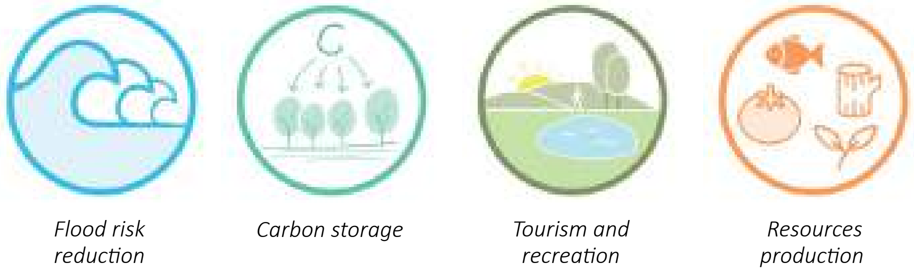
Exact figures for this project were not detailed in the sources, but it aligns with typical medium-scale forest restoration initiatives.

Description

The Pineta di Alberese is a coastal stone pine forest (Pinus pinea) *situated in the Maremma Regional Park in Tuscany. This forest plays a crucial role as a protective barrier against coastal erosion, buffering wind and salt spray and supporting rich biodiversity, including migratory bird species. Restoration efforts focused on thinning overly dense stands to improve air circulation and forest health; addressing soil salinization, which impacted root vitality due to proximity to coastal groundwater; and increasing ecosystem resilience against climate stressors and human pressures.*

Benefits

- *By stabilizing soil and reducing surface water runoff, the forest mitigates local flood risks and improves regional hydrological dynamics.*
- *Mature stone pines have high carbon uptake potential. With healthy management, they contribute to significant carbon storage, aiding Italy's climate goals.*
- *The forest provides sustainable resource production (timber and nuts).*
- *The Pineta attracts visitors for hiking, birdwatching, and photography, making it a vital contributor to ecotourism and local economies.*
- *The project improved habitat conditions for native species—including forest birds, small mammals, and insects—and bolsters ecosystem health and biodiversity.*



Challenges

- *Rising salinity in the groundwater, driven by sea-level rise and over-extraction of freshwater, posed significant threats to tree health.*
- *Urbanization in nearby areas and high visitor numbers required careful intervention to balance restoration with sustainable tourism.*
- *Securing sufficient financial resources and coordinating interventions across multiple stakeholders, including park authorities and local governments, demanded robust planning.*

Lessons learned

- *Integrating groundwater and soil moisture management into forest restoration is vital in coastal environments, highlighting the importance of hydrology.*
- *Collaborating with local communities and stakeholders ensured project success and social acceptance.*
- *Regular monitoring and the ability to modify strategies in response to climatic and environmental feedback supported long-term resilience.*

Source (references)

Parco della Maremma [Maremma Regional Park]. No date. https://parco-maremma.it/

Garfì, V. and Garfì, G. 2024. Differential tree growth response to management history and climate in multi-aged stands of *Pinus pinea* L. *Plants*, 13(1):61. https://doi.org/10.3390/plants13010061

PROJECT #4
Coastal Pine Forest, Japan (Ongoing)

Bird's-eye view of restoration efforts in coastal pine forests, Japan. Photo by OISCA.
Source: OISCA (Organization for Industrial, Spiritual and Cultural Advancement). Coastal Forest Restoration Project in Natori City, Miyagi Prefecture. *https://oisca-international.org/environmental-restoration/356/*

Location

Coastal regions of Japan

Approach

Restoration

Size

The coastline of Japan encompasses extensive pine shelterbelts, covering about ***1,640 square kilometers*** *of coastal forests, with ongoing restoration efforts.*

Cost

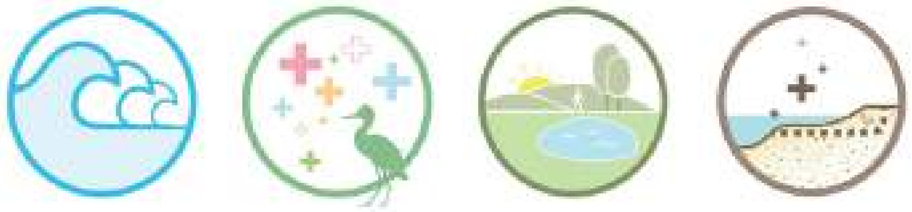
Exact figures for this project were not detailed in the sources, but it aligns with typical medium-scale forest restoration initiatives.

Description

Coastal pine trees along Japan's shores are known to protect communities from tsunamis and surges. The dense pine trees can reduce the wave energy and wind speeds before reaching inland areas. Pine forest restoration is part of post-tsunami restoration efforts, supported by various stakeholders including local governments, nongovernmental organizations, forestry specialists, and community volunteers.

Benefits

- *Pine belts reduce flooding by dissipating wave and wind energy, serving as a buffer against tsunamis. They reduce maintenance needs and increase resilience of coastal infrastructure. Furthermore, inland forest belts can also trap debris during floods and may help washed out people during tsunamis by providing a soft landing or surface to cling to.*
- *Root systems stabilize sandy soils and reduce beach erosion.*
- *Pine belts provide habitat for coastal flora and fauna, increasing biodiversity.*
- *Many pine forests have symbolic importance in Japan, linking to heritage and coastal landscapes; they also serve as a tourist attraction.*



Flood risk reduction · *Biodiversity enhancement* · *Tourism and recreation* · *Coastal erosion reduction*

Challenges

- *Securing adequate funding and resources for large-scale restoration efforts can be challenging, particularly in remote areas. Historically, coastal forest management has lacked a coordinated, long-term strategy integrating ecological and disaster mitigation goals, which can lead to fragmented efforts.*
- *Managing forests to serve both biodiversity conservation and tsunami defense requires complex planning, often facing trade-offs.*

Lessons learned

- *Community involvement is essential for the success and sustainability of coastal pine forest restoration projects, and combining forest restoration with other works such as debris removal and coastal dike rehabilitation is beneficial.*
- *Adaptive governance involves multiple stakeholders and modifies the restoration approaches based on societal changes, improving forest restoration outcomes.*
- *Balancing ecological and protective functions requires integrated planning to address trade-offs effectively. Hence, forest management is required to also deal with forest aging and degradation. Furthermore, selecting the right tree species for both local conditions and biodiversity is important.*

Source (references)

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CORAL REEFS

Maldives

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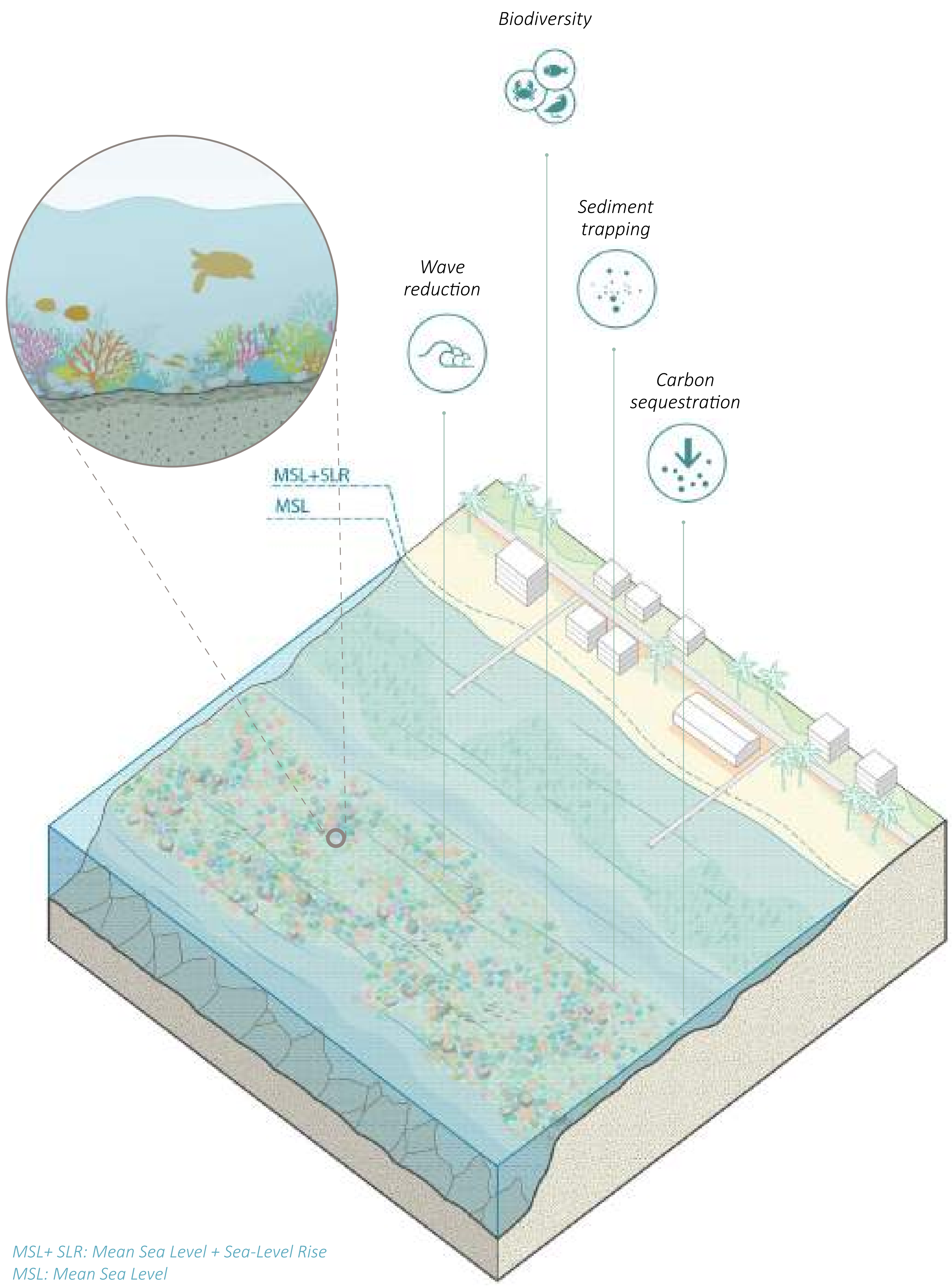
FACTS AND FIGURES

Reefs broadly encompass a variety of submerged structures, including biogenic coral and shellfish reefs as well as engineered artificial or hybrid reef systems. Coral reefs are formed by hard corals and other reef-building organisms such as coralline algae, which generate the calcium carbonate that constitutes the structural framework of the reef. In tropical regions with water temperatures typically ranging from 20°C to 30°C, warm-water corals are primarily responsible for constructing the expansive and complex morphological features that characterize most coral reefs. Nevertheless, smaller colonies of hard corals can inhabit colder and deeper marine environments. Conventional approaches to mitigating coastal flooding and erosion have largely relied on hard coastal structure such as rubble mound breakwaters and concrete groins. However, coral and shellfish reefs can also be effective. Natural reefs, formed by a variety of marine organisms, create shallow, submerged structures in the ocean that can have a profound influence on coastal hydrodynamics and sediment transport (Lowe et al. 2021). Reefs act as the first line of defense along many coasts worldwide, protecting against flooding, storm damage, and erosion (Beck et al. 2018; Escudero et al. 2021; Reguero et al. 2019, 2021). The nature and morphological complexity of reefs also support some of the world's most productive marine ecosystems and provide habitats for many species (Burke et al. 2008; Edwards 2013).

Reefs provide coastal protection and risk reduction services by dissipating wind waves (Lowe et al. 2021). Coral reefs can dissipate most incident wave energy before the waves reach the shore (Ferrario et al. 2014). However, reefs' effectiveness in reducing coastal flooding depends on complex interactions and feedback between waves, water levels, reef morphology, roughness, and habitat properties, among other factors (Lowe et al. 2021). Coral reefs are commonly categorized as fringing reefs, barrier reefs, atolls, and patch reefs. The type of reef and its morphology has a large effect on their coastal protection role (Costa et al. 2016; Escudero et al. 2021). Fringing reefs *form close to shorelines, often around islands and continental margins. They are typically separated from the land by narrow, shallow lagoons and can significantly reduce the energy of waves reaching the coast.* Barrier reefs*, by contrast, run parallel to the shoreline and are separated from it by broader lagoons, whose geomorphology conditions the level of coastal protection they can provide.*

In addition to coastal protection, coral reefs provide valuable ecosystem services such as habitat creation, enhanced biodiversity, tourism, fisheries, and cultural values, among others (Lokesha and Sannasiraj 2013; Rinkevich 2005). However, coral reefs have experienced degradation from both natural and anthropogenic stressors (Hughes et al. 2017). It has been estimated that 19 percent of global coral reefs (i.e., ~48,450 square kilometers) are considered to be severely degraded and at imminent risk of being lost (Wilkinson 2008). The degradation of reefs can lead to changes in the seafloor elevation (Alvarez-Filip et al. 2022; Yates et al. 2017) and increased flooding on land (Quataert et al. 2015; Reguero et al. 2021).

Coral reef degradation is driven by multiple factors. Local human activities such as overfishing, destructive fishing methods, and those that contribute to sedimentation and nutrient pollution all play a role in the decline of reefs. In addition, climate-related stressors such as rising sea temperatures and increased ocean acidification further threaten coral health (Hoegh-Guldberg et al. 2007; Hughes et al. 2018, 2017). Natural events such as tropical cyclones and storms can also cause significant structural damage to reefs (Vercelloni et al. 2020). The combined impact of these stressors greatly impairs the ability of coral reefs to recover from disturbances. However, the implementation of effective management strategies can help strengthen reef resilience and support the vital ecosystem services that reefs offer. The urgent need to sustain coral reefs has increased momentum for the restoration of reefs, driving an increase in investment, research, and on-the-ground projects. However, coral reef restoration remains an emerging field: many projects and techniques remain experimental and small-scale. Coral restoration includes two main approaches. Passive restoration *relies on natural coral recovery once stressors are reduced, through actions such as controlling predators, removing algae, and creating protected areas.* Active restoration *involves direct interventions such as coral transplantation, adding helpful species, or enhancing larval settlement to rebuild reefs. The choice depends on reef damage severity: passive methods work where reefs can recover naturally, while active measures are needed when natural recovery is unlikely.*



Visualizing the processes and benefits of coral reefs.

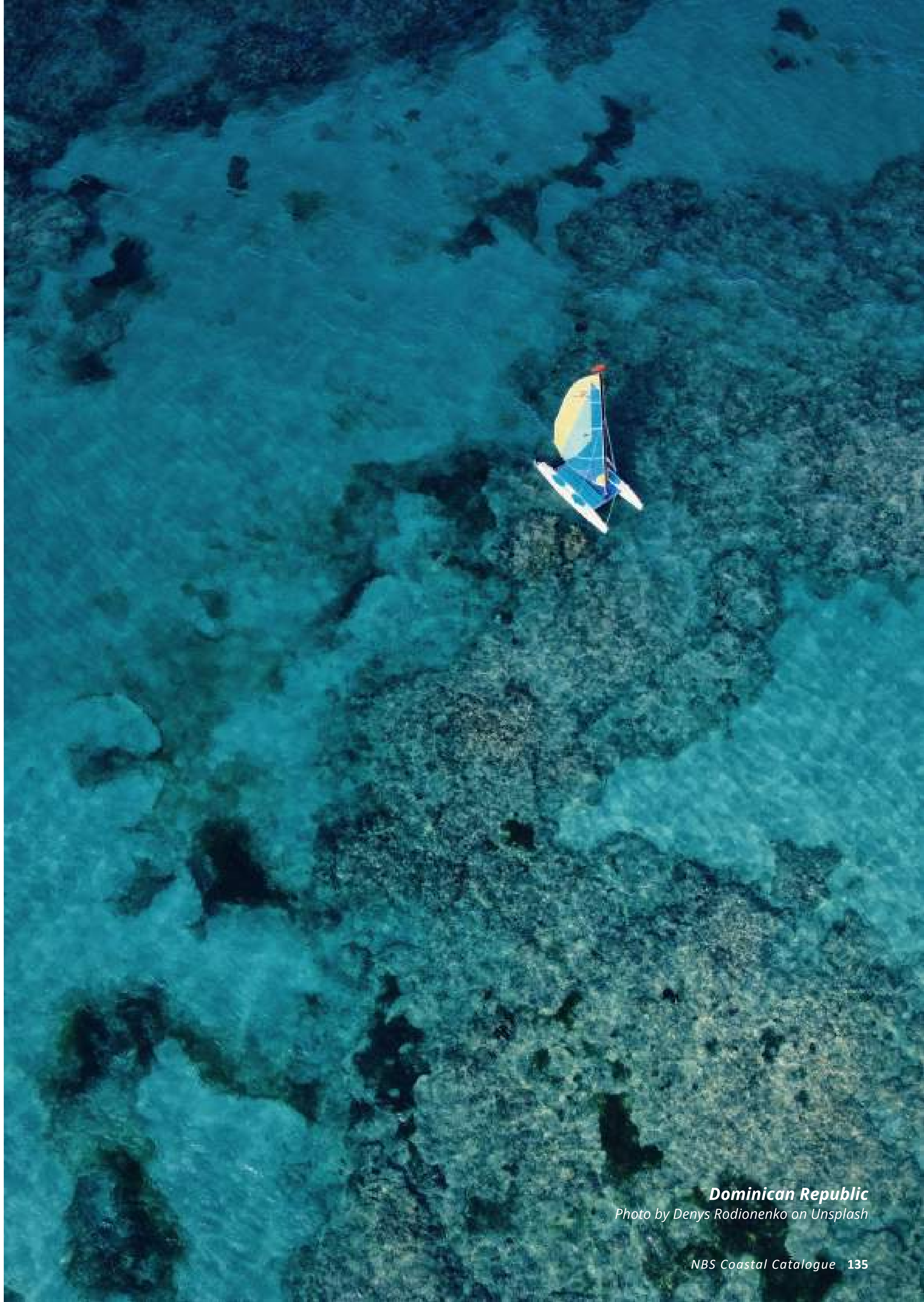
SUITABILITY CONSIDERATIONS

The selection of site, depths, reef orientation, and local patterns in waves and circulation are factors that can influence the effectiveness and success of the restoration project. Restoration efforts should also consider the appropriate coral species and the geomorphological characteristics of the site to ensure project suitability.

Location and climate: Coral species are found in all the world's oceans, from polar to tropical regions, inhabiting both warm and cold waters. However, most reef-building corals are concentrated in tropical and subtropical zones, primarily between 35° north and 35° south latitude. These corals generally thrive in shallow waters less than 25 meters deep, where sunlight penetrates easily and temperatures range from 23°C to 29°C (Zimmer 2014).

Hydrodynamics: Coral reefs occur in high wave energy environments. However, large storms and high wave energy can dislodge and break corals, reducing overall coral cover and altering the species composition of a reef (Lange et al. 2021). Currents and water flow circulation around reefs can also influence sedimentation and larva transport, which can be critical to the reef's functions and health (King et al. 2023).

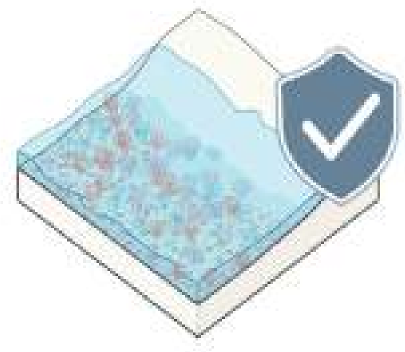
Turbidity and water quality: Coral reefs require low turbidity because high turbidity reduces light penetration and the photosynthesis of symbiotic algae and therefore coral growth. High sedimentation rates can smother and bury coral, threatening its survival (Henkel 2010). Many wastewater pollutants—including agricultural fertilizers and pesticides, domestic and municipal waste, trace metals, and petroleum products—can also harm coral reefs even at low concentrations. Recognizing these impacts is essential for shaping effective policies and reef management practices. Wastewater outfalls expose reef environments to excess nutrients, increased turbidity, sedimentation, pathogens, and chemical contaminants, which collectively make corals more vulnerable to thermal stress and reduce their ability to recover from bleaching events.



Dominican Republic
Photo by Denys Rodionenko on Unsplash

NBS INTERVENTIONS

PROTECTION MEASURES

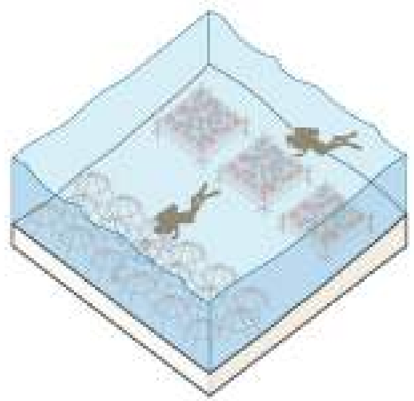


Conservation and protection strategies play a crucial role in supporting reef recovery and preserving the ecosystem services reefs provide to local communities. These strategies may include limiting or prohibiting damaging human activities—such as fishing, tourism, and anchoring—in particular areas, as well as implementing restoration efforts. For instance, marine protected areas have been effective at enhancing the protection and recovery of coral reefs and potentially increasing their resilience to future climate threats (Almany et al. 2009; Halpern and Warner 2002). Additionally, conservation actions can address land-based sources of stress by reducing sediment and nutrient runoff through improved wastewater management (Donovan et al. 2020; Prouty et al. 2017). Protection efforts are often combined with other active restoration techniques for more comprehensive reef recovery.

RESTORATION AND ENHANCEMENT MEASURES

Although restoration (returning a degraded ecosystem to its original state) and rehabilitation (partially restoring lost structure or function) have different goals, the key considerations and protocols for maximizing success are often similar. Restoration efforts should be driven by a clear understanding of the reasons for intervention, such as historical damage, and should aim to enhance habitat quality and ecosystem resilience to future disturbances.

Active restoration methods aim to reintroduce coral (e.g., coral fragment transplantation or larval enhancement) or augment coral assemblages (e.g., substrate stabilization or algal removal) to restore the reef ecosystem (Shaver et al. 2020). Methods of coral restoration can be grouped into three categories (Edwards 2010): asexual propagation methods, sexual propagation methods, and substrate enhancement:

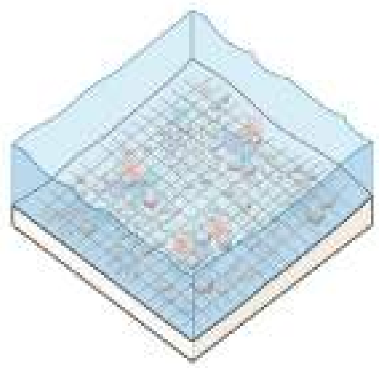


Asexual propagation

Asexual propagation refers to coral restoration techniques that transplant coral colonies (coral fragments covered with live coral polyps) from a healthy reef or coral farming operation to a degraded reef. This intervention may also involve "coral farming," where small fragments of live coral in nurseries are outplanted to a degraded reef after they have grown enough to be viable without additional human intervention.

Sexual propagation

Sexual propagation involves measures to restore coral reefs by utilizing coral spawning techniques to improve recruitment. This typically includes collecting and fertilizing coral gametes, rearing larvae, and settling them onto substrates for outplanting on degraded reefs, which can promote genetic diversity and long-term ecosystem recovery.



Substrate enhancement:

Substrate enhancement strategies aim to improve conditions for coral recruitment by making the reef environment more suitable for coral larvae to settle, without necessarily cultivating or propagating coral colonies directly. However, these approaches are often combined with the transplantation of coral fragments to maximize restoration success. Substrate enhancement can include the construction of artificial reefs, which are human-made objects or structures placed on the sea floor to increase reef complexity and encourage natural coral recruitment (Higgins et al. 2022; Vivier et al. 2021). Additionally, substrate enhancement strategies may need substrate stabilization in areas where coral structures have been damaged by disturbances such as storms or ship groundings, to restore the physical framework necessary for reef recovery.

In practice, these methods are often used together—for example, stabilizing the substrate with artificial reefs in combination with coral transplantation. However, a variety of factors can influence whether a particular strategy succeeds or fails. Even when the same techniques and materials are used, results may differ depending on the situation. For instance, artificial reefs may be ineffective if constructed with unsuitable materials or left unsecured. To achieve effective outcomes, coral restoration strategies aimed at enhancing coastal resilience must take into account ecological, hydrodynamic, and engineering considerations across three key spatial scales: regional (10–100 kilometers), reefscape (10 meters–10 kilometers), and colony level (<10 meters) (Viehman et al. 2023).

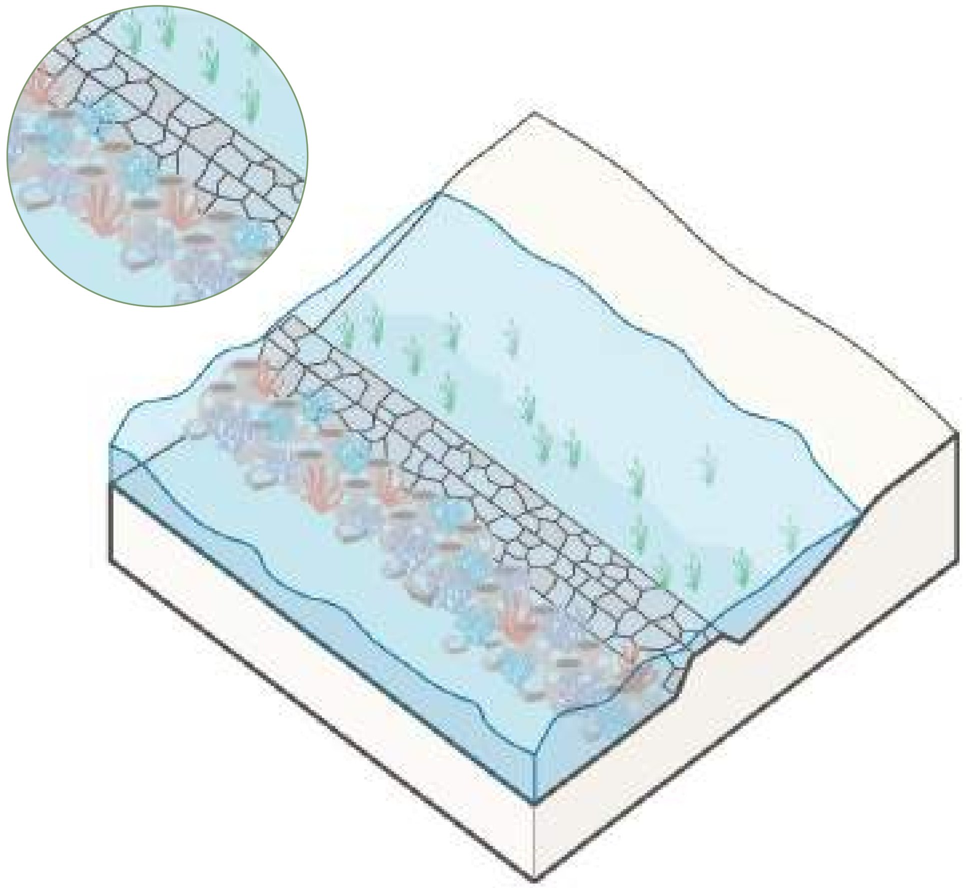
Restoration planning should begin with assessing why active restoration is necessary, whether the site still supports coral communities, the underlying causes of degradation, the potential for natural recruitment, and the type and condition of the substrate. The feasibility of any restoration or rehabilitation plan depends on local environmental conditions, available human and financial resources, and logistical challenges.

At regional scales, one important factor is determining where reefs and coral reef restoration could help reduce coastal risk. The areas where coral reef restoration can reduce flooding risks can be determined by characterizing both the risks and the risk reduction services that the reefs provide in rigorous, spatial explicit ways (Reguero et al. 2021; Storlazzi et al. 2025). Resilient coral reef restoration would also require ecological connectivity with adjacent coral populations. Species composition is also a key design factor and evaluation indicator of ecological restoration (Gann et al. 2019). Developing a restoration plan may also involve deciding on nursery methods; setting targets for the number of transplanted corals; and establishing specific, time-bound objectives. Successful restoration also requires careful planning and close collaboration with local stakeholders, experts, and decision-makers.

HYBRID INTERVENTIONS

The degradation of coral reefs has led to growing momentum for the use of hybrid solutions as a strategy to help enhance reefs' coastal protection services (Reguero et al. 2018; Viehman et al. 2023). *Hybrid solutions* refer to the combination of engineered innovative structures with more traditional reef restoration techniques, which, together, can offer coastal protection services while creating reef habitat complexity (Norris et al. 2025). Artificial hybrid reefs are a prime example of hybrid infrastructure that combines engineering and ecological design factors. Reefs can be designed to mimic the complexity of natural coral reefs, providing substrates for coral attachment and promoting marine biodiversity. Artificial reefs can be combined with ecological restoration methods to influence coastal dynamics and reduce flooding and erosion (Reguero et al. 2018).

However, the effectiveness of artificial reefs for coastal protection and other ecosystem services depends on multiple design factors, including sustainability, durability, materials used, and structural form. Suitable materials must be nontoxic, long-lasting, and supportive of coral growth, while the reef's design needs to provide stability, prevent scouring, and promote water and sediment flows that benefit coral health (Viehman et al. 2023). Ongoing monitoring and maintenance are also often necessary to ensure that these structures continue to function as intended, supporting both coral vitality and overall biodiversity. Additionally, involving local communities and stakeholders, leveraging their knowledge, and encouraging their engagement in long-term stewardship can enhance the sustained effectiveness of artificial reefs.



Bahamas
Photo by Ricky Beron on Unsplash

BENEFITS

Flood risk reduction: Coral reefs play a vital role in coastal protection, with estimates showing they reduce flood damages by 91 percent, or approximately US$272 billion, for a 100-year storm event globally (Beck et al. 2018). These benefits are especially critical in developing countries, including Cuba, Indonesia, Malaysia, Mexico, and the Philippines, each of which saves over US$400 million in annual expected flood-related costs as a result of the presence of reefs. In the United States alone, coral reefs provide annual flood protection valued at over US$2.4 billion (in 2023 US dollars), with reefs in Florida and Hawai'i preventing more than US$10 million in damages per kilometer (Reguero et al. 2021). Regional assessments further highlight the value of reefs as natural infrastructure. For instance, the Mesoamerican Reef—the largest in the Western Hemisphere—protects vital tourism and infrastructure in Quintana Roo, Mexico, a global tourism destination (Reguero et al. 2019). Recognizing these benefits, coral reefs have been declared as natural infrastructure in the United States (NOAA 2024). Moreover, reefs work in tandem with coastal dunes and other ecosystems to enhance shoreline resilience and reduce risks from storm impacts (Reguero et al. 2019).

The effectiveness of reefs to attenuate wave energy and protect coastlines depends on their size, orientation, elevation, and location relative to the shore, as well as tidal range, among other characteristics (Lowe et al. 2021). One of the most important characteristics that governs coastal protection is the elevation of the reef crest (the shallowest part of a reef) relative to sea level. Reefs dissipate wind-wave energy through both depth-limited wave breaking and friction (drag) associated with the large bottom roughness and porosity that is typical of reefs (Lowe et al. 2005). But wave dissipation processes also transform part of the incident wave energy into wave-driven currents, mean water levels via wave setup, and low-frequency waves, also known as *infragravity waves* (Lowe et al. 2007; Quataert et al. 2015; van Dongeren et al. 2012), which are a primary driver of coastal flooding and erosion behind reefs (Buckley et al. 2018). For these reasons, local hydrodynamics are central to the design of successful reef restoration activities aimed at coastal protection (Reguero et al. 2018; Viehman et al. 2023).

Erosion reduction: Coral reefs function as submerged structures that can affect coastal hydrodynamics and provide shoreline erosion control services. Shoreline movement depends on the depths and widths of reef flats through changes in the wave energy flux and the radiation stresses of breaking waves (Escudero et al. 2021). For example, in the Mesoamerican Reef, the most remarkable efficacy in preventing beach erosion is due to reefs with shallow crests, wide reef flats, and a dissipative lagoon seabed, located at ~ 300 meters from the coastline (Escudero et al. 2021). In Hawai'i, beaches shielded by coral reefs experienced 97 percent less beach volume loss than those without such protection (Bitterwolf et al. 2024). This effect on wave hydrodynamics can be used to define reef restoration projects for erosion control by restoring lost areas of reefs (Reguero et al. 2018).

Resources production: Beyond their coastal protection functions, coral reefs are essential to millions of people worldwide who rely on them for food, livelihoods, and tourism (Spalding et al. 2017). They support critical ecological processes, such as nutrient and carbon cycling (Pellowe et al. 2023) and are interconnected with other coastal habitats such as seagrass meadows, mangroves, and beach systems. Coral reefs also provide important habitat for species that support both commercial and recreational fisheries (Newton et al. 2007; Teh et al. 2013). Coral reef fisheries are worth US$6.8 billion globally in 2010 US dollars (Burke et al. 2011). While coral reefs provide about 10 percent of the fish caught worldwide, they provide up to 25 percent in developing countries and even reach as high as 70 to 90 percent in Southeast Asian countries. These fisheries provide the primary source of protein for many coastal communities and support their socioeconomic well-being. More than a quarter of the world's small-scale fishers fish primarily on coral reef ecosystems (Teh et al. 2013). Reefs also provide other materials, including sand for beaches and corals, used for construction and trade (Woodhead et al. 2019). Overall, reefs are estimated to contribute roughly US$375 billion each year in goods and services on a global scale (Costanza et al. 1997).

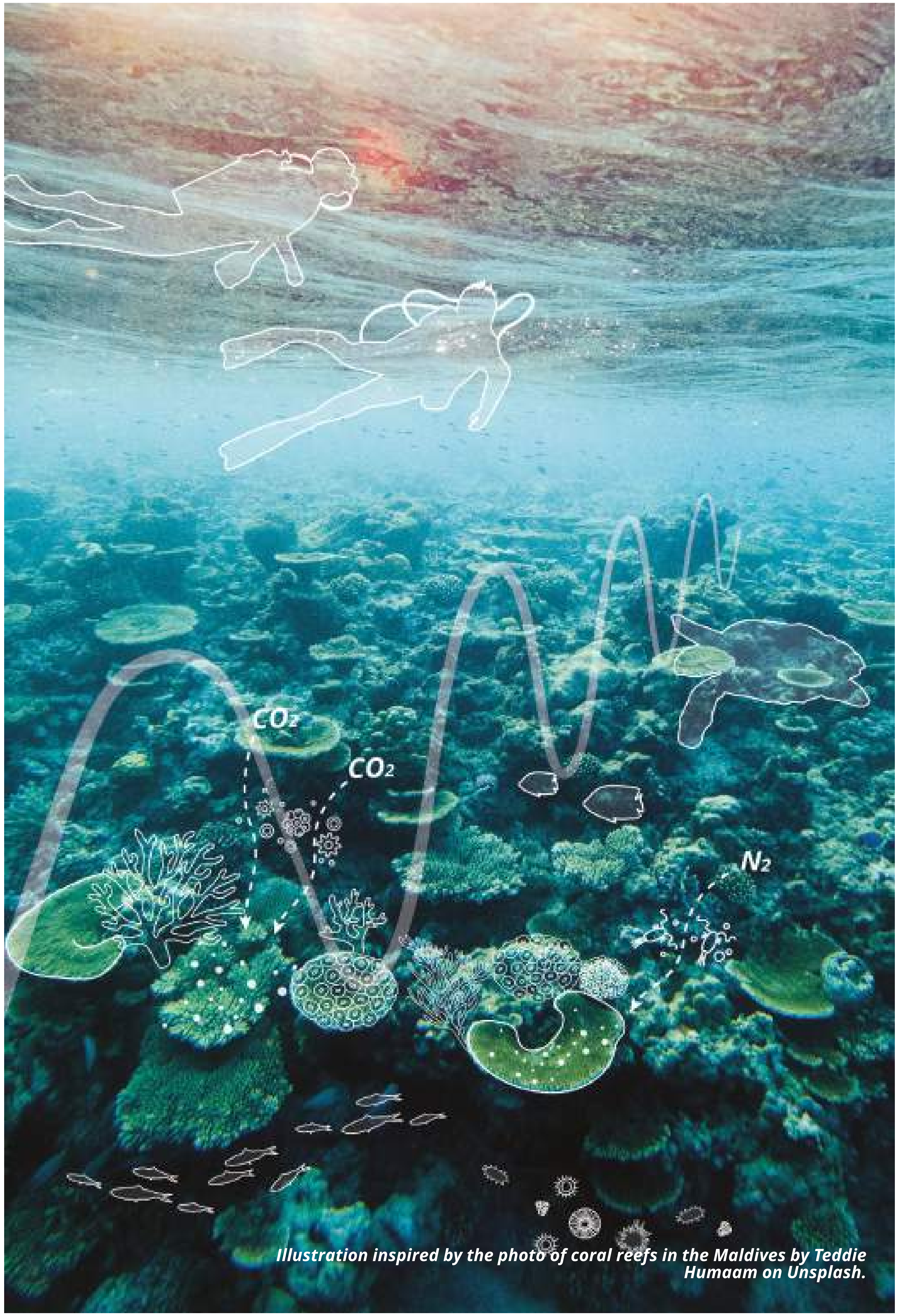
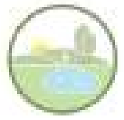


Illustration inspired by the photo of coral reefs in the Maldives by Teddie Humaam on Unsplash.



Tourism and recreation: Coral reef tourism is a major economic driver, especially for small island nations, where over 90 percent of new economic development relies on coastal tourism. Globally, coral reef–related tourism represents one of the most significant forms of nature-based tourism provided by a single ecosystem. Coral reefs draw both international and local visitors, generating revenue and foreign exchange earnings across more than 100 countries and territories and estimated at US$36 billion annually (Spalding et al. 2017). For example, in Hawai'i, reef-related recreation contributed US$304 million for the year in 2004 (Cesar et al. 2004). In the Caribbean, coral reef tourism attracts 11 million visitors annually and generates over US$7.9 billion each year, about 23 percent of all tourism expenditures in the region (Escovar-Fadul et al. 2022). Beyond revenue, it raises awareness and can fund reef conservation. However, reef tourism can damage coral ecosystems through physical impacts, pollution, and overuse, creating trade-offs between economic benefits and environmental protection. Sustainable tourism practices—such as visitor education, eco-friendly infrastructure, conservation partnerships, and limits on tourist numbers—are essential to reduce harm and help preserve coral reefs while supporting local livelihoods.

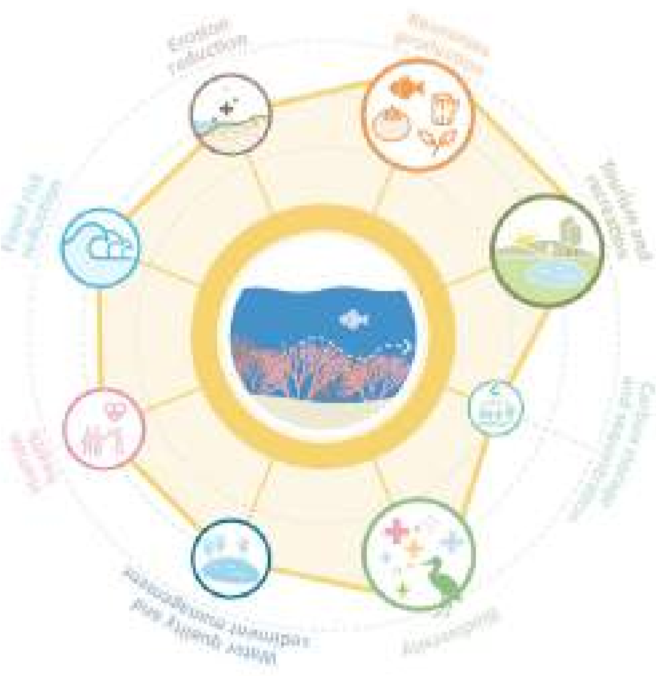
Artificial reef establishment can also help maintain and recover healthy reefs by providing shelter to marine life, improving fisheries, and benefiting tourism (Belhassen et al. 2017; Cardoso et al. 2020; D'itri 1985; Folpp et al. 2020; Hamer et al. 2017; Komyakova et al. 2019).

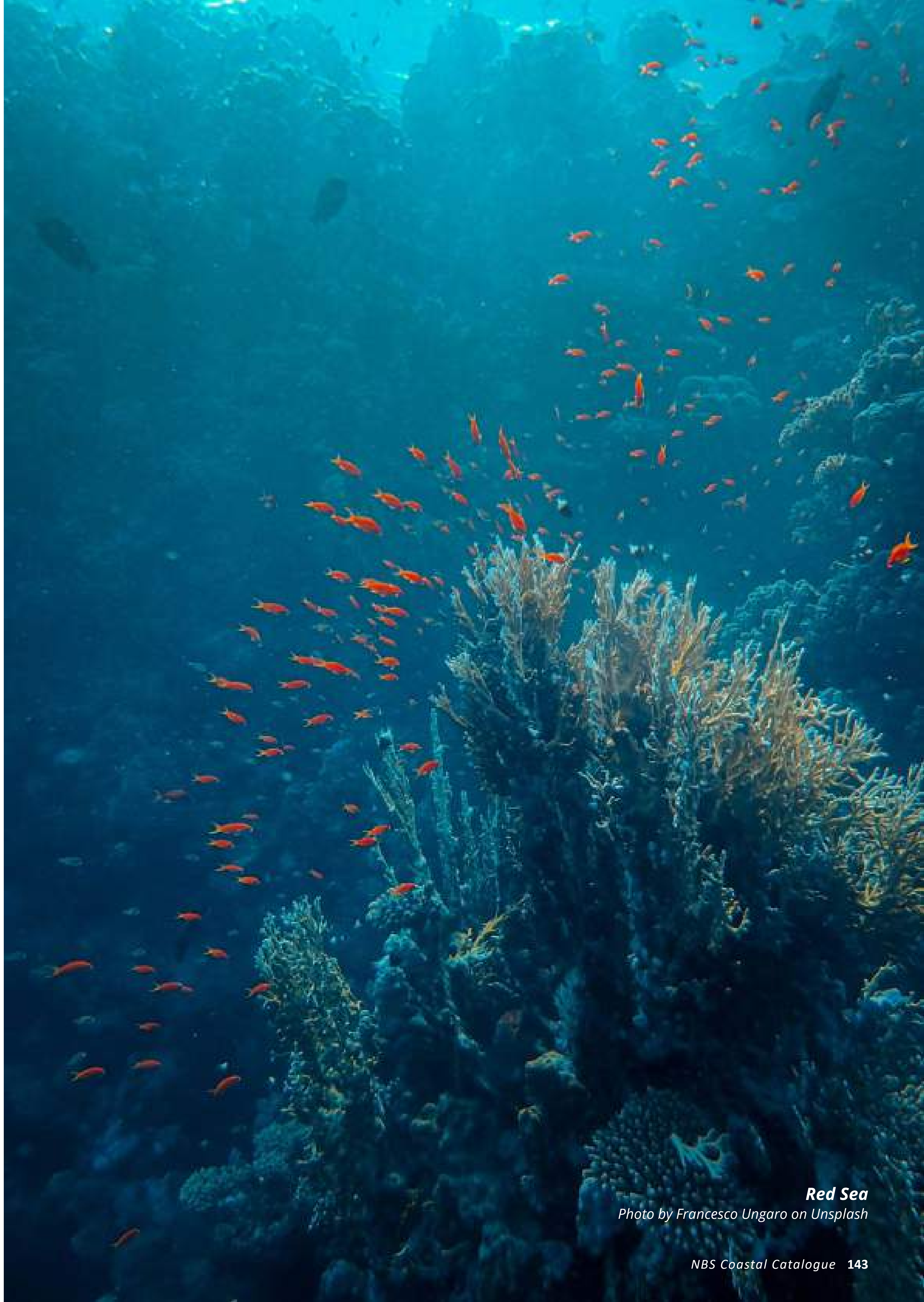
Biodiversity: Coral reefs are biodiverse hotspots and support up to 1,330,000 species worldwide (Fisher et al. 2015). Reefs with high live coral cover and high structural complexity provide habitat for reef-associated species (Woodhead et al. 2019); they also provide refuge for fish and invertebrate species through different life stages (Ortiz and Tissot 2012). Globally, the annual net benefit of biodiversity-supporting services provided by coral reefs has been estimated at US$5.5 billion (Cesar et al. 2003). In Hawai'i, the biodiversity value of coral reefs has been estimated at US$17 million per year (Brander and van Beukering 2013; Cesar and van Beukering 2004). However, these monetary estimates of biodiversity are often debated as they may fail to capture the ecological functions and significance of biodiversity, which varies greatly across sites. Instead, non-monetary indicators such as biomass, species richness, and habitat complexity are more meaningful metrics for assessing reef health and quality.

Carbon storage and sequestration: Because coral reefs and seagrass meadows in the tropics use to occur together, this connective relationship between ecosystems has implications for carbon sequestration (Huxham et al. 2018). Coral reefs facilitate blue carbon potential in seagrass meadows as sediments in seagrass meadows protected by a reef barrier avoid erosion and enhance seagrass capacity to retain organic matter in soils. Therefore, loss of coral reef structure due to bleaching and other stressors will likely result in a reduction of blue carbon storage capacity of adjacent seagrass meadow (Guerra-Vargas et al. 2020).

Water quality and sediment management: Coral reef biochemical processes play a crucial role in nitrogen fixation and the cycling of nutrients and other substances (Woodhead et al. 2019). Reefs and their associated organisms, such as sponges, facilitate the transfer of energy and nutrients across different trophic levels and connect coral ecosystems with others, including the pelagic food web (Moberg and Folke 1999). In addition, coral reefs provide limited waste assimilation services by immobilizing or sequestering pollutants from the surrounding water (Moberg and Folke 1999). The value of these waste assimilation services has been estimated at approximately US$58 per hectare per year in a Galapagos case study (in 1992 US dollars) (de Groot 1992).

The multiple benefits of coral reefs on a qualitative scale





Red Sea
Photo by Francesco Ungaro on Unsplash

COSTS

Implementation costs

Biological restoration (e.g., coral transplantation) presents costs on the order of several US$10,000s per hectare, which is not dissimilar to the costs for restoring other ecosystems such as mangroves, seagrasses, or saltmarshes (Edwards 2010). However, if damage to the reef framework is severe, physical restoration (engineering hybrid interventions) may be needed.

Costs for hybrid reefs are estimated from ship-groundings in the Caribbean range from US$2.0 to US$6.5 million per hectare to repair injured reefs. Costs for artificial reefs are estimated at a median structural reef restoration cost of US$1,290 per meter (Ferrario et al. 2014). In Grenada, a pilot artificial reef constructed with local materials was implemented at an estimated cost of US$3,600 per linear meter (Reguero et al. 2018). However, these estimates do not include other associated costs such as those for designing, permitting, and providing ongoing maintenance. Data from low-cost active biological restoration projects in Fiji, the Philippines, and Tanzania suggest costs ranging from US$2,000–US$13,000 per hectare, whereas a study in Australia suggested that transplantation to replace 10 percent of the target density of corals would cost at least US$40,000 per hectare (Edwards and Gomez 2007). Lower coral reef restoration cost estimates can come from community-based projects. One example involved transplanting two corals per square meter onto reefs with approximately 20 percent existing coral cover, costing about US$2,000 per hectare. Another example involved raising coral cover on reef patches from 10 percent to 20 percent through transplantation at a cost of US$4,590 per hectare (Edwards and Gomez 2007). While these projects represent promising initial steps, these figures likely underestimate the full costs of restoring coral reefs. Generally, rehabilitating unconsolidated habitats is significantly more expensive—often 10 to 100 times more—than restoring consolidated reef areas (Edwards 2010).

Restoration costs typically include conducting comprehensive feasibility studies, running pilot projects, meeting licensing and permitting requirements, sourcing materials for substrate or artificial reef structures, deploying these structures, and acquiring coral fragments or larvae. Most cost data available in the literature for mangrove and reef projects focus on upfront capital expenditures directly related to habitat restoration (Beck et al. 2022). For instance, enhancing coral larval settlement can range widely, from US$6,000 to US$4 million per hectare (in 2010 US dollars), while the full process of coral gardening (including collection, nursery rearing, and transplantation) is typically estimated to be between US$130,000 and US$380,000 per hectare (Bayraktarov et al. 2019).

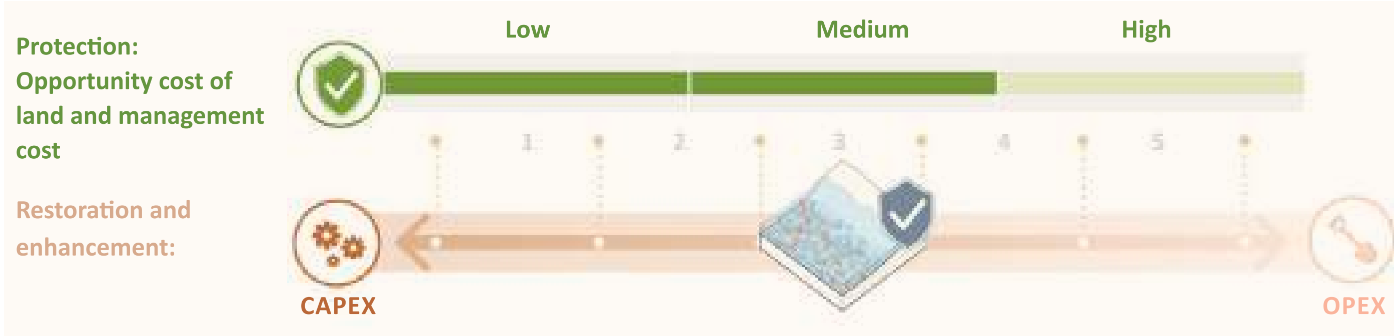
Operations & maintenance costs

Reef restoration projects may also have other operation and maintenance costs that can include monitoring and maintenance activities such as transplanting reef organisms, and controlling predators, algal overgrowth, and detachment (Edwards and Gomez 2007). Hybrid and artificial reefs may also require maintenance and upkeep such as further substrate stabilization. The costs associated with developing and maintaining corals are highly variable; these costs depend on the restoration method used and resources available (Bayraktarov et al. 2019), and as well as national regulations (e.g., the U.S. designation of threatened coral species).

Repairs following extreme storms may also be necessary to maintain the flood risk reduction benefits provided by restored reefs. These repairs could be required more frequently during the early, more vulnerable stages of reef development, especially when using propagation or gardening approaches. It is important to consider the whole-life cost of restoration, which encompasses all anticipated long-term maintenance and repair of reef structures as well as ongoing adaptation measures. Collection, nursery rearing, and transplantation cycles may need to continue for decades in order to establish and sustain a healthy, resilient reef habitat.

Other cost considerations

Access to, or ownership of, land in coastal and marine areas is essential for the conservation and restoration of coral reefs and can often represent a cost factor. Land may be publicly or privately owned, and areas inland can be necessary to support reef restoration efforts. Depending on the project's goals and characteristics, land, accessibility and permitting can increase costs and often necessitate engagement and collaboration with multiple landowners and stakeholders. Other general capital costs cover the design, permitting, and construction of the project, along with ongoing maintenance and monitoring expenses. Construction costs can typically involve building both the hard (natural or artificial) substrate and maintaining the living coral component for restoration purposes (Lowe et al. 2021).



CAPEX: Implementation costs
OPEX: Operations and maintenance costs

GUIDELINES AND RESOURCES

The resources listed provide guidance for protecting and restoring coral reefs, supporting their assessment, planning, and implementation as nature-based solutions. They also include information on creating suitable conditions for coral reefs, as well as guidance on monitoring approaches.

Design guidelines

Escovar-Fadul, X., Hein, M. Y., Garrison, K., McLeod, E., Eggers, M., and Comito, F. 2022. *A Guide to Coral Reef Restoration for the Tourism Sector: Partnering with Caribbean Tourism Leaders to Accelerate Coral Restoration.* The Nature Conservancy. https://www.nature.org/content/dam/tnc/nature/en/documents/Coral_Restoration_Guide_for_the_Tourism_Sector.pdf

Hein, M. Y., McLeod, I. M., Shaver, E. C., Vardi, T., Pioch, S., Boström-Einarsson. L., Ahmed, M., and Grimsditch, G. 2020. *Coral Reef Restoration as a Strategy to Improve Ecosystem Services: A Guide to Coral Restoration Methods.* United Nations Environment Program, Nairobi, Kenya. https://www.unep.org/resources/report/coral-reef-restoration-guide-coral-restoration-method

ICRI Coral Reef Restoration Guidelines (various). https://icriforum.org/coralrestoration/

Iyer, V., Mathias, K., Meyers, D., Victurine R., and Walsh, M. 2018. *Financing Tools for Coral Reef Conservation: A Guide.* Wildlife Conservation Society. https://www.icriforum.org/wp-content/uploads/2019/12/50+Reefs+Finance+Guide.pdf

Lowe, R. J., McLeod, E., Reguero, B. G., Altman, S., Harris, J., Hancock, B., Hofstede, R. ter, Rendle, E., Shaver, E., Smith, J. M. 2021. Reefs. In *International Guidelines on Natural and Nature-Based Features for Flood Risk Management*, edited by Bridges, T. S., J. K. King, J. D. Simm, M. W. Beck, G. Collins, Q. Lodder, and R. K. Mohan. Vicksburg, MS: U.S. Army Engineer Research and Development Center, chapter 12. https://ewn.erdc.dren.mil/nnbf-guidelines/12-reefs/

Morris, R. L., Bishop, M. J., Boon, P., Browne, N. K., Carley, J. T., Fest, B. J., Fraser, M. W., Ghisalberti, M., Kendrick, G. A., Konlechner, T. M., Lovelock, C. E., Lowe, R. J., Rogers, A. A., Simpson, V., Strain, E. M. A., Van Rooijen, A. A., Waters, E., and Swearer, S. E. 2021. *The Australian Guide to Nature-Based Methods for Reducing Risk from Coastal Hazards*. Earth Systems and Climate Change Hub Report No. 26. NESP Earth Systems and Climate Change Hub, Australia. University of Melbourne. https://www.researchgate.net/publication/351655220_The_Australian_guide_to_nature-based_methods_for_reducing_risk_from_coastal_hazards

Shaver, E. C., Courtney C. A. West, J. M., Maynard, J., Hein, M., Wagner, C., Philibotte, J., MacGowan, P., McLeod, I., Böstrom-Einarsson, L., Bucchianeri, K., Johnston, L., and Koss, J. 2020. *A Manager's Guide to Coral Reef Restoration Planning and Design.* NOAA Technical Memorandum CRCP: 36. https://doi.org/10.25923/vht9-tv39

Stovall, A. E., Beck, M. W., Storlazzi, C., Hayes, J., Reilly, J., Koss, J., and Bausch, D. 2022. *Coral Reef Restoration for Risk Reduction (CR4): A Guide to Project Design and Proposal Development.* [white paper]. University of California Santa Cruz. https://doi.org/10.5281/zenodo.7268962

In addition, the Nature-Based Solutions Opportunity Scan (NBSOS) is a tool that helps identify NBS investment opportunities, providing information on NBS types, suitable locations, costs, and coastal protection benefits and co-benefits. It supports decision-makers in integrating NBS into planning, and investment strategies for both urban and coastal areas.

CORAL REEFS CASE STUDIES

PROJECT #1
Coral Reef Restoration for Coastal Resilience, Seychelles (2018–21)

PROJECT #2
Coral Restoration Programme for Resilient Ecosystems and Sustain-able Livelihoods, Saint Lucia (2019–20)

PROJECT #3
Coral Gardening for Climate Change Adaptation, Vanuatu (2014–17)

PROJECT #4
Fragments of Hope, Belize (2013–ongoing)

Lord Howe Island, New South Wales, Australia
Photo by Dylan Shaw on Unsplash

PROJECT #1
Coral Reef Restoration for Coastal Resilience, Seychelles (2018–21)

THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP

The coastline of the Seychelles is naturally protected by coral reefs. Photo by Mariia Kamenska/Shutterstock.
Source: Taken from Jongman et al. 2021. Blue barriers: A nature-based solution to build resilience. World Bank Blogs, February 24, 2021. https://blogs.worldbank.org/en/climatechange/blue-barriers-nature-based-solution-build-resilience

Location

Côte d'Or, Seychelles

Approach

Coral reef restoration pre-feasibility study

Size

The pre-feasibility study identified that the offshore blue barrier solution would cover an area of ***6,354 square meters.***

Cost

- *Upfront implementation costs:* ***US$1,500–$2000*** *per unit reef*
- *Between 1,300 and 1,700 artificial reef units. Coral reef rehabilitation costs are* ***US$100,000*** *(for 18 months of maintenance)*

Description

The World Bank provided technical assistance to the Seychelles government to enhance coastal management and develop a pilot "Blue Barrier" approach through hybrid coral reef restoration for disaster risk reduction. The study, with funding from the Global Facility for Disaster Reduction and Recovery (GFDRR), identified priority locations for reef restoration. Coastal modeling studies determined that a hybrid approach to restoration alongside artificial structures would be required to deliver significant coastal protection. The scoping study and pre-feasibility assessment explored strategies, costs, and benefits of blue barrier solutions, which the government of Seychelles is now exploring in more detail.

Benefits

Modeling outputs predicted risk reduction benefits through a 28 percent reduction in wave energy and reduced flood exposure of vulnerable coastal assets. The model also predicted sand accumulation benefits via a reduction in longshore sediment transport rates of up to 74 percent. Furthermore, restoring coral reefs supports tourism and recreation, increases biodiversity, and supports the carbon storage and sequestration of surrounding ecosystems (such as seagrass meadows).

Flood risk reduction | *Coastal erosion reduction* | *Tourism and recreation* | *Biodiversity enhancement* | *Carbon sequestration*

Challenges

- *The risk reduction economic valuation is only partial and limited by certain factors.*
- *The project requires further cost-benefit analysis to estimate benefits fully and compare them with potential alternatives.*

Lessons learned

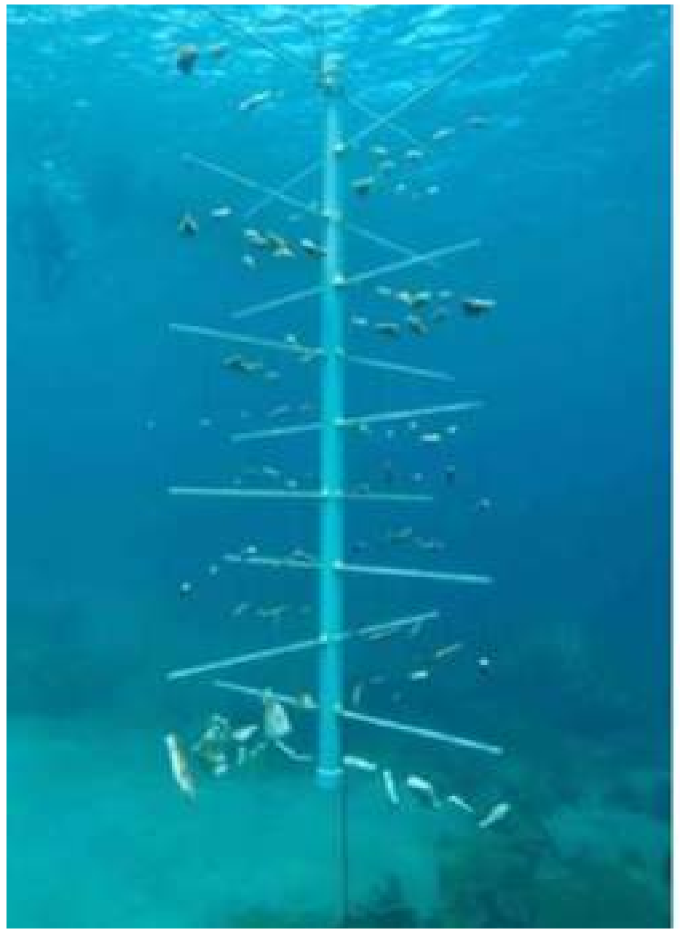
- *The valuation of other important benefits and co-benefits (such as fisheries and tourism value) would provide a more complete understanding of the economic benefits of the intervention.*
- *To fully inform implementation decisions, comprehensive engagement with the local community and key stakeholders should be conducted.*

Source (references)

van Zanten, B., Gutierrez Goizueta, G., Brander, L. M., Gonzalez Reguero, B., Griffin, R., Macleod, K. K., Alves Beloqui, A. I., Midgley, A., Herrera Garcia, L. D., and Jongman, B. 2023. *Coral Reef Restoration in Assessing the Benefits and Costs of Nature-Based Solutions for Climate Resilience: A Guideline for Project Developers*. World Bank. http://hdl.handle.net/10986/39811

Jongman, B., Gutierrez Goizueta, G., van Zanten, B., and Gonzalez Reguero, B. 2021. Blue barriers: A nature-based solution to build resilience. World Bank Blogs, February 24, 2021. https://blogs.worldbank.org/en/climatechange/blue-barriers-nature-based-solution-build-resilience

PROJECT #2
Coral Restoration Programme for Resilient Ecosystems and Sustainable Livelihoods, Saint Lucia (2019–20)




Newly populated tree (left) and one ready to harvest (right). Photos by Day and Eristhee.
Source: Public-Private Partnership for the Saint Lucia Coral Restoration Programme for Resilient Ecosystems and Sustainable Livelihoods: Final Report. CLEAR Caribbean Ltd. https://panorama.solutions/sites/default/files/final_report_-_coral_restoration_project_st_lucia_march_2020_comp_0.pdf

Location

Saint Lucia, Caribbean

Approach

Coral reef restoration

Size

Not available.

Cost

*The full costs are unpublished, but they include **€3,500** for education and **US$2,500** for analysis of coral genotypes.*

Description

From 2019 to 2020, the Centre for Livelihoods, Ecosystems, Energy, Adaptation and Resilience in the Caribbean Ltd (CLEAR Caribbean) delivered a project to develop a public-private partnership with the Sandals Foundation and the government of Saint Lucia based on a sustainable financing mechanism to ensure the long-term sustainability of coral restoration and capacity building in Saint Lucia. This project was developed in response to the growing need for ecosystem-based adaptation to climate change in the Caribbean. Project activities included:

- *The expansion of coral restoration programs with local partners*
- *Restoration monitoring plan*
- *Capacity building*
- *Development of a communication and marketing strategy.*

Benefits

- *An existing coral nursery was expanded, and reef-building coral fragments were out-planted to the natural reef. Their branched structure of the fragments, large size, and high growth rates contribute to benefits for reef growth, island formation, fisheries habitats, and coastal protection.*
- *Community members were trained in SCUBA diving and coral restoration techniques.*
- *The communication strategy and education and awareness program delivered several outputs including promotional materials, outreach videos, and articles. Various media outlets expressed interest in the project, resulting in radio, television, and newspaper coverage that generated public support and awareness.*

Flood risk reduction | *Coastal erosion reduction* | *Tourism and recreation* | *Biodiversity enhancement* | *Resource production*

Challenges

- *Despite efforts to promote the Coral Nursery Dive (an initiative to raise funds for restoration activities), uptake among recreational divers and Sandals guests was lower than expected and disrupted by the COVID-19 pandemic.*
- *The presence of multiple partners created complexity in delivering a successful project generating benefits across multiple stakeholders.*

Lessons learned

- *It is vital to work alongside government departments to ensure the legitimacy of activities.*
- *The project highlighted the benefits of actively engaging community members to assist Fisheries Officers and Marine Protected Area Managers in their other conservation work.*
- *The public-private partnership was successful due to a focus on effective communication and coordination throughout.*

Source (reference)

Day, O. and Eristhee, N. 2020. *Public-Private Partnership for the Saint Lucia Coral Restoration Programme for Resilient Ecosystems and Sustainable Livelihoods: Final Report*. CLEAR Caribbean. https://panorama.solutions/sites/default/files/final_report_-_coral_restoration_project_st_lucia_march_2020_comp_0.pdf

PROJECT #3
Coral Gardening for Climate Change Adaptation, Vanuatu (2014–17)

Coral Gardening for Climate Change Adaptation in Vanuatu: Coral frame and participants of coral gardening. Source: Panorama Solutions. No date. Coral gardening for climate change adaptation in Vanuatu. https://panorama.solutions/en/solution/coral-gardening-climate-change-adaptation-vanuatu

Location

Nguna and Pele, Vanuatu.

Approach
Coral reef restoration

Size
*Over **3,000** coral fragments*

Cost
Unpublished

Description

Over 3,000 inhabitants of Vanuatu archipelago participated in the community-based coral reef restoration project conducted by the Nguna-Pele Marine and Land Protected Area (MLPA) network. The project's objectives were to harness climate change adaptation benefits and promote ecotourism. Coral gardening mariculture activities were undertaken, trialing coral varieties that are particularly resilient to temperature-induced bleaching and ocean acidification. Coral reef frames were then relocated to restore areas of reef previously damaged by cyclones or invasive species. The ecotourism element of the project ensured the successful upscaling of coral gardening and provided locals with a sustainable source of income.

Benefits

- *Over 3,000 coral fragments were planted on artificial structures, resulting in the stabilization of eroding coastlines.*
- *The project has significantly boosted ecotourism opportunities and sustainable income for the members of seven island villages.*
- *The project has empowered woman and youth to proactively participate in decision-making and be involved in climate adaptation activities.*
- *The network is the first nationally recognized example of a community-managed network of marine reserves in Vanuatu. The network has successfully impacted policy at a national level.*

Tourism and recreation | *Coastal erosion reduction* | *Biodiversity enhancement*

Challenges

- *The Nguna-Pele Marine and Land Protected Area network faces juridical challenges as the village council members are not formally endorsed by national legislation. Support is not provided for enforcing community-level conservation actions and preventing trespassing.*

Lessons learned

- *Women and girls had the greatest success in coral planting. Coral fragments collected by women had a 75 percent survival rate while those handled by men had a 55 percent success rate.*
- *Visitors are very willing to contribute actively and financially to accessible ecotourism activities.*
- *Developing sustainable income opportunities as part of climate adaptation projects is essential for communities whose financial well-being is intrinsically linked to ecosystems.*

Source (references)

Barlett, C. 2017. Coral Gardening for Climate Change Adaptation in Vanuatu. Panorama Solutions for a Healthy Planet. https://panorama.solutions/en/solution/coral-gardening-climate-change-adaptation-vanuatu

UNDP (United Nations Development Programme). Nguna-Pele Marine and Land Protected Area Network, Vanuatu. Equator Initiative Case Study Series. New York. https://www.equatorinitiative.org/wp-content/uploads/2017/05/case_1348163605.pdf

PROJECT #4
Fragments of Hope, Belize (2013–ongoing)

Fragments of Hope, Belize, Coral Nurseries.
Source: [*https://fragmentsofhope.org/coral-nurseries/*](https://fragmentsofhope.org/coral-nurseries/)

Location

The Laughing Bird Caye National Park, Belize

Approach

Coral reef restoration

Size

*More than **82,000** coral fragments have been planted in multiple restoration sites within a **4,095** hectare area.*

Cost

Unpublished

Description

When Hurricane Iris hit Laughing Bird Caye Island in 2001, the coral reefs were severely damaged; some areas were completely destroyed. Without coral reefs, coastal communities were left susceptible to storm surge damage. Fragments of Hope works with scientists, fishers, and tour guides to carry out coral reef restoration, promote the social and economic benefits of coral reefs, and advocate for sustainable management of the national park. The project is considered by many to be the most successful coral reef restoration project in the world and is endorsed by the Belize Fisheries Department.

Benefits

- *As of 2020, over 82,000 coral fragments have been planted across restoration sites with survival rates of 89 percent. Improvement of live coral cover rose from 6 percent to 50 percent of the National Park between 2010 and 2017.*
- *The project has improved reef structure and function, leading to marine biodiversity benefits.*
- *The project has created local employment opportunities.*
- *The project provides a replicable model and techniques for scaling up coral reef restoration. These have been successfully applied across other areas of Belize, as well as Colombia, Jamaica, and Saint Barts.*

Tourism and recreation | *Biodiversity enhancement* | *Resource production*

Challenges

- *The nurseries and restored reefs are sporadically impacted by bleaching events, which are on the rise in Belize.*
- *Long-term funding is challenging to secure and resource heavy, requiring time-consuming administrative work.*
- *Regular monitoring and maintenance at nurseries and out-plant sites is a costly activity, and the processing technology required to accurately quantify restoration results must be outsourced due to lack of capacity in the country.*

Lessons learned

- *Vast local knowledge and engagement with multiple partners, in combination with a science-based approach, have led to significant project success.*
- *Ensuring the genetic diversity of coral at restoration sites has been critical to reef resilience and survival.*
- *Project success has been facilitated in part by a low human population density and the long-term establishment of no-take zones.*

Source (references)

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Great Barrier Reef, Australia
Photo by Kristin Hoel on Unsplash

SHELLFISH REEFS

Tampa, Florida, United States

Photo by The Tampa Bay Estuary Program on Unsplash

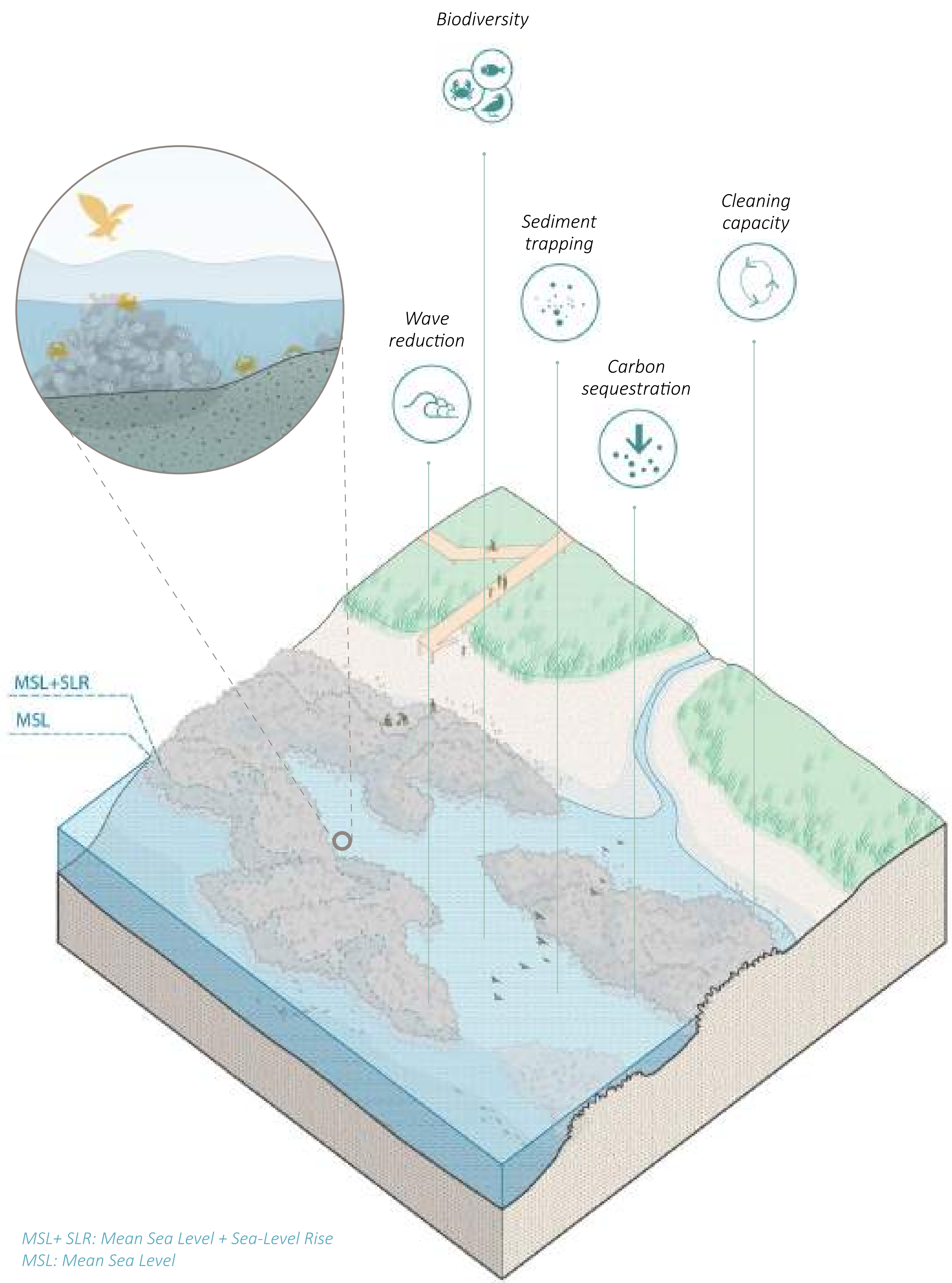
FACTS AND FIGURES

Natural reefs are formed by a variety of marine organisms and create shallow, submerged structures in the ocean that can have a profound influence on coastal hydrodynamics and sediment transport (Lowe et al. 2021). The term reef *encompasses a range of shallow, submerged formations in the ocean, shaped by different organisms. While coral reefs are the most renowned, other reef types exist—from temperate rocky reefs (Wernberg et al. 2009) to shellfish reefs (Grabowski and Peterson 2007), each influencing coastal processes and ecological dynamics in unique ways.* Shellfish reefs *are structural formations from the aggregation and accumulation of bivalve mollusks, notably oysters and mussels, in coastal environments. These bivalves characteristically form dense assemblages, which result in the development of three-dimensional, structure-forming populations known as* shellfish reefs*. The vertical extent and complexity of these reefs are influenced by the species present, as well as by factors such as water depth and the physical characteristics of the surrounding bay, estuary, or inlet (Fitzsimons et al. 2019). These natural underwater structures protect coastlines by reducing wave energy while also supporting marine biodiversity and providing ecosystem services that enhance the ability of coastal communities to adapt to climate change.*

Shellfish reefs affect shorelines differently than coral reefs because shellfish reefs are formed in sheltered waters, in the intertidal and shallow subtidal zones, and thus typically exist in low wind-wave energy environments (Gillies et al. 2020; Gillies et al. 2015). Shellfish reefs typically inhabit sheltered areas of temperate and tropical bays, estuaries, and nearshore coastal zones. The persistence and growth of these reefs depend on appropriate temperature and salinity regimes, which differ by species. As communities of filter-feeding organisms, shellfish reefs also require sufficient food availability in the water column, such as phytoplankton and detritus, to support optimal growth. Large shellfish reefs are primarily formed by oysters, although other taxa have created reef structures in some situations (Gillies et al. 2015). Once established, these reefs can confer significant benefits, including enhanced coastal protection (Chowdhury et al. 2021, 2019; Scyphers et al. 2011). Shellfish reefs also can have a substantial indirect influence on flood reduction by supporting salt marsh growth and expansion behind shellfish reefs, which can further enhance coastal protection (Lowe et al. 2021). Shellfish reefs act as a natural breakwater providing wave energy attenuation and stabilizing shorelines (Scyphers et al. 2011). Wave attenuation rates by shellfish reefs can reach 30 to 50 percent for water depths between 0.5 and 1 meters (given reef crest heights of 0.3 to 0.5 meters) and drop below 20 percent for greater depths (Wiberg et al. 2018). Shellfish reefs can also keep up with sea level rise given their ability to grow vertically (Rodriguez et al. 2014). Shellfish reefs also protect other habitats from wave action and promoting sediment retention in their lee, preventing erosion to saltmarshes (Chowdhury et al. 2019; Fivash et al. 2021; Gillies et al. 2015). Shellfish reefs can also have a substantial indirect influence on flood reduction by supporting salt marsh growth and expansion behind shellfish reefs, which can further enhance coastal protection (Lowe et al. 2021).

Shellfish reefs can deliver multiple benefits to ecosystems and people in addition to coastal protection, such as supporting bivalve fisheries and other fisheries species, improving water quality, and enhancing cultural value (Fitzsimons et al. 2019). Ecosystem services provided by shellfish reefs, excluding oyster harvesting, have been valued (in 2011 US dollars) at US$5,500 to US$99,000 per hectare per year (Grabowski et al. 2012). Although this chapter focuses on shellfish (oyster) reefs, there are other types of reefs, such as rocky reefs, which are submerged rock outcrops with varying topography that offer refuge for juvenile and small fish, as well as surfaces for algae and invertebrate colonization. These reefs occur in various forms, each supporting distinct biological communities (NOAA, n.d.)—for instance, rocky reefs shelter groundfish species from predators.

Both oysters and mussels have experienced comparable declines due to overexploitation and habitat degradation, prompting widespread restoration efforts in various regions globally. Approximately 85 percent of oyster reefs globally have been lost, driven by a suite of anthropogenic stressors including overharvesting, habitat destruction, degraded water quality, destructive fishing practices such as dredging and trawling, sedimentation, anoxia, and disease (Beck et al. 2011). The introduction of non-native species, facilitated by ballast water discharge and transfers associated with aquaculture, has also exacerbated declines (Beck et al. 2008). Further impacts stem from coastal development, altered freshwater inflows, and increased inputs of sediments, nutrients, and other pollutants, all of which have contributed to the degradation of oyster reef ecosystems (Beck et al. 2008).



Visualizing the processes and benefits of shellfish reefs.

SUITABILITY CONSIDERATIONS

The successful establishment of an oyster reef depends on several conditions. Among the most fundamental environmental conditions are appropriate water quality regime, characterized by suitable salinity levels, stable temperatures, and sufficient dissolved oxygen; hard substrate to facilitate some species of oysters to develop reefs; and supply of larvae to support population recruitment and growth. These parameters support oyster survival, growth, and reproductive processes, while minimizing stress and disease susceptibility.

Location and climate: Shellfish reefs occur in temperate and tropical regions in shallow coastal and estuarine regions. Native species often best withstand local environmental conditions, but the selection of species may also consider future suitability and species more resilient to increases in water temperatures, acidification, or local pollution.

Hydrodynamics: Shellfish reefs often occur at the subtidal and intertidal levels, where many bivalve species are capable of building reefs (Richardson et al. 2022). Hydrodynamic design can influence the ecology because water flows shape the physical, biological, and chemical conditions of a site, directly affecting oyster survival, recruitment, growth, and reef sustainability. Hydrodynamics can also affect larval dispersal and settlement, food delivery and waste removal, sediment deposition and erosion, water quality and residence time, and can influence the reef structure.

Shellfish are generally tolerant of turbulence and wave energy associated with short, low-intensity storm events. During such disturbances, some individuals may become dislodged and transported, potentially enhancing genetic connectivity among populations. Shellfish reefs typically develop in shallow flat areas, where wave energy and current flow allow juveniles to settle. They thrive in areas where wave- and tide-driven flows deliver nutrients and oxygen while flushing away sediment and waste. However, prolonged or extreme events, such as sustained storms or unusually high flow velocities, can lead to elevated mortality rates. While occasional mortality may promote population turnover and resilience, frequent or severe disturbances can degrade reef structure and ecosystem integrity.

Shellfish reefs are adaptable to a range of current velocities, and reef growth is typically greater in areas with stronger currents because food and oxygenated water delivery is increased (Brumbaugh et al. 2006). However, extreme hydrodynamic conditions, especially those with high flow velocities, can dislodge bivalves from the reef, reducing stability and biomass (Fivash et al. 2021). For instance, the optimal current velocity range for the European native oyster (*Ostrea edulis*) is approximately 0.25 to 0.8 meters per second, beyond which stress or dislodgement may occur (Preston et al. 2020).

Salinity: Critical lower and upper bounds of salinity tolerance differ between species. For example, mussel species such as *Mytilus galloprovincialis* grows in waters with a salinity range between 32 and 37 parts per thousand and can still survive in larger salinity ranges between 22 and 42 parts per thousand (Katsoulis and Rovoli 2019). Oyster species typically occur at salinities ranging from 10 to 30 parts per thousand (Gunter 1955).

Sedimentation rate: The sedimentation rate must not be so high that the reef is buried, as this negatively impacts bivalve survival, growth, and recruitment (Preston et al. 2020). Sewerage outfalls and pollution events can hold high sediment loads, smothering shellfish ecosystems by either slowly degrading the habitat over time or via rapid burial.

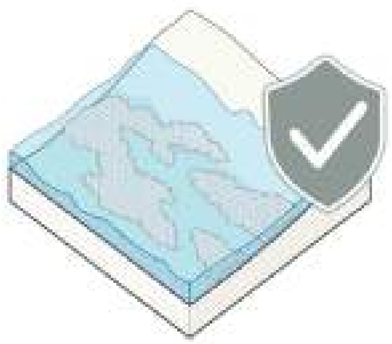
Soil: Shellfish inhabit a wide range of soil types, from fine muds and sands to rocky seashores. Within species exist a range of suited habitats—for example, while some species of oyster form reefs attached to a base of rock or sand, other species are non-reef building yet aggregate and attach to each other on cobble (small rocks) beds.

Matunuck Oyster Farm in Rhode Island, United States
Photo by John Angel on Unsplash

NBS INTERVENTIONS

Greater appreciation and understanding of both the benefits of shellfish reefs and the threats to their survival have increased interest in their restoration and protection, which has led to the development of various guidelines for practitioners and scientists (Fitzsimons et al. 2019).

PROTECTION MEASURES



Conservation and protection measures are fundamental to enabling the recovery of shellfish reefs and support natural recruitment processes. Effective reef protection requires addressing principal threats, including unsustainable and destructive harvesting practices, poor water quality, and biological invasions by non-native species (Beck et al. 2011). The establishment of marine protected areas (MPAs) has been recognized as a significant strategy for the conservation of shellfish reefs (Beck et al. 2008). In recognition of their ecological value, shellfish reefs were included in 2012 as a wetland type eligible for designation under the Ramsar Convention on Wetlands, which increased momentum for their restoration, particularly within the Asia-Pacific region, Europe, the United Kingdom, and the Americas (Beck et al. 2011). These restoration efforts have been accompanied by technical guidelines and best practices, further advancing conservation efforts for these critical habitats.

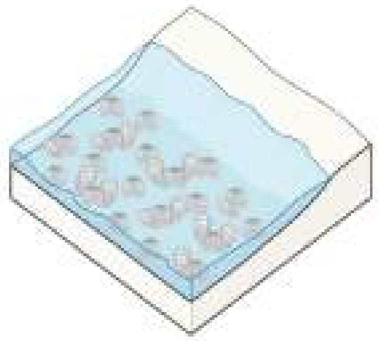
RESTORATION AND ENHANCEMENT MEASURES

Common goals of shellfish reef restoration projects may include biodiversity enhancement, nature-based coastal defense, fisheries productivity, and coastal water quality (Coen et al. 2007; Gilby et al. 2018; Howie and Bishop 2021). Additionally, because intertidal oysters can, through the effects of moisture retention and shading, mitigate heat stress to associated organisms, oyster reef restoration may contribute to management strategies aimed at climate change adaptation of various species (McAfee et al. 2017).

Some of the key design considerations for shellfish reef restoration include (1) site selection that accounts for biological, chemical, and human factors (e.g., water quality, salinity, wave exposure, and human use conflicts); (2) substrate type and availability, ensuring suitable material for larval settlement; (3) species and genotypes chosen for seeding, selected based on current and future environmental suitability for survival, growth, and reproduction; (4) reef structure, including factors such as vertical relief, patch size, and spatial arrangement, to support ecological function and ecosystem service delivery (Howie and Bishop 2021). Local hydrodynamics are central to the design of a successful reef restoration project aimed for coastal protection.

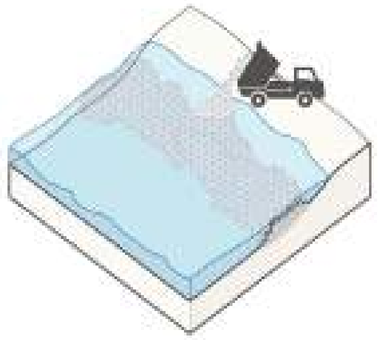
For coastal protection, width and height of the reef critically influence their effectiveness, while differences in reproductive biology between species can also influence design and placement. For example, *Crassostrea* species (e.g., the Eastern oyster) are broadcast spawners with free-swimming larvae, while *Ostrea* species (e.g., the European flat oyster) brood their young, which has implications for larval dispersal and recruitment potential.

Shellfish reef restoration can employ various complementary strategies, each designed to specific ecological barriers and site histories:



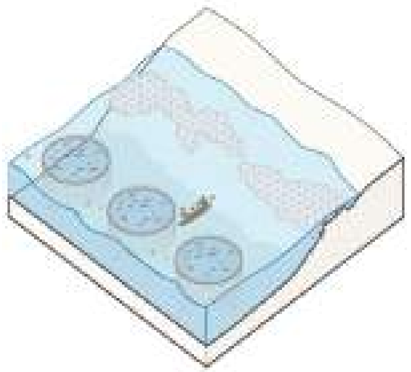
Assisted regeneration

In ecosystems where the natural recruitment of oysters is insufficient, restoration requires targeted interventions (Gillies et al. 2015). Typical approaches involve seeding existing reefs with juvenile oysters produced in hatcheries or ponds, or collected from the wild. Additional shell materials must be introduced to mimic the conditions required for successful settlement where oyster spat (recently settled larvae) are not pre-attached to substrate. Furthermore, the involvement of community-based broodstock programs has not only bolstered recruitment but also cultivated public support and involvement in restoration activities (Fitzsimons et al. 2019).



Reconstruction restoration

Historically, many oyster reefs have been lost to dredging or modifications that eliminate the critical shell base. In such contexts, comprehensive reconstruction may be necessary; this typically involves the deployment of structural materials such as shell, stone, concrete, porcelain, stabilized coal ash, or engineered reef units (Goelz et al. 2020). The selection of materials must be guided by local environmental parameters, regulatory frameworks, community preferences, and restoration objectives (Fitzsimons et al. 2020). Steep slopes pose difficulty in the construction and maintenance of reef restoration (Howie and Bishop 2021).



Partnerships with aquaculture

The collapse of wild oyster populations, driven by overharvesting, disease, and environmental pollution, has left many areas with insufficient spawning stock (Beck et al. 2011). In such cases, hatcheries can serve as a reliable source of juvenile oysters for seeding efforts. Partnering with aquaculture operations also offers the benefit of sharing technical knowledge and reduces pressure on wild stocks. Such collaborations can also support public outreach and advocacy, while helping to secure funding and promote the broader benefits of reef restoration (Beck et al. 2011). Importantly, both the restoration and aquaculture sectors share mutual interests in improving water quality and estuarine conditions, suggesting that collaborative watershed management presents a strategic and sustainable pathway for long-term ecosystem recovery.

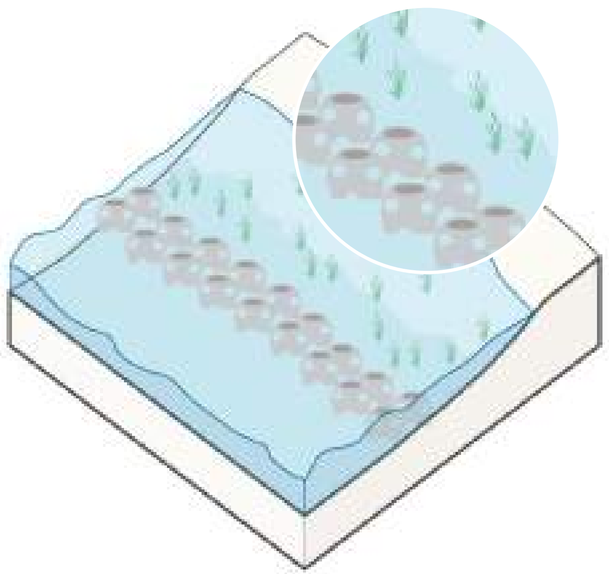
HYBRID INTERVENTIONS

Hybrid solutions can integrate shellfish reef restoration techniques with traditional hard-engineering approaches to deliver enhanced coastal defense while supporting biodiversity and ecosystem services (Morris et al. 2019). These projects can combine natural and artificial elements, such as concrete-based reef structures, and they can stabilize shorelines, attenuate wave energy, and create marine habitat.

Bio-engineered and artificial reefs

In recent years, the development and implementation of bio-engineered and artificial oyster reefs have emerged as prominent strategies for sustainable coastal protection. These engineered structures are increasingly recognized for their dual capacity to mitigate shoreline erosion by dissipating wave energy and to provide ecological benefits such as increased biodiversity and enhanced fisheries productivity (Beck et al. 2011; Chowdhury et al. 2021; Fitzsimons et al. 2019; La Peyre et al. 2014; Morris et al. 2019). Traditionally, oyster shells have been the substrate of choice, primarily due to their biological compatibility with larval settlement, but their scarcity has also prompted the adoption of alternative materials such as rock, concrete, and recycled industrial byproducts (Baggett et al. 2014; Coen and Humphries 2017; Fitzsimons et al. 2020; Goelz et al. 2020).

Bio-engineered reefs are typically categorized into three principal configurations (Chowdhury et al. 2021): (1) loose cultch reefs, which utilize unconsolidated shell or rock in varying relief profiles; (2) constrained cultch reefs, in which the substrate is housed within containment systems such as mesh bags or cages; and (3) precast concrete modules, designed with internal cavities to optimize oyster recruitment and growth. The choice of system and substrate is influenced by site-specific variables, ranging from tidal dynamics to resource availability, and must be aligned with both ecological and engineering objectives (Coen and Humphries 2017; Fitzsimons et al. 2020; Morris et al. 2019). The appropriate choice of materials, shape design, and ecological considerations are key to ensuring longevity and broader ecological objectives (Morris et al. 2019; Vivier et al. 2021).



Artificial reefs also offer multifunctional infrastructure solutions. Artificial reefs can provide substrate stability in otherwise sediment-dominated environments (Chowdhury et al. 2019). This directly facilitates the colonization of oysters and other marine organisms, thereby promoting complex ecological assemblages. By acting both as physical barriers as well as biogenic habitats, these reefs can have a synergistic effect on coastal protection by promoting sediment accretion, buffering vegetative shorelines, and supporting adjacent marsh and seagrass habitats (Chowdhury et al. 2019). Moreover, these reefs can offer recreational and economic values through enhanced fisheries and increased tourism, broadening the societal benefits of such engineered interventions (Komyakova et al. 2019).

However, careful consideration of material choice, configuration, and site specificity is essential to maximize adaptive capacity and ecological resilience in coastal ecosystems. Examples of successful hybrid applications include oyster breakwater reefs in Bangladesh (Chowdhury et al. 2019) and artificial Pacific oyster reefs in the Netherlands, demonstrating that artificial reef structures can facilitate reef establishment and that artificial reefs can perform at the level of healthy reefs (Walles et al. 2016). Notably, some of the largest hybrid reef systems have been implemented along the US Gulf Coast and Australian shorelines (Gillies et al. 2020; Morris et al. 2019; Scyphers et al. 2011).

Lassing Park, Florida, United States
Photo by Joe Whalen on Unsplash

BENEFITS

Flood risk reduction: Designing a shellfish reef for flood risk reduction must take into account the effectiveness of shellfish reefs to attenuate wave energy and protect coastlines, which depends on their size, orientation, elevation, and location relative to shore, as well as tidal range, among other characteristics (Lowe et al. 2021). One of the most important characteristics is the elevation of the reef crest (the shallowest part of a reef) relative to sea level. Reefs dissipate wind-wave energy through both depth-limited wave breaking and friction (drag) associated with large bottom roughness and porosity. For objectives such as wave attenuation and sediment stabilization, it is critical that the reefs be positioned to run parallel to the stretch of coastline requiring protection.

Erosion reduction: The average value of oyster reefs to protect shorelines, most notably from coastal erosion, is estimated at an average of US$860 per hectare per year with maximum values extending to US$85,998 per hectare per year (in 2011 US dollars) (Grabowski et al. 2012). When artificial substrates are employed to facilitate reef establishment, factors such as reef length, spacing, and proximity to shore warrant careful analysis. These variables play a central role in optimizing sediment deposition processes (Lowe et al. 2021; Morris et al. 2019). Conversely, poorly planned configurations can alter local hydrodynamics in ways that promote erosive circulation patterns rather than accretion.

Carbon storage and sequestration: The ability of shellfish reefs to capture and store carbon is an area of ongoing research. Bivalves extract carbon from seawater to build their shells but also deposit organic matter into the reef creating a carbon store (Fodrie et al. 2017). Current shellfish production levels are inconsequential for carbon sequestration of current anthropogenic greenhouse gas emissions (Zavell et al. 2023), but shellfish reefs also contribute indirectly to carbon sequestration by protecting adjacent mangrove and salt marsh habitats, which are among the most effective natural carbon sinks (Fodrie et al. 2017).

Resources production: Coastal communities, particularly in developing countries, can rely heavily on shellfish reefs and their associated species for food and income (Grabowski et al. 2012; Richardson et al. 2022). Bivalves are also important in many regions worldwide, with marine bivalve production for human consumption exceeding 15 million metric tons per year between 2010 and 2015 (Wijsman et al. 2019). Shellfish reefs also provide environmental services including cultural development and identity (Gillies et al. 2015); prey supporting commercially important fish and crustaceans (Hancock and zu Ermgassen 2019); and microhabitat for other organisms to grow, shelter, and act as a nursery and feeding ground (Fitzsimons et al. 2019). In Bangladesh, modeling outputs calculated that installed oyster breakwater reefs allow for the sustainable harvest of 5.6 kilograms of oysters per square meters per year (Tangelder et al. 2015). By a global estimate, 1 hectare of shellfish reef can provide US$4,123 annual income for commercial finfish and crustacean fisheries (in 2011 US dollars) (Grabowski et al. 2012). In the United States, the oyster reef restoration industry's overall size, measured as annual spend, is US$70–90 million, directly supporting an estimated 1,500 jobs and contributing US$210 million in economic output (Hall and DeAngelis 2024).

Tourism and recreation: Shellfish reefs hold important cultural value in many places by creating a sense of connection between communities and the coastal environment. In the United Kingdom, oyster festivals are growing in popularity, creating recreational experiences, sustaining cultural association, and raising awareness of the European oyster (*Ostrea edulis*) (Fitzsimons et al. 2020; Fitzsimons et al. 2019). Shellfish reefs can support local tourism and generate significant economic benefits. For instance, the Stranraer Oyster Festival in Scotland attracted 14,000 visitors in 2018, contributing approximately £1.1 million to the local economy. By 2023, the festival's impact had grown substantially, generating an estimated £2.3 million in economic activity. Shellfish reefs also support recreational activities by supporting associated species targeted by anglers (Fitzsimons et al. 2020) and by improving adjacent water quality to enhance desirable tourism areas (Beck et al. 2011).

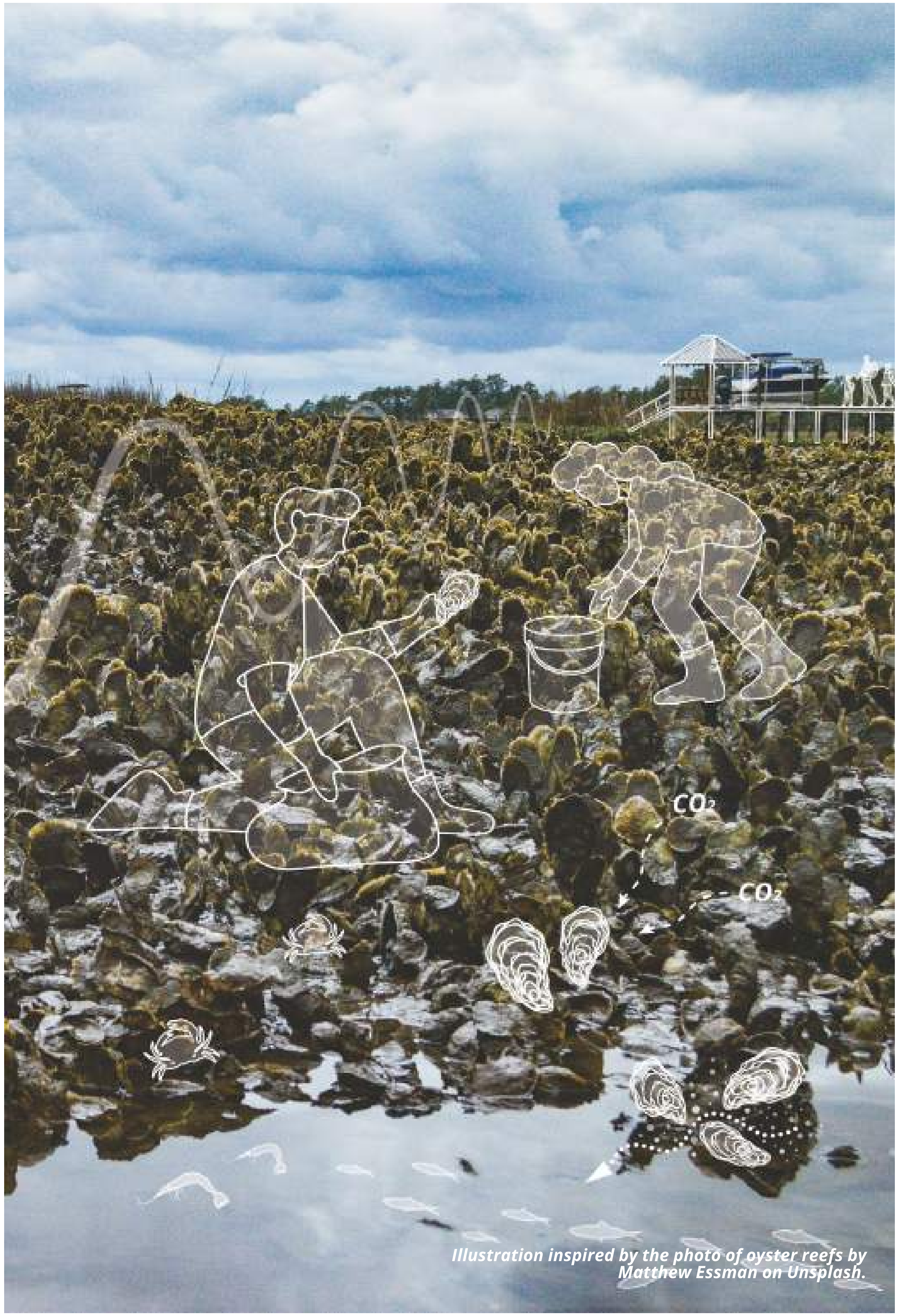
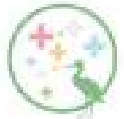


Illustration inspired by the photo of oyster reefs by Matthew Essman on Unsplash.



Biodiversity: The complex, three-dimensional habitat created by shellfish aggregations provides spawning and nursery grounds for many species. Shellfish reefs support high density and diverse algae, crabs and other invertebrates, and fish, while offering shelter for marine species from tidal and heat stress (Craeymeersch and Jansen 2019). The value of shellfish reefs in promoting the recovery, productivity, and maintenance of seagrasses in estuaries has been estimated at US$1,292 per hectare per year (in 2011 US dollars) (Grabowski et al. 2012).

Human health: Public health benefits may arise through pathogen removal that would accrue from increased oyster reef habitat.

Water quality and sediment management: Bivalves are filter feeders, improving water quality and clarity by removing suspended material. Bivalves provide water filtration services, enhancing water quality and clarity, reducing the likelihood of harmful algal blooms, and removing excess nutrients via sediment burial (Newell et al. 2005; Richardson et al. 2022). Bivalves serve as effective bioindicators of water quality, exemplified by their application in studies assessing microplastic pollution (Patterson et al. 2019). Shellfish reefs actively enhance coastal environments by filtering sediments from the water column and stabilizing underlying substrates through deposition processes (Fitzsimons et al. 2019). Shellfish reefs have also been shown to reduce and, in some cases, reverse coastal erosion while facilitating sediment accumulation along neighboring vegetated habitats, such as salt marshes (Chowdhury et al. 2019; Scyphers et al. 2011). Their nitrogen removal services have been valued at between US$1,385 and US$6,716 per hectare per year (in 2011 US dollars) (Grabowski et al. 2012).

The multiple benefits of shellfish reefs on a qualitative scale

Sunshine Skyway Fishing Pier, FLorida, United States
Photo by Joe Whalen on Unsplash

COSTS

Implementation costs

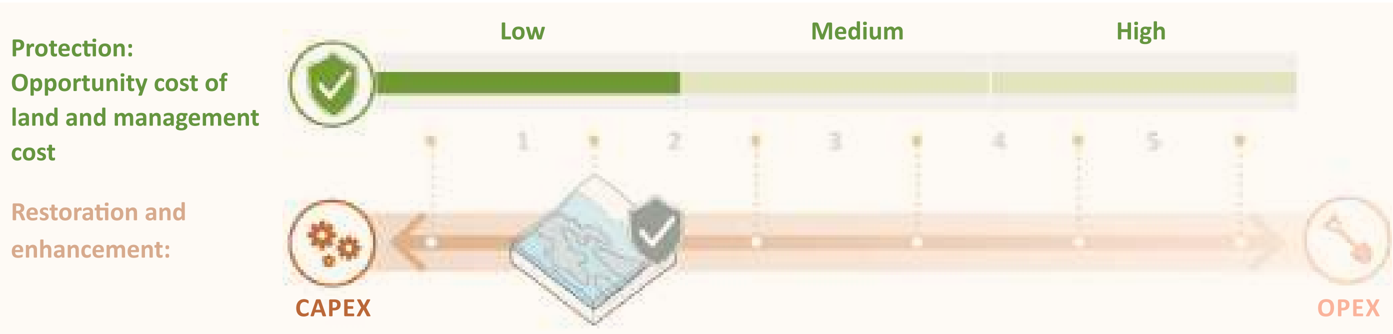
Restoration costs vary markedly, shaped not only by the specific techniques and materials employed but also by environmental variables such as local settings and climate conditions. Other cost factors include feasibility studies, running pilot studies, licensing and permitting requirements, sourcing reef substrate, and sourcing juvenile or adult shellfish. Examples of costs range from US$8,555 per hectare for 10- to 40-centimeter diameter stones as used for oyster restoration in Zhejiang, China, to US$570,000 per hectare for stone, mixed shells, and 3D-printed sandstone as used in the North Sea (Fitzsimons et al. 2019). The average cost in the United States is over US$100,000 per acre, although it is recognized that efficiencies can be increased and costs reduced (TNC 2022). Given the ranges in costs, cost-benefit ratios associated with shellfish reef projects generally lack uniformity and would be sensitive to local conditions and project-specific parameters. As a result, accurate assessment of shellfish reef restoration initiatives requires a nuanced, site-based analysis that accounts for these diverse influences.

Operations & maintenance costs

Shellfish reef maintenance should be minimal beyond monitoring and ensuring the continued control of environmental stressors to allow for natural recruitment. While juvenile mussel beds may be impacted by storm events, mature beds are typically more resilient (Dankers et al. 2001), serving as an indicator of successful restoration (Fitzsimons et al. 2019). Potential maintenance efforts may include the control of invasive species, parasites, and diseases.

Other cost considerations

Access to, or ownership of, land in coastal intertidal and subtidal zones is fundamental for effective shellfish reef protection and restoration. Both public and private land tenure are possible, but careful site selection can ensure long-term project success. Key land-related costs include acquisition, land use payments (such as fees paid to landowners), and ongoing expenses for site protection and access management. For example, oyster reef leasing costs in the United States range from an initial fee of US$25 to US$1,000 initial fee and annual payments between US$1.50 and US$350 per acre (Beck et al. 2004).



CAPEX: Implementation costs
OPEX: Operations and maintenance costs

GUIDELINES AND RESOURCES

The resources listed provide guidance for protecting and restoring shellfish reefs, supporting their assessment, planning, and implementation as nature-based solutions. They also include information on creating suitable conditions for shellfish reefs, as well as guidance on monitoring approaches.

Design guidelines

Adapta Blues. 2023. *Catalogue of Adaptation Measures to the Effects of Climate Change in the Coastline*. https://lifeadaptablues.eu/wp-content/uploads/2023/04/Catalogue_EN.pdf

Brumbaugh, R. D., Beck, M. W., Coen, L. D., Craig, L., and Hicks, P. 2006. *A Practitioners Guide to the Design & Monitoring of Shellfish Restoration Projects: An Ecosystem Services Approach.* NOAA and The Nature Conservancy. https://repository.library.noaa.gov/view/noaa/3470

Fitzsimons, J., Branigan, S., Brumbaugh, R. D., McDonald, T., and zu Ermgassen, P. S. E. 2019. *Restoration Guidelines for Shellfish Reefs*. Arlington, VA: The Nature Conservancy. https://www.natureaustralia.org.au/content/dam/tnc/nature/en/documents/australia/TNC_Shellfish_Reef_Restoration_Guidelines_WEB.pdf

Lowe, R. J., McLeod, E., Reguero, B. G., Altman, S., Harris, J., Hancock, B., Hofstede, R. ter, Rendle, E., Shaver, E., and Smith., J. M. 2021. Reefs. In *International Guidelines on Natural and Nature-Based Features for Flood Risk Management,* edited by Bridges, T. S., King, J. K., Simm, J. D., Beck, M. W. Collins, G., Lodder, Q., and Mohan, R. K. Vicksburg, Mississippi U.S. Army Engineer Research and Development Center, chapter 12. https://ewn.erdc.dren.mil/nnbf-guidelines/12-reefs/

Morris, R. L, Bishop, M. J., Boon, P., Browne, N. K., Carley, J. T., Fest, B. J., Fraser, M. W., Ghisalberti, M., Kendrick, G. A., Konlechner, T. M., Lovelock, C. E., Lowe, R. J., Rogers, A. A., Simpson, V., Strain, E. M. A., Van Rooijen, A. A., Waters, E., and Swearer, S. E. 2021. *The Australian Guide to Nature-Based Methods for Reducing Risk from Coastal Hazards.* Earth Systems and Climate Change Hub Report No. 26. NESP Earth Systems and Climate Change Hub, Australia. https://nespclimate.com.au/wp-content/uploads/2021/05/Nature-Based-Methods_Final_05052021.pdf

Oyster Reef Restoration Workgroup. http://www.oyster-restoration.org/

zu Ermgassen, P, Hancock, B., DeAngelis, B., Greene, J., Schuster, E., Spalding, M., Brumbaugh, R. 2016. *Setting Objectives for Oyster Habitat Restoration Using Ecosystem Services: A Manager's Guide*. Arlington, VA: The Nature Conservancy.

In addition, the Nature-Based Solutions Opportunity Scan (NBSOS) is a tool that helps identify NBS investment opportunities, providing information on NBS types, suitable locations, costs, and coastal protection benefits and co-benefits. It supports decision-makers in integrating NBS into planning, and investment strategies for both urban and coastal areas.

SHELLFISH REEFS CASE STUDIES

PROJECT #1
Creation of Oyster Breakwaters for Coastal Protection, Bangladesh (2016)

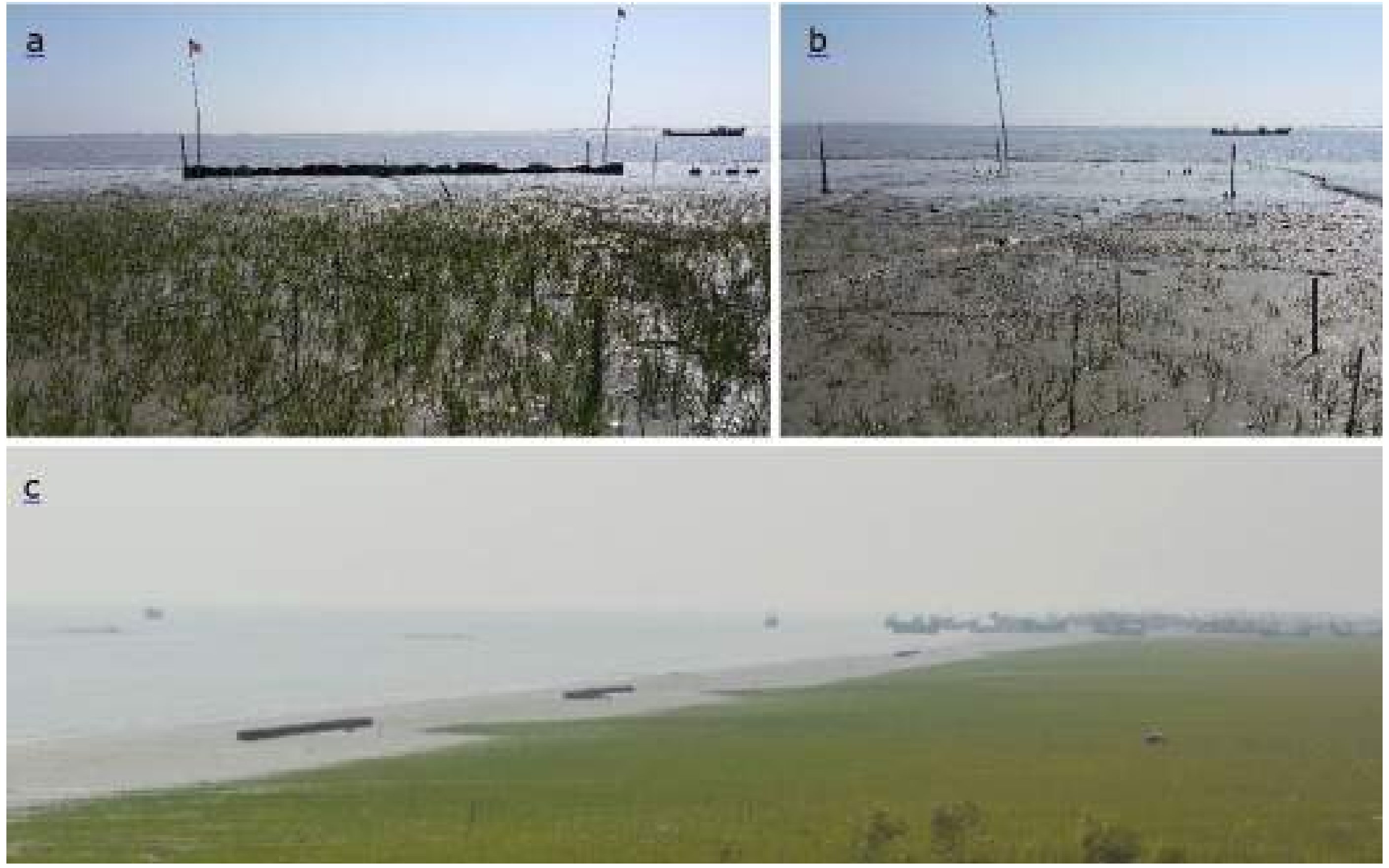
PROJECT #2
Port Stephens Oyster Reef Restoration Project, Australia (2019–28)

PROJECT #3
Oyster Reef Restoration in the Chesapeake Bay, United States (2011–15)

PROJECT #4
The Oyster Reef Stabilization Project, United States (2003–ongoing)

Florida, United States
Photo by Joe Whalen on Unsplash

PROJECT #1
Creation of Oyster Breakwaters for Coastal Protection, Bangladesh (2016)



Photographs showing the difference in salt marsh growth at (a) reef and (b) control sites in December 2017, and (c) seaward salt marsh expansion (photo was taken in February, 2019).
Source: Chowdhury, M. S. N., Walles, B., Sharifuzzaman, S., Shahadat Hossain, M., Ysebaert, T, and Smaal, A. C. 2019. Oyster breakwater reefs promote adjacent mudflat stability and salt marsh growth in a monsoon dominated subtropical coast. Scientific Reports, 9:8549. https://doi.org/10.1038/s41598-019-44925-6

Location

Kutubdia Island, Bangladesh

Approach

Artificial oyster reefs

Size

__3__ reefs, each __20 meters__ long

Cost

Approximately __US$15,000 (US$5,000__ per structure)

Description

This project involved the deployment of artificial oyster breakwater reefs along the intertidal flats of Kutubdia Island, located off the southeastern coast of Bangladesh. The reefs were designed to protect eroding shorelines while enhancing local biodiversity. A total of 123 units of precast concrete rings were deployed across three 20-meter-long experimental reef sites. The reefs provided habitats for diverse marine species, fostering the growth of oysters, polychaetes, and other benthic organisms, as well as reducing wave loads and stabilizing sediments.

Benefits

- *Oyster reefs successfully functioned as breakwaters for tidal levels between 0.5 and 1.0 meters, and fully blocked waves for water levels below 0.5 meters.*
- *The reefs reduced erosion by up to 54 percent and helped stabilize fine sediments, promoting macrobenthic colonization and supporting salt marsh expansion.*
- *Seasonal sediment accumulation increased, fostering organic matter retention and providing food for deposit-feeders.*
- *These reefs serve as nurseries and foraging grounds for transient fish and mobile macroinvertebrates.*

Flood risk reduction | *Coastal erosion reduction* | *Biodiversity enhancement*

Challenges

- *Seasonal variations influenced faunal communities and sediment characteristics, complicating long-term assessments.*
- *Oyster reef effects were localized, limiting the broad ecological impact to areas adjacent to the reefs.*
- *High hydrodynamic actions during certain seasons posed risks to sediment stability and reef integrity.*

Lessons learned

- *Oyster breakwater reefs are effective at stabilizing shorelines and enhancing local biodiversity, even in dynamic environments.*
- *Seasonal dynamics must be considered when evaluating reef performance, as they significantly impact macrobenthic communities.*
- *Soft-sediment environments benefited from reef deployment, especially through sediment stabilization and organic matter enhancement.*

Source (references)

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PROJECT #2
Port Stephens Oyster Reef Restoration Project, Australia (2019–28)

Intertidal shellfish reef bases at the Myall River mouth. Photo by Kirk Dahle.
Source: Taken from [The Nature Conservancy Australia. 2024.](https://www.natureaustralia.org.au/what-we-do/our-priorities/oceans/ocean-stories/restoring-shellfish-reefs/port-stephens/) Port Stephens intertidal shellfish reef restoration. A Reef Builder project. https://www.natureaustralia.org.au/what-we-do/our-priorities/oceans/ocean-stories/restoring-shellfish-reefs/port-stephens/

Location

New South Wales, Australia

Approach

Reef restoration

Size

***2.5 hectares** (total for both reef sites)*

Cost

US$2 million

Description

The Port Stephens Oyster Reef Restoration project involves two reef restoration sites in New South Wales: Karuah and Myall. Karuah focuses on augmenting historic rock leases, while Myall involves creating new reefs on sandy substrates. The reefs, totaling 2.5 hectares, aim to improve ecosystem productivity, increase finfish stocks, and boost recreational opportunities. After seven years, the reefs are expected to significantly enhance habitat productivity, support recreational activities, and stimulate local economic benefits.

Benefits

- *The reef habitat is estimated to become 250–300 percent more productive compared to original conditions.*
- *Opportunities for fishing, diving, and snorkeling are expected to increase, enriching local recreational activities and benefiting local businesses.*

Biodiversity enhancement

Tourism and recreation

Challenges

- *Accurately estimating economic benefits and accounting for rising costs in future expansions is challenging.*
- *Ensuring ongoing community and stakeholder support requires effective communication and involvement strategies.*
- *The choice of reef materials needs to be tailored to specific oyster species and restoration goals.*

Lessons learned

- *Locally sourced rock is better for oyster recruitment than shells, but may not always be beneficial ecologically.*
- *Clear economic benefits from the project help boost continued investment and policy support for restoration.*
- *Overall, the project's cost-benefit ratio is estimated at 1:14.*
- *Comprehensive tracking of project outcomes and benefits is essential for future decision-making.*

Source (reference)

Blackwell, B. D., Jenkins, C., Russell, K., and Cole, V. 2024. Oyster reefs as a success story for ecological restoration: A cost-benefit study from Port Stephens, Australia. Preprint. http://dx.doi.org/10.2139/ssrn.4835732

PROJECT #3
Oyster Reef Restoration in the Chesapeake Bay, United States (2011–15)

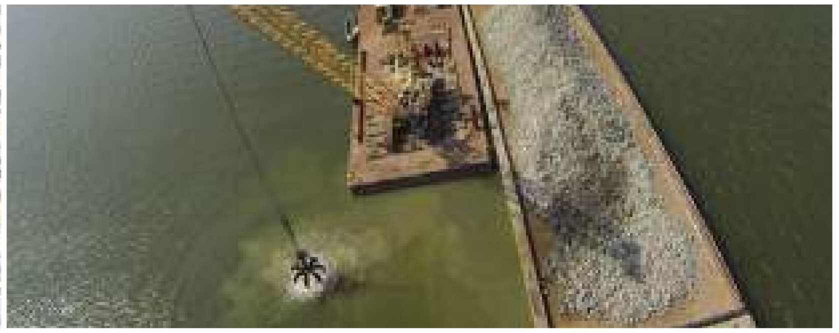

Photo by Chesapeake Bay Foundation.
Sources: Map showing location of restored oyster reefs in Harris Creek, Maryland. NOAA (National Oceanic and Atmospheric Administration). 2025. [Oyster Reef Restoration in the Chesapeake Bay: We're Making Significant Progress.]
Living shorelines, built using oysters and reef material, make waterfront property more resilient. Wiliams, J. P. 2024. [Bay Foundation puts new hope in oysters for water restoration. February 20, 2024. Chesapeake Bay Magazine.]

Location

Harris Creek, Chesapeake Bay, United States

Approach

Reef restoration

Size

142 hectares

Cost

US$28.37 million

Description

*Chesapeake Bay was once home to a thriving population of native oyster (*Crassostrea virginica*) populations, which supported a healthy ecosystem and economy. Due to disease, large-scale exploitation, and degraded water quality, their numbers declined to only 1 percent of their historic population. Under the Chesapeake Bay Watershed Agreement, multiple organizations are leading a large-scale restoration effort to restore reefs in 10 tributaries by the end of 2025. This includes Harris Creek, Maryland, where 2.49 billion oyster seeds were planted.*

Benefits

- *343 of 348 restored acres of reefs met the Oyster Metrics success criteria for a successfully restored oyster reef. The value of restored reefs' ability to cycle nutrients is conservatively estimated at US$3 million annually. Modeling results estimate that these reefs can remove over 46,650 kilograms of nitrogen and 2,140 kilograms of phosphorous per year.*
- *Actions to restore reefs in Harris Creek have benefited biodiversity and local fisheries.*

Water quality | *Biodiversity enhancement* | *Resource production*

Challenges

- *Not all areas within the tributaries are suitable for oyster restoration because of poor water quality and/or the presence of docks and navigational channels.*
- *Oyster shell is in high demand and there is limited availability for shell material for use in oyster restoration. Most reefs can be successfully built using alternative materials such as stone. However, hatcheries are reliant on oyster shells to produce spat-on-shell.*

Lessons learned

- *Monitoring revealed that reefs constructed using a stone-substrate base averaged four times greater oyster density than reefs built using a shell-substrate base.*
- *Logistic considerations associated with restoration at this scale included the proximity of the shell-cleaning facilities, hatchery, and jetty required for mechanized loading of spat-on-shell directly to a boat re-fitted for shell deployment.*

Source (references)

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PROJECT #4
The Oyster Reef Stabilization Project, United States (2003–ongoing)

Aerial view of the Oyster Reef Stabilization Project, United States. Photo by Olivier Mesnage, Taken from Case Study Platform. Source: Oyster Reef Shoreline Stabilization Project. https://casestudies.naturebasedsolutionsinitiative.org/casestudy/oyster-reef-shoreline-stabilization-project/

Location

MacDill Air Force Base, Tampa Bay, Florida, United States

Approach

Artificial oyster reefs

Size

***10,560** linear feet of oyster reef installed by 2018.*

Cost

Costs unpublished.

Description

The MacDill Air Force Base, Florida, is located near an important shipping lane, with heavy boat traffic and tidal action contributing to rapid shoreline erosion. This erosion has threatened the coastal airbase infrastructure, Native American historical sites, and coastal biodiversity. To counteract this, oyster reefs were designed and deployed for shoreline protection and habitat creation. The multi-phase project involved the use of oyster shell bags, concrete oyster domes (or "reef balls"), and loose shell to create a living shoreline. A program was designed to monitor the created oyster reefs for a 3-year period following installation.

Benefits

- *2023 marked the successful deployment of over 10,000 oyster reef balls. The living shoreline has successfully adapted the shoreline to reduce erosion. The nearshore oyster reefs reduce wave energy and encourage sediment accumulation.*
- *The oyster reef installation allowed the creation of 11.4 acres of salt marsh, further protecting the shoreline from erosion.*
- *The project reports biodiversity benefits. The living shoreline and adjacent marshes are vital habitat for fish and bird species, such as the American oyster catcher, ibis, and egret.*
- *The oyster reefs have improved water quality and clarity, with each individual oyster filtering up to 5 gallons of water per hour.*

Coastal erosion reduction

Biodiversity enhancement

Water quality

Challenges

- *The availability of reef substrate has proven a challenge. To overcome this, the project collaborated with various local seafood restaurants to source waste oyster shells.*

Lessons learned

- *Leveraging volunteer support has led to a cost-effective project and aided in generating community interest in the scheme.*
- *The restored living shoreline has proven to be a self-maintaining system, recovering and regrowing when impacted by storm events, and adjusting naturally to gradual sea-level change.*

Source (references)

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MANGROVE FORESTS

Akwidaa, Ghana
Photo by Ato Aikins on Unsplash

FACTS AND FIGURES

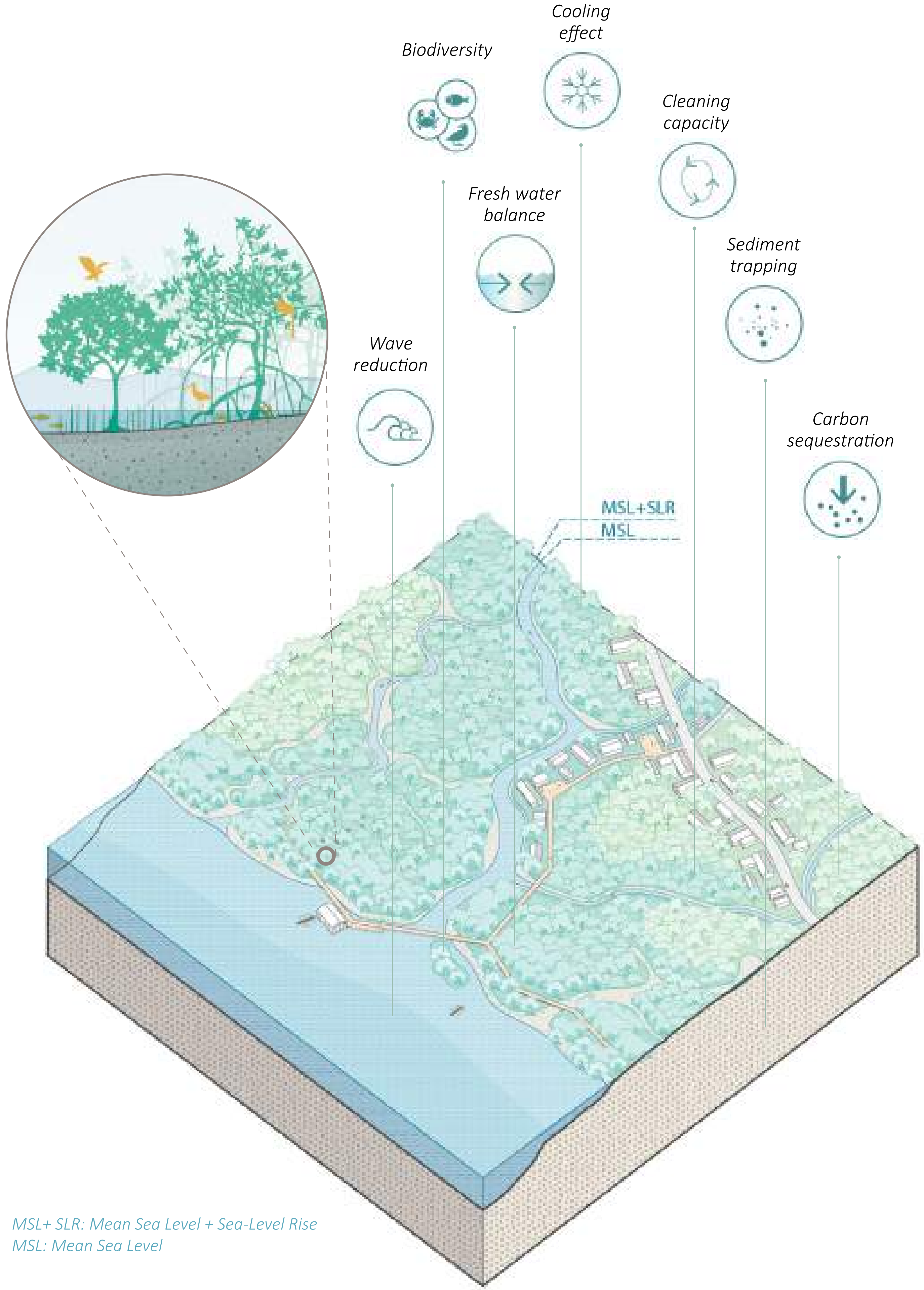
Mangrove forests (also known as mangroves, mangrove swamps*, or* mangal*) are unique, salt-tolerant ecosystems composed of trees and shrubs (halophytes) that thrive in intertidal zones of tropical and subtropical coastlines. They include 68 true mangrove species of red, white, and black mangrove and 16 hybrids or subspecies (Duke and Lee 2024). Mangrove forests predominantly occur in protected environments such as deltas, estuaries, and lagoons with fine alluvial sediments, and around marine islands.*

These ecosystems are naturally resilient and adapt to dynamic coastal conditions (Krauss et al. 2014; Krauss and Osland 2020). Globally, mangroves are estimated to reduce the cost of flood damage by over US$65 billion annually (Menendez et al. 2020). The ecosystem is highly complex and robust. A dense network of emergent roots and trees provides coastal protection by significantly reducing wave energy and storm surges. Mangroves develop specialized root systems, with forms that vary across species. These roots, such as prop roots or pneumatophores, stabilize trees in soft sediments, trap particles, attenuate waves, and promote soil accretion, enhancing shoreline stability (Alongi 2008).

In addition to their protective function, mangroves contribute to water quality regulation, carbon sequestration, biodiversity support via nursery and feeding habitat for marine life—and, therefore, the livelihoods of millions in coastal communities (zu Ermgassen et al. 2020, 2024). Mangroves are also among the most carbon-rich tropical forests, storing large quantities of blue carbon particularly in their deep, organic-rich soils (Choudary et al. 2024; Taillardat et al. 2018). This makes them important both for adaptation to and mitigation of climate change. An economic value of all the ecosystem services from mangroves has been estimated at US$21,000 per hectare per year (Getzner and Islam 2020).

Despite these benefits, mangrove forests are in decline: they are degrading and disappearing at an alarming rate (Giri et al. 2010; Goldberg et al. 2020; Hagger et al. 2022). Key drivers of this decline include urban encroachment, aquaculture, hydrological disruption, and land reclamation (Barbier and Cox 2003; Goldberg et al. 2020; Valiela et al. 2001). Although the global rate of loss has slowed, the net decline persists, with recent data showing a 44 percent decrease in annual loss rates from 2000 to 2020 (Patriarca et al. 2024). Climate change exacerbates these pressures: sea-level rise, altered storm regimes, and salinity changes threaten mangrove stability. The International Union for the Conservation of Nature (IUCN) estimates that 50 percent of the world's mangroves could be vulnerable to sea-level rise in the next 50 years (Leal and Spalding 2024). While mangroves can keep pace with moderate sea-level rise if sediment supply and space for migration are sufficient (Saintilan et al. 2020), their continued existence depends on maintaining hydrological connectivity and avoiding physical barriers to landward movement (Schuerch et al. 2018). Sea-level rise is likely to influence mangrove forests in all regions even though local impacts will vary (Ward et al. 2016).

Mangrove restoration, particularly when paired with hydrological improvements, offers a promising strategy for enhancing resilience (Beeston et al. 2023). Coordinated conservation, restoration, and adaptive management are essential to secure their long-term function in a changing climate. To support this, a range of nature-based solution (NBS) interventions can be applied. These include protecting natural, healthy mangrove areas; restoring and enhancing degraded habitats; and implementing hybrid approaches that integrate mangroves afforestation sensitively with coastal engineering structures, such as levees or embankments.



MSL+ SLR: Mean Sea Level + Sea-Level Rise
MSL: Mean Sea Level

Visualizing the processes and benefits of mangrove forests.

SUITABILITY CONSIDERATIONS

Mangrove forests are suited to sheltered coastlines such as estuaries, lagoons, and deltas, where low wave energy and fine sediments enable propagules to establish and seedlings to develop. Optimal ecological conditions include high tidal amplitudes, reduced salinity fluctuations, and steady freshwater inputs (Alongi 2015). For further technical details on site conditions, see the restoration guidelines provided by Wetlands International (Beeston et al. 2023).

Location and climate: Mangroves are predominantly found in tropical and subtropical zones, typically between 30°N and 30°S latitude, where water temperatures range from 20°C to 30°C (Alongi 2008). Some species extend into warm temperate areas such as southern China and northern New Zealand. Climate change (including shifts in temperature, precipitation, and sea level) can influence species composition, productivity, and freshwater inflows, impacting mangrove health (Alongi 2008, 2015).

Hydrodynamics: Mangroves occupy the intertidal zone between mean sea level and the highest astronomical tide (Woodroffe et al. 2016). Species exhibit distinct tolerances for inundation frequency and duration. Pioneer species (red and black) establish near the mean sea level, while less salt-tolerant (white) species colonize higher zones. Establishment depends on appropriate flooding regimes, reduced wave energy, and sustained hydrological connectivity, which supports nutrient cycling, salinity gradients, and sedimentation (Ellison 2015; Hutchings and Saenger 1987).

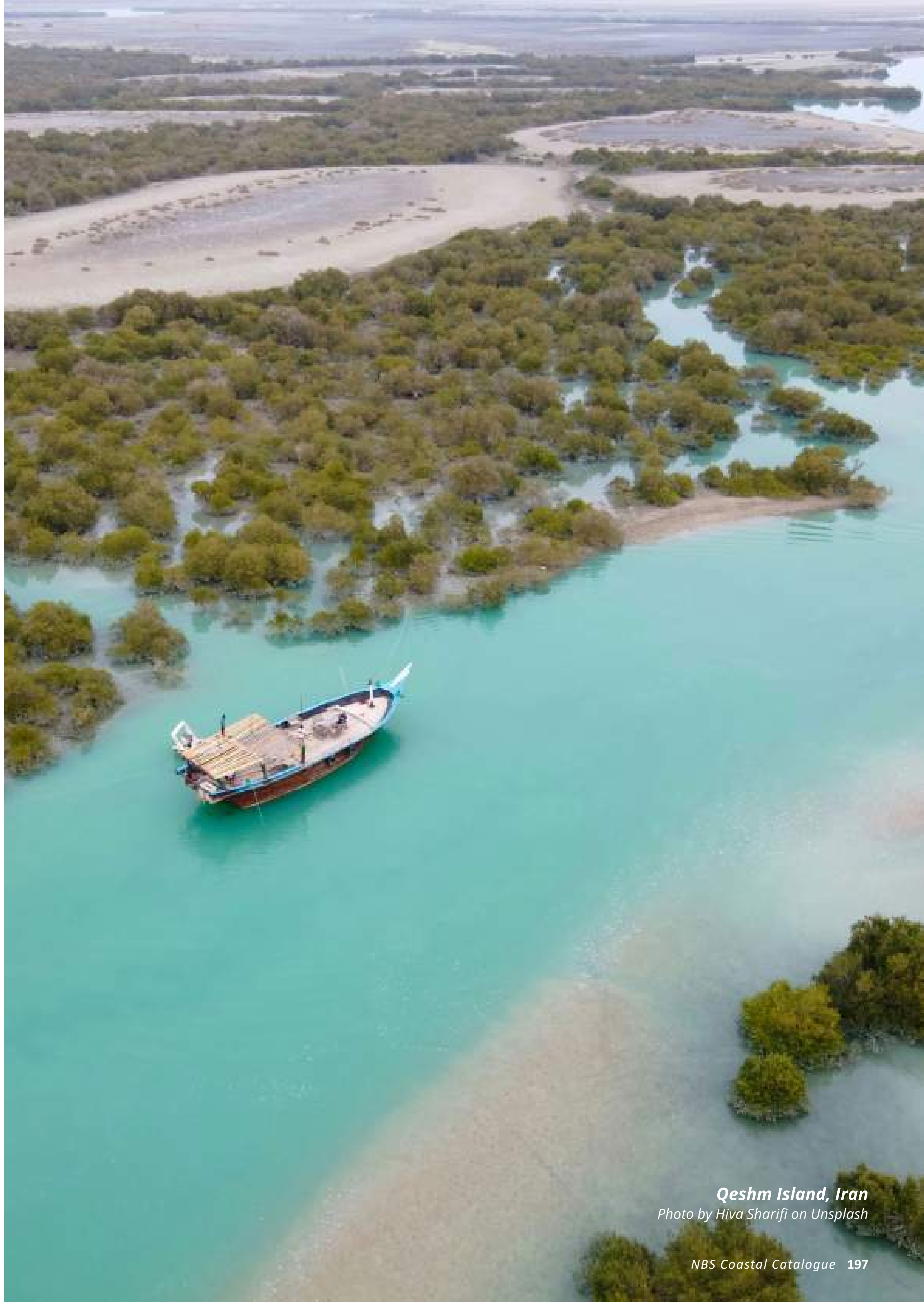
Mangroves can adapt to sea-level rise of up to 6 millimeters per year if sediment supply and landward space for migration are sufficient. However, projected rises exceeding 50 centimeters by 2100 may surpass their adaptive capacity in sediment-starved or constrained systems (Gilman et al. 2008; IPCC 2007). Furthermore, protected shorelines with low wave and low current energy support seedling survival. Excessive exposure can erode soils and dislodge propagules (Balke et al. 2011). Natural shelter is provided by gently sloping muddy sandbanks and established mangrove belts. In exposed areas, artificial structures such as biodegradable, permeable fencing may be used to reduce energy and scour resulting from waves, tides, and storm surge.

Salinity: Salinity significantly influences mangrove species distribution. Most seedlings thrive in brackish water with salinity between 3–27 parts per thousand, compared to 33–38 parts per thousand for seawater. Salt tolerance varies by species and life stage; seedlings are less tolerant than mature trees (Kathiresan and Bingham 2001; Krauss et al. 2008). Prolonged hypersaline or freshwater conditions can limit propagules from becoming established and growing.

Sedimentation rate: Mangroves rely on sediment input to maintain elevation relative to sea level. Complex root systems trap sediments, enabling vertical accretion and resilience to sea-level rise (Van Santen et al. 2007). Sediment deficits can lead to land subsidence and forest retreat, especially in high-energy settings where erosion or burial hinders seedling establishment (Balke et al. 2011).

Soil: Mangrove soils are typically waterlogged, saline, acidic, and oxygen-poor. Substrates rich in clay and organic matter support seedling growth, while compacted or sandy soils can hinder establishment (Field 1996). Soil salinity, pH, redox potential, sulfides, and nutrient levels (e.g., levels of nitrogen and phosphorus) influence productivity and species success (Hutchings and Saenger 1987; Reef et al. 2010). Bioturbation by crabs, mud lobsters, and other fauna enhances oxygenation and nutrient availability (Smith III et al. 1991).

Slope: Mangroves favor flat or gently sloping intertidal zones, where the elevation relative to mean sea level allows regular submergance. Shallow slopes promote propagule retention, reduce runoff, and improve sediment stability. Steep slopes limit mangrove development to narrow fringe zones exposed to wave action (Berger and Hildenbrandt 2000). Gentle slopes promote seedling establishment and reduce erosion, while steep gradients may lead to rapid runoff, increased exposure, and poor anchorage (Berger and Hildenbrandt 2000).



Qeshm Island, Iran
Photo by Hiva Sharifi on Unsplash

NBS INTERVENTIONS

PROTECTION MEASURES

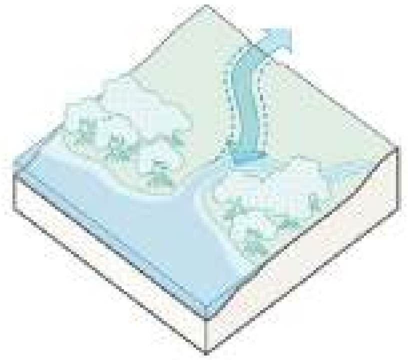
Mangrove conservation encompasses a broad set of actions that collectively form strategies for their protection (Flint et al. 2018). These actions include the care and protection of existing mangroves; their rehabilitation, restoration (afforestation and reforestation), and sustainable use; and the consideration of policy that governs mangrove forests. The Global Mangrove Alliance's *Best Practice Guidelines* (Beeston et al. 2023) emphasizes conservation as a first principle. The guidelines highlight prioritizing existing forests and biodiversity and minimizing further degradation, focusing on ecosystem health and the full engagement of local communities.

Natural colonization by mangroves is determined by hydrological patterns that control seedling distribution and establishment, species ecology (adaptations for reproduction, seedling dispersal, and growth), and human modifications (barriers and activities). Mangroves produce seeds that germinate rapidly into propagules (seedlings). Transported by the current between forests, propagules settle into the sediments in sheltered areas among established trees. Rapid colonization of expanding shores and mudflats can occur if they are protected from waves or currents and have access to the right nutrients and oxygen. Mature mangroves are more tolerant of nutrient-limited or acidic soils. Soil parameters such as size, texture, salinity, and pH strongly influence forest establishment and health. Bioturbation plays a critical role in maintaining soil aeration and fertility—for example, the burrowing activity of the mud lobster *Thalassina* aerates the soil in Southeast Asia (Reef et al. 2010).

Creating reserve areas and implementing effective environmental policies can address the causes of mangrove degradation such as deforestation and pollution. For example, improving wastewater and stormwater management reduces the nutrient and sediment load entering mangrove forests and prevents unwanted algal blooms that lead to deoxygenation and smothering the habitat. Controlling invasive species helps sustain a healthy forest by maintaining species diversity. Other protective measures include maintaining buffer zones to prevent coastal squeeze, preserving hydrological flows, and reserving setback zones for landward migration (Beeston et al. 2023). These areas should be evaluated for their contribution to risk reduction and maintained as natural infrastructure (Beck and Lange 2016; Menendez et al. 2020).

RESTORATION AND ENHANCEMENT MEASURES

The aim of restoring and enhancing mangrove forests is to recover degraded ecosystems and re-establish their ecological functionality. Restoration is particularly effective when it focuses on restoring natural processes, especially hydrology, and enabling natural regeneration. Interventions must be tailored to site-specific physical and ecological conditions, including elevation, tidal range, soil properties, and salinity. The Global Mangrove Alliance (Beeston et al. 2023) and international guidance (Bridges et al. 2021) stress the importance of ecological feasibility assessments, participatory planning, and adaptive monitoring to maximize project success.

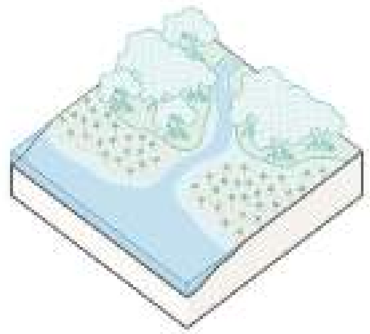


Hydrological restoration

Creating the right biophysical conditions for establishing seedlings—such as appropriate inundation regimes and sediment dynamics—is critical. Mangrove ecosystems depend on freshwater and tidal saltwater flows to function. In many cases, restoring hydrology alone can enable natural regeneration; this should therefore be prioritized. Strategic restoration of river flows and tidal connectivity can re-establish natural hydrology (water flows) where it has been restricted by human activities. Interventions may include restoring elevations and channels by infilling dredged sites or exacvating reclamation areas. Successful projects often integrate ecological understanding, elevation surveys, numerical modeling and assessments, and stakeholder engagement (Beeston et al. 2023; Bridges et al. 2021). Under climate change, particularly sea-level rise, conservation and adaptive restoration strategies must anticipate the need for space to support landward migration.

Wave action protection

Where erosion (by waves and currents) threatens the shoreline, establishing mangroves may require temporary buffering to waves and currents to facilitate sediment accumulation and seedling survival. Permeable brushwood structures (e.g., bamboo or twig fences) and biodegradable materials can provide shelter by reducing wave energy and promote favorable conditions for propagule colonization. These permeable structures are often deployed in grid patterns aligned with tidal flow to maximize sediment capture and reduce scour. Community participation and adaptive monitoring are essential to ensure stability, assess performance, and adjust techniques as needed (Bridges et al. 2021; Wilms et al. 2020). Often challenging to implement, construction methods in these soft sediment intertidal zones should prioritize safety and feasibility.



Reforestation

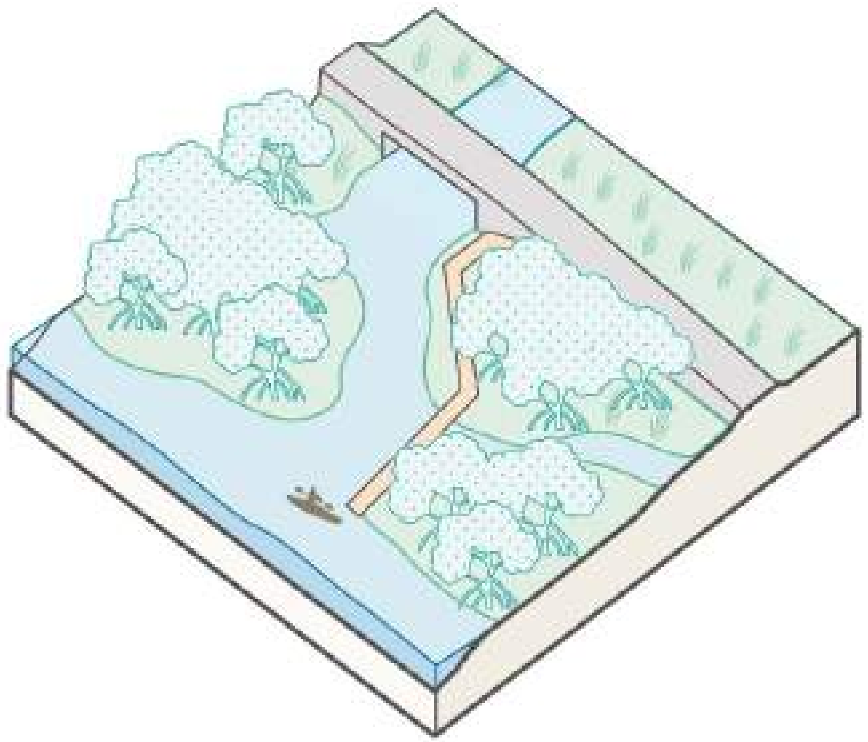
Where natural propagule supply is limited or hydrological conditions are suboptimal, it may be necessary to assist regeneration by manual planting. Reforestation typically involves manual planting of nursery-raised seedlings, prioritizing native and site-appropriate species. Site investigations must confirm biophysical suitability, such as salinity, elevation, and water exchange. Restoration design should avoid monocultures and reflect the native, site-appropriate species and typical diversity to enhance resilience. Allowing sufficient space for species zonation and higher biodiversity is recommended to maximize resilience to environmental stressors, such as pests or storms (Krauss and Osland 2020; van Hespen et al. 2023). In planning, allow a margin for forest migration landward with sea-level rise: the area required depends on the projected rate of change and local gradient. Local and indigenous knowledge should inform planning and planting methods (Beeston et al. 2023). Long-term monitoring and adaptive management are key elements of sustainable restoration. Success depends on monitoring performance indicators (e.g., vegetation cover, sediment accretion, hydrological function) and triggering replanting or counter strategies where benchmarks are not met.

HYBRID INTERVENTIONS

Mangroves can be effectively integrated with levees (rock sills or earthen embankments) and other engineered defenses to reduce coastal flooding and wave energy. Traditional engineered defenses are generally less aligned with nature-based principles than hybrid ones, whereas hybrid designs take into account the requirements of mangrove growth by, for instance, maintaining tidal flow and ecological connectivity required by the mangrove forests. Hybrid solutions are particularly suitable in estuarine environments, where extensive mangrove belts can reinforce storm surge defenses.

Hybrid solutions must ensure the structural integrity of engineered structures. Mangrove root systems can damage or destabilize engineered structures, so planting directly on levee slopes is discouraged. Instead, mangroves should be positioned as reinforcing buffers using concepts such as the horizontal levee, which has been applied to other coastal vegetation systems (Taylor-Burns et al. 2025). This approach allows mangroves to attenuate wave action and water levels in front of the levee, potentially reducing design heights and associated construction costs (van Zelst et al. 2021). Shorter, dense mangrove belts along the shoreline also buffer wind-wave energy during elevated sea levels or storm surge events (Vuik et al. 2016).

It is essential that hybrid systems allow mangroves to develop and expand, even taking into account landward migration under sea-level rise, to ensure long-term sustainability. Poorly integrated projects have in some cases led to root damage and the undermining of levee bases. Sound hydrodynamic modeling, site-specific soil characterization, and design for ecological compatibility are critical, as a full-system approach is essential for ensuring the effectiveness and persistence of mangrove ecosystems (Horstman et al. 2021). Where propagule supply is limited or hydrological conditions are suboptimal, assisted regeneration may be necessary. While these solutions may involve higher upfront costs than ecological approaches alone, they can offer enhanced resilience in high-risk settings where ecological measures alone would be less feasible or slower to take effect.



Zhuwei, Tamsui District, New Taipei City, Taiwan, China
Photo by Winston Chen on Unsplash

BENEFITS

Flood risk reduction: Mangrove forests serve as natural buffers against coastal flooding and storm surges, with effectiveness influenced by forest width, structure, and species (Spalding et al. 2014). For instance, 100 meters of *Sonneratia* spp. can reduce wave energy by 50 percent, while 50 meters of *Avicennia* sp. may reduce it by 70 percent (Alongi 2008; Othman 1994). Storm surge attenuation may require several kilometers of forest (Blankespoor et al. 2016; Narayan et al. 2016), though this declines in fragmented landscapes (Temmerman et al. 2023). Mangroves also reduce river flooding (Bann 1998) and avert over US$65 billion in global flood damage annually (Menendez et al. 2020). Restoration yields benefit-cost ratios of 2.19 to 1, reaching 16.75 to 1 for conservation and up to 104 to 1 when combined with levees and ecological benefits (Su et al. 2021; Vuik et al. 2019).

Erosion reduction: Mangroves stabilize shorelines by reducing wave height and velocity, and by trapping sediment in their dense root networks (Sánchez-Núñez et al. 2019). Wave energy can be reduced by 13–66 percent over a 100-meter mangrove belt, and storm surge attenuated by up to 0.25 meters/kilometer (McIvor et al. 2012; Temmerman et al. 2023). By retaining sediment and buffering wave impact, mangroves reduce long-term erosion risks, especially when maintained as wide, contiguous belts.

Resources production: Mangrove forests are among the world's most productive ecosystems, supporting fisheries and yielding vast numbers of fish, crabs, shrimps, and mollusks. Globally, over 4 million artisanal fishers rely on mangroves (zu Ermgassen et al. 2020). Mangroves can also provide sustainable timber and non-timber forest products such as round wood, poles, fuel wood, and charcoal, as well as non-wood products such as nipa palm shingles, bark for tannin, traditional foods, dyes, and resins. However, sustainable harvesting practices are required to ensure the continuity and quality of the forest and its produce (Bann 1998). Fishing and other livelihoods means communities depend on mangroves because of their high productivity and yields (e.g., fish, wood, fruit, and honey). This has created deep cultural connections to the forests.

Tourism and recreation: Mangroves offer high-value, low-impact opportunities for ecotourism. Approximately 3,945 mangrove-related tourist attractions exist across 93 countries and territories, with boating being the most widespread activity (Spalding and Parrett 2019). Ecotourism, which is becoming increasingly popular across the tourism spectrum, can support local economies while at the same time incentivizing mangrove conservation.

Carbon storage and sequestration: Mangroves are globally significant blue carbon sinks, storing an average of 1,000 metric tons of carbon per hectare in biomass and deep soils (Donato et al. 2011; Mukherjee et al. 2014). Their sequestration rates surpass many other forest systems. Restoration can boost carbon uptake to 23.1 metric tons CO_2 per hectare per year initially, then stabilize at 10.5 metric tons (Bernal et al. 2018). Reforesting former mangrove areas can sequester 60 percent more carbon than afforestation (Song et al. 2023). Globally, restoration could offset ~3 percent of annual emissions by 2030 (Macreadie et al. 2021), reinforcing their value for blue carbon markets and ecosystem service schemes (Su et al. 2021).

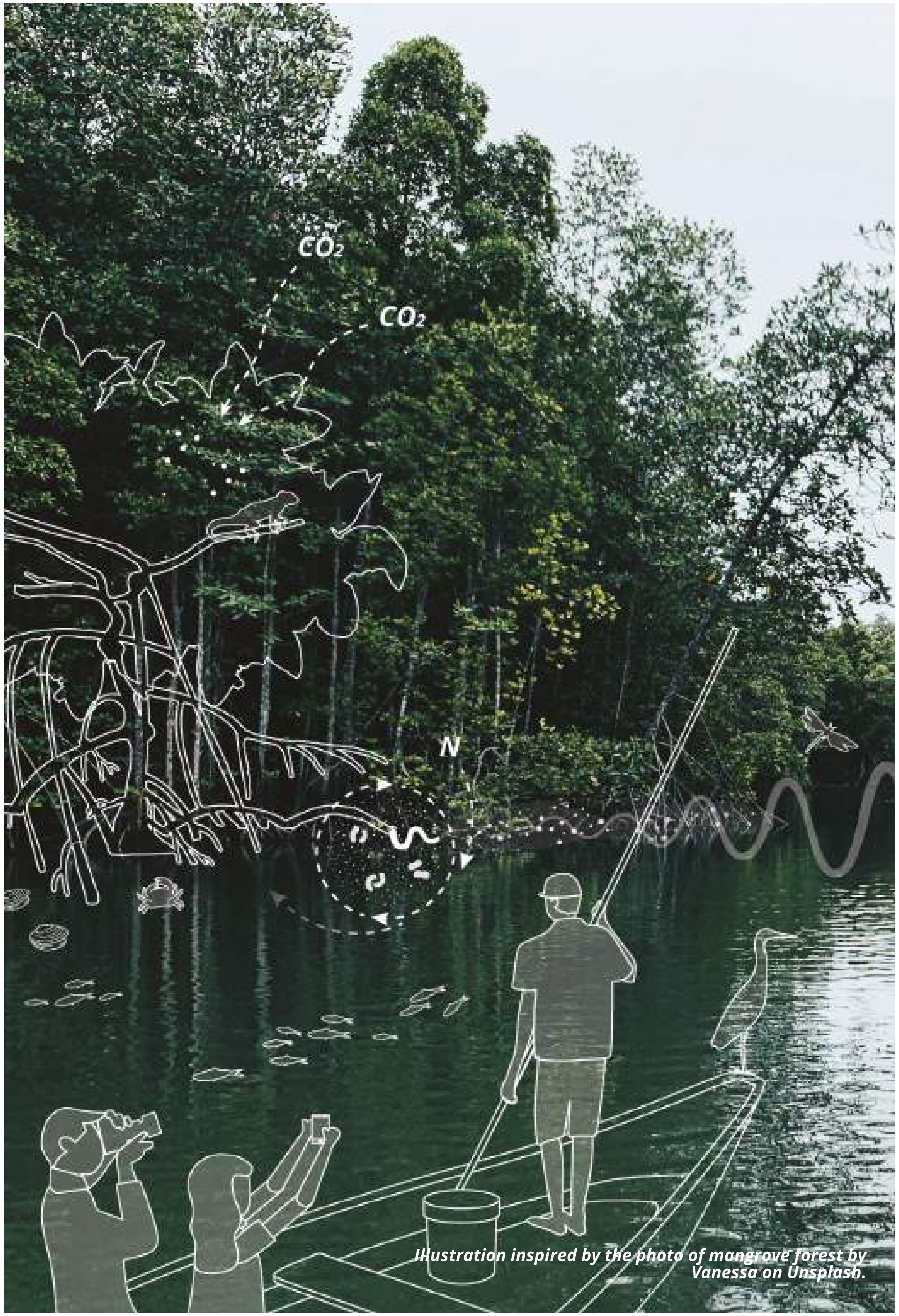
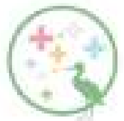


Illustration inspired by the photo of mangrove forest by Vanessa on Unsplash.

Water quality and sediment management: Mangroves regulate water quality and sediment dynamics by trapping sediments and filtering runoff through their dense root systems. This reduces nutrient and pollutant loads entering nearby marine habitats, protecting seagrass beds and coral reefs from smothering and eutrophication (Bann 1998; FAO 2007). By slowing water flow, they promote sediment deposition, nutrient cycling, and sequestration of pollutants such as heavy metals and excess nitrogen (Beeston et al. 2023; Mukherjee et al. 2014). Mangroves also buffer salinity by limiting saltwater intrusion and supporting aquifer health. These functions enhance ecological stability, reduce algal blooms, and maintain the resilience and productivity of coastal waters.



Biodiversity: Mangroves support a wide range of species, providing critical habitat, nurseries, and feeding grounds. They host endangered species such as crocodiles, iguanas, tigers, otters, manatees, dolphins, and birds, including herons, egrets, pelicans, and eagles. Mangroves also help sustain coral reefs and seagrass beds by trapping sediment and filtering runoff (FAO 2007), supporting the health of broader coastal ecosystems.

Human health: Mangroves support public health by regulating disease vectors and improving water quality. Their complex habitats sustain predator species that help control mosquito populations, reducing the risk of diseases such as malaria, dengue, Zika, and chikungunya (Beeston et al. 2023; Mukherjee et al. 2014). By filtering pollutants and stabilizing sediments, mangroves also limit waterborne diseases and contribute to cleaner aquatic systems. Conservation efforts can enhance access to clean water, as seen in Kenya's Mikoko Pamoja project, which improved community health through mangrove-linked water infrastructure (UNEP 2018). These services highlight the vital role mangroves play in sustaining both environmental and human well-being.

The multiple benefits of mangrove forests on a qualitative scale

Quanzhou, Fujian, China
Photo by Lastmayday on Unsplash

COSTS

Implementation costs

Mangrove protection (conservation) and restoration implementation costs vary widely depending on degradation level, site accessibility, and restoration method (Bayraktarov et al. 2016; de Groot et al. 2012; Flint et al. 2018).

Key activities that affect implementation costs may consist of those used for *hydrological restoration*, which includes the removal of obstacles, dredging, soil placement, and building permeable structures (at a cost of US$10,000–US$50,000 per hectare). This applies particularly in former aquaculture or impounded areas, which require heavy machinery and engineering design to restore former conditions (e.g., knocking down walls or leveling pond embankments in former aquaculture sites).

Another category of key activities encompasses those used for *reforestation/afforestation*, which involves nursery-raised seedlings, labor, transport, and monitoring (at a cost of US$5,000–US$25,000 per hectare). *Assisted regeneration*, which involves fencing, hydrological adjustment, and limited planting (at a cost of US$500–US$5,000 per hectare) and *natural regeneration*, which is the least expensive (as it relies on existing seed banks and hydrology, at a cost of US$100–US$1,000 per hectare), are the last two categories to consider.

Economies of scale and secure land tenure reduce costs and improve outcomes. Case study ranges include Kenya and Viet Nam at US$500–US$8,000 per hectare; Mikoko Pamoja (Kenya) costs US$427 per hectare per year. The median global cost for mangrove restoration is US$3,061 per hectare (Bayraktarov et al. 2016). Where flood protection levees are integrated into hybrid approaches, coordination in design and construction offers cost and time efficiencies. Increased engineering needs in urban or industrial areas may raise costs to US$20,000–US$75,000 or more per hectare.

Operations & maintenance costs

Effective maintenance ensures long-term viability and improves ecosystem performance. Operations and maintenance costs are typically 10–30 percent of the capital investment annually for the first 3–5 years (Flint et al. 2018). Maintenance needs vary depending on restoration type and mangrove function.

Monitoring and supervision consists mainly of two elements: (1) community-based monitoring, which comes to US$50–US$200 per hectare per year, and (2) technical or scientific monitoring, including Geographic Information System (GIS) per satellite data, gages, and carbon sampling costs relatively more—US$200–US$1,000 per hectare per year.

Site maintenance involves weeding, replanting, and the upkeep of fences or permeable structures, which typically comes to US$100–US$1,000 per hectare per year. Identification of plant health and substratum stability may include sensitive local dredging and the addition of nourishment where needed. Enforcement and protection is another element to consider. Signage, guards, and patrolling to reduce grazing or harvesting pressures costs US$150–US$500 per hectare per year. Forest management comprises yet another cost. Forestry rangers for nursery management, training, and governance are usually trained by the initial project.

Other cost considerations

Access to or ownership of intertidal coastal land is essential. Restoration typically requires large areas, which involves raising acquisition and transaction costs and requiring stakeholder engagement. Land may be publicly or privately owned. Associated costs—which depend on the region and the extent of land involved—include legal changes to enable land lease/acquisition, land acquisition or leasing costs, payments to landowners for use or conservation, costs associated with protection and management of restored areas (e.g., fencing, patrolling), and potential costs of community resettlement in the case of encroachment. Additional factors that increase restoration costs include sites that are severely degraded or remote. Furthermore, sites in industrial/urban zones face higher engineering and compliance costs. Other factors that affect costs include legal tenure security, which reduces costs and increases success rates, as well as community involvement, which can reduce labor costs and improve outcomes.

CAPEX: Implementation costs
OPEX: Operations and maintenance costs

GUIDELINES AND RESOURCES

The resources listed provide guidance for protecting and restoring mangrove forests, supporting their assessment, planning, and implementation as nature-based solutions. They also include information on creating suitable conditions for mangrove forests, as well as guidance on monitoring approaches.

Design guidelines

Beeston, M., Cameron, C., Hagger, V., Howard, J., Lovelock, C., Sippo, J., Tonneijk, F., van Bijsterveldt, C. and van Eijk, P. Editors. 2023. *Best practice guidelines for mangrove restoration*. Global Mangrove Alliance. https://www.mangrovealliance.org/best-practice-guidelines-for-mangrove-restoration/

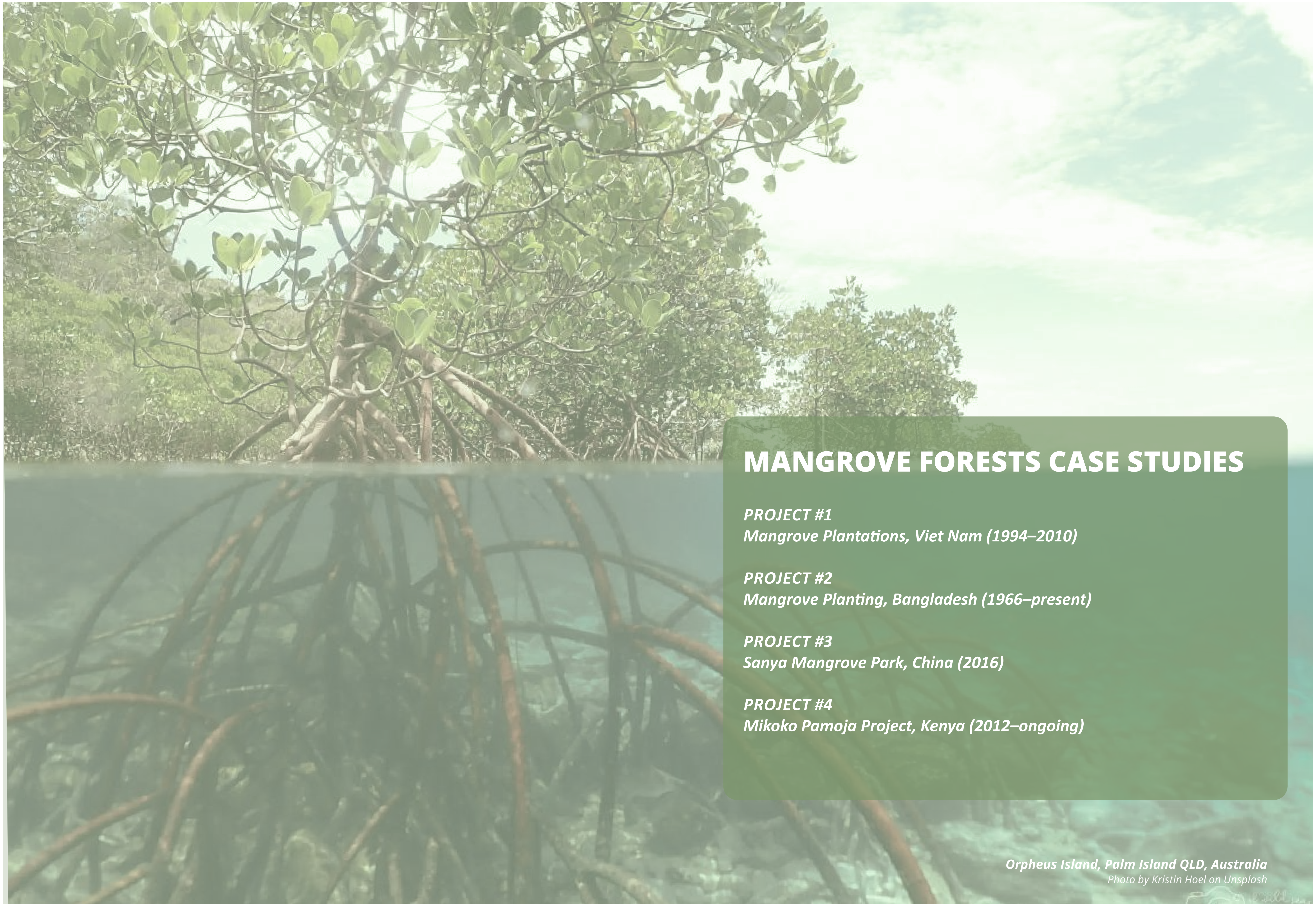
Morris, R. L., Bishop, M. J., Boon, P., Browne, N. K,, Carley, J. T, Fest, B. J., Fraser, M. W., Ghisalberti, M., Kendrick, G. A., Konlechner, T. M., Lovelock, C. E., Lowe, R. J., Rogers, A. A., Simpson, V., Strain, E. M.A., Van Rooijen, A. A., Waters, E., and Swearer, S. E. 2021. T*he Australian Guide to Nature-Based Methods for Reducing Risk from Coastal Hazards: Earth Systems and Climate Change Hub Report* No. 26. NESP Earth Systems and Climate Change Hub, Australia. https://nespclimate.com.au/wp-content/uploads/2021/05/Nature-Based-Methods_Final_05052021.pdf

Piercy, C. D., Pontee, N., Narayan, S., Davis, J., and Meckley, T. 2021. Coastal Wetlands and Tidal Flats. In I*nternational Guidelines on Natural and Nature-Based Features for Flood Risk Management*, edited by Bridges, T. S., King, J. K., Simm, J. D., Beck, M. W., Collins, G., Lodder, Q., and Mohan, R. K., chapter 10. Vicksburg, MS: U.S. Army Engineer Research and Development Center. https://issuu.com/poweroferdc/docs/nnbf-guidelines-2021/442?fr=sZTFiNjQyNjA2NDQ

World Bank. 2021. *A Catalogue of Nature-Based Solutions for Urban Resilience*. Washington, DC: World Bank Group. https://hdl.handle.net/10986/36507

WWF (World Wildlife Fund). 2016. *Natural and Nature-Based Flood Management: A Green Guide.* https://files.worldwildlife.org/wwfcmsprod/files/Publication/file/538k358t40_WWF_Flood_Green_Guide_FINAL.pdf

In addition, the Nature-Based Solutions Opportunity Scan (NBSOS) is a tool that helps identify NBS investment opportunities, providing information on NBS types, suitable locations, costs, and coastal protection benefits and co-benefits. It supports decision-makers in integrating NBS into planning, and investment strategies for both urban and coastal areas.



MANGROVE FORESTS CASE STUDIES

PROJECT #1
Mangrove Plantations, Viet Nam (1994–2010)

PROJECT #2
Mangrove Planting, Bangladesh (1966–present)

PROJECT #3
Sanya Mangrove Park, China (2016)

PROJECT #4
Mikoko Pamoja Project, Kenya (2012–ongoing)

Orpheus Island, Palm Island QLD, Australia
Photo by Kristin Hoel on Unsplash

PROJECT #1
Mangrove Plantations, Viet Nam (1994–2010)

Photo by Monika Guzikowska on Unsplash.

Location

Viet Nam

Approach

Mangrove afforestation, rural

Size

8,961 hectares *of mangroves were rehabilitated or afforested.*

Cost

US$8,885,000

Description

Viet Nam is vulnerable to climate change and cyclones. The rehabilitation (planting, yet not necessarily of the native species) of mangrove forests and afforestation (planting of newly accreted areas) have been a central focus of both governmental and nongovernmental actors in Viet Nam, primarily to combat the loss of natural coastal defenses and also to protect mangrove-based livelihoods. The investment has translated into the creation of mangrove forests in 166 communes, and the protection benefit of approximately 100 kilometers of levee (dikes or embankment) lines. Mangrove plantations have positively impacted the income for coastal communities through an increase in yield of aquaculture products such as clams and oysters, important aquaculture products in northern Viet Nam.

Benefits

Two million people benefit from the flood protection provided by mangrove forest restoration efforts. The livelihoods of an estimated 350,000 people have been improved. Furthermore, levee damage during extreme events has been significantly reduced by hybridizing mangrove forest restoration with levees. Mangroves participate in improved flood risk by ensuring the upkeep of the levees; the avoided repair costs are estimated to be between US$80,000 and US$295,000 per site.

Flood risk reduction

Resource production

Challenges

- *Valuing co-benefits, such as culture and disease control, is challenging.*
- *Planting survival varied between 28 and 89 percent at five selected monitored sites; poorer survival rates (below 70 percent) were likely due to lack of hydrological restoration and water quality management.*
- *One-off capacity training courses were not sufficient to train local mangrove monitoring teams.*
- *Lack of coordination between ministries regarding overlapping projects.*

Lessons learned

- *The planting density was too high: mangrove forests have become too dense for natural regeneration to occur, and the high density of vegetation restricts access for local communities to fish and harvest.*
- *Dense plantations do not provide the same ecological conditions as natural forests as the canopy blocks light penetration to the substratum.*
- *Mature trees seaward of embankments are still vulnerable to damage from typhoons and storms*
- *Long-term planning should ensure sufficient accommodation of space seaward of levees to allow for the continued development of forests in accreting areas.*

Source (reference)

IFRC (International Federation of Red Cross and Red Crescent Societies). No date. Mangrove plantation in Viet Nam: Measuring impact and cost benefit. https://preparecenter.org/wp-content/sites/default/files/case-study-vietnam.pdf

PROJECT #2
Mangrove Planting, Bangladesh (1966–present)

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A nursery of native mangrove tree saplings maintained by coastal communities (left). Mangrove trees planted between the sea and an embankment (right). Photos obtained from Mongabay with associated captions, courtesy of Friendship.
Source: Siddique, A. 2022. Bangladeshi coastal communities plant mangroves as a shield against cyclones. Mongabay, June 3, 2022. https://news.mongabay.com/2022/06/bangladeshi-coastal-communities-plant-mangroves-as-a-shield-against-cyclones/

Location

Bangladesh

Approach

Mangrove afforestation, rural

Size

28,000 hectares** were established successfully by 2020 out of a total of **200,000 hectares.

Cost

*The afforestation costs for planting 120,000 hectares between 1980 and 1990 were **US$20 million.***

Description

Since the 1960s, mangrove plantations have been introduced along the low-lying Bangladesh coastline in response to increasing coastal flood hazards caused by extensive deforestation, climate change, and cyclones. Initial afforestation efforts planted mangrove on newly accreted land to create a protective belt seaward of coastal communities for flood and erosion management. Mangroves were observed to accelerate accretion of soils locally; therefore they were additionally planted to raise and stabilize areas for agriculture. As planting efforts scaled up, research studies were conducted to optimize nursery, plantation, and management techniques.

Benefits

- *Mangrove afforestation efforts with ages between 5 and 42 years have sequestered an estimated 76,607 megagrams of carbon per year in biomass and 37,542 megagrams of carbon per year in soils.*
- *If mangrove planting continues at the current rate, it is projected that by 2030, 664,850 megagrams of carbon will be sequestered. This would contribute to 4.4 percent of Bangladesh's greenhouse gas reduction target for 2030.*
- *Estimates suggest that incorporating the wave reduction benefits of existing mangrove belts into levee designs could reduce the thickness of the revetment by 18–80 percent, reducing the material required and the cost.*

Flood risk reduction

Carbon sequestration

Challenges

- *Planting survival rates range from 6.8 percent to 42.5 percent.*
- *As of 2020, only 28,000 hectares out of a total of 200,000 hectares that have been planted have survived. Planting failures have been attributed to various factors including sediment dynamics and insect pests.*

Lessons learned

- Sonneratia apetala *and* Avicennia officinalis *are the most frequently planted mangrove species in Bangladesh because of their high survival rates in early plantations. Both species are native pioneers known for their rapid growth and high salinity tolerance.*
- *Plantations also show evidence of natural colonization.*
- *After 20 years, the biomass of planted tree communities matched that of natural forests, and after 39 years, their tree density was comparable to that of natural forests.*

Source (references)

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PROJECT #3
Sanya Mangrove Park, China (2016)

Bird's-eye view of Sanya Mangrove Park, China. Photos by Turenscape.
Source: Turenscape. 2019. Sanya Mangrove Park. Video. [*https://www.turenscape.com/en/project/detail/4654.html*](https://www.turenscape.com/en/project/detail/4654.html)

Location

Hainan, China

Approach

Mangrove forest creation, urban

Size

10 hectares

Cost

Undisclosed.

Description

The Sanya Mangrove Park was created primarily to tackle flood risk during cyclones and extreme storms, against a backdrop of rapid urban development and growing demand for green space. Landscape architects and the city government successfully transformed a 10-hectare area of landfill behind a concrete flood wall into a flourishing mangrove park, showcasing urban renewal and ecological regeneration. The project recycled onsite debris and concrete materials in the park design to create landforms of "interlocking fingers," creating space for mangrove planting. Bioswales were added to the design to collect and filter stormwater. The intervention has secondary benefits of recreation, health, and well-being.

Benefits

- *The accessible park supports public welfare, creating recreational value for local residents while supporting the city's tourism industry.*
- *The project has resulted in a biodiversity benefit through restoration of natural processes and connectivity between the sea and the Sanya River.*
- *The restoration site is home to diverse fauna and flora, including various mangrove species that are well-established.*
- *The interlocking finger–like layout has increased the shoreline from 700 meters to over 4,000 meters, increasing the interface between vegetation and the water and maximizing edge effects such as nutrient removal.*

Biodiversity enhancement | *Tourism and recreation* | *Water quality*

Challenges

- *Tropical monsoons bring strong winds and floods, posing a challenge for mangrove restoration and survival rates.*
- *The city is heavily urbanized with pollution run-off impacting the restoration site.*

Lessons learned

- *Ecosystem restoration must be balanced with public access requirements, right of way, and wider social and cultural benefits.*
- *Challenges of storm damage and pollution were mitigated by designing a landform of interlocking fingers that allow ocean tides to enter the waterways while attenuating storm surges and flash floods originating upstream.*
- *Biodiversity abundance and diversity is partly due to the design. which entailed habitats of various elevations.*

Source (references)

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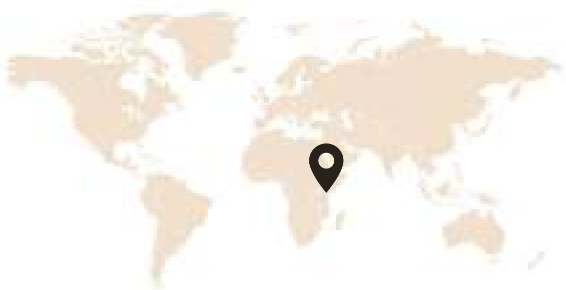
PROJECT #4
Mikoko Pamoja Project, Kenya (2012–ongoing)

Aerial view of mangroves in Gazi Bay, Kenya. Photo by Google Earth.

Location

Gazi Bay, Kenya



Approach

Mangrove protection and restoration

Size

117 hectares

Cost

US$381,453 *for project development;*
US$9,742 to US$10,687 *per year for operations.*

Description

Mikoko Pamoja is an innovative community-led mangrove conservation and restoration project, with the additional benefit of selling mangrove carbon credits. While the main objective is to protect the existing forest, a mangrove nursery for small-scale restoration has also been established. The project created a community Casuarina woodlot (which actively protects 117 hectares of mangroves) as a fast-growing alternative source of resources and income, and the community plants an additional 0.4 hectares annually. These activities have successfully rehabilitated an eroding beach to a stable forested area, secured community well-being, and supported livelihoods associated with mangrove forests. The project is considered an international case of best practice, providing a model for scale-up efforts by neighboring villages and replication internationally.

Benefits

- *From 2014 to 2018, the project generated 9,880 Plan Vivo carbon credits, representing 9,880 metric tons of CO_2 avoided. The annual revenue generated from carbon credits ranges from US$11,984 to US$14,833 (for the period 2013–17).*
- *As of 2023, 1,081 households had benefited generally from all combined project activities.*

Coastal erosion reduction | *Carbon sequestration* | *Human health* | *Resource production*

Challenges

- *Successfully securing sufficient alternative community income that allows for mangrove protection, such as a carbon credit scheme, requires significant grant financing and volunteer hours upfront.*
- *It is highly challenging to undertake cost-effectiveness assessments for mangrove projects without expert involvement.*
- *Grazing pressure from livestock and unpredictable weather patterns threaten the survival of mangrove seedlings that came from nurseries.*

Lessons learned

- *Mangrove projects involve a complex array of costs and activities but can generate multiple benefits.*
- *Key success factors include the community's support and engagement; cost-savings linked to volunteers; and a robust monitoring scheme.*
- *There is a great opportunity to secure additional carbon credits by integrating carbon stored in soils.*
- *Replanting success has been outpaced by natural regeneration rates of the existing protected forest, concluding that the project is healthy and self-sustaining.*
- *The provision of sufficient alternative timber and fuel sources has effectively compensated for the illegal harvesting pressures to the site.*
- *The project has secured revenue for other community projects, including a new water pump that improved access to clean drinking water, resulting in sustained health benefits.*
- *Health benefits include reduced waterborne diseases and improving overall public health via hydration and reduction of general illness. In children, these have been attributed to improved learning outcomes.*

Source (references)

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Akwidaa Mangrove forest, River Ezile, Ghana
Photo by Ato Aikins on Unsplash

SALT MARSHES

Folly Beach, South Carolina, United States
Photo by A. Shuau on Unsplash

FACTS AND FIGURES

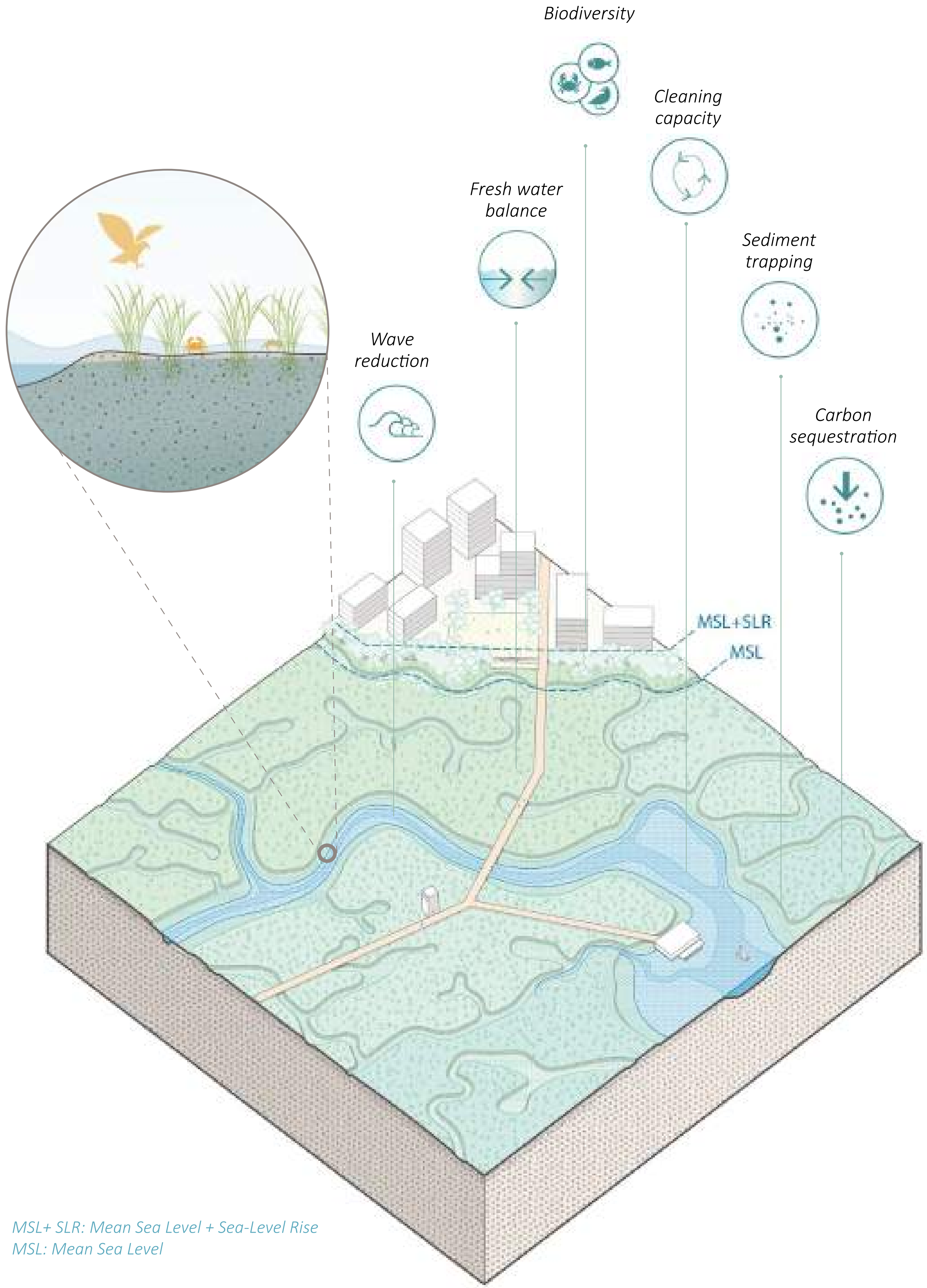
Salt marshes (also called salt meadows *or* tidal marshes*) are transitional coastal wetland ecosystems commonly found in estuaries across middle to high latitudes and characterized by low wave energy environments and with high concentrations of fine sediment. Regular tidal flooding allows salt-tolerant plants to be established. Local tidal reach typically differentiates salt marshes into three zones: the pioneer, low marsh, and high marsh zones, each of which present different vegetation species and characteristics. The high marsh zone can transition into adjacent landscapes, such as sand dunes, cobble or sand beaches, freshwater marshes, grass plains, or woodlands (JNCC, n.d.).*

Marshes can serve in coastal flood protection and coastline stabilization while providing many other ecosystem services. Salt marsh vegetation reduces the energy of incoming waves and storm surges, particularly in low-energy coastal environments (Kiesel et al. 2022; Stark et al. 2015). The vegetation's rough surface decreases flow velocities and enhances sediment trapping, which promotes coastline stability. With sufficient sediment supply, marshes can also build up soil and keep pace with sea-level rise.

Salt marsh ecosystems provide a wide range of other essential services (Liu et al. 2024). Their vertical growth helps them keep up with sea-level rise, a process that builds up soil layers with high organic content and low oxygen levels, making them excellent carbon stores. Marshes support complex food web and substantial biomass, comprising primary producers such as salt-tolerant plants, seaweeds, and plankton, as well as a wide range of primary and secondary consumers including zooplankton, insects, and fish. They also provide habitat and breeding grounds for animals—serving as critical refuge, for example, for migratory birds. Other services include improving water quality, filtering pollutants from land runoff, and enhancing nutrient cycling (Nelson and Zavaleta 2012). Salt marsh ecosystems can represent multi-functional, adaptive elements within flood risk management strategies.

However, salt marshes have faced considerable loss historically and recently. In Europe, large areas were reclaimed for agriculture and urban development starting in Roman times; examples include reclamations in Britain (Fulford et al. 1994) and the Netherlands (Bakker 2022). Over the past century, pressures such as reduced sediment supply, drainage changes, eutrophication, and sea-level rise have continued to drive this loss. Where landward migration is restricted (for example, by urbanization or artificial barriers), salt marshes may experience coastal squeeze and decline (Campbell et al. 2022; Schuerch et al. 2018). Most salt marsh loss to date has been due to reclamation, often involving the construction of banks (levees) or walls to exclude seawater or control river flow. Yet, when sufficient sediment and accommodation space are available, salt marshes can adapt by accreting vertically and migrating landward (Borchert et al. 2018; Tognin et al. 2021).

Recent awareness of their importance for coastal protection and biodiversity has led to reduced reclamation in many countries. Remaining marsh areas are especially important for conservation (JNCC, n.d.). To counteract the loss of salt marsh ecosystems, and hence the loss of their flood protection, biodiversity and other co-benefits, NBS interventions can be implemented. These NBS interventions can either be protection measures (to protect existing salt marshes), restoration and enhancement measures (to restore degraded salt marsh areas); or hybrid interventions, where salt marshes are combined with hard structures such as levees.



Visualizing the processes and benefits of salt marshes.

SUITABILITY CONSIDERATIONS

To ensure healthy and functioning salt marsh ecosystems—essential for delivering both flood risk reduction and broader co-benefits—a range of environmental conditions must be met. These site suitability considerations apply to all types of NBS, including protection, restoration and enhancement, and hybrid interventions.

Location and climate: Salt marshes are naturally restricted to temperate coastlines in middle to high latitudes. Their development is controlled by a combination of geomorphological, physical, and biological processes shaped by local climate. At meso-scale, estuaries and sheltered coastal environments provide the foundational setting for salt marsh formation and persistence, since they provide shelter from high wave energy and have a surplus of fine, nutrient-rich sediment (Whitfield and Elliott 2011).

Hydrodynamics: Salt marshes form the upper portion of the intertidal mudflats, between the mean high-water neap tides and the mean high-water spring tides (Mcowen et al. 2017). Salt marshes rely on the tidal regime and wind–wave conditions to regularly flood and drain salt water. Where coastal processes are blocked, salt marshes will function poorly or be lost entirely. Salt marshes require low to medium wave exposure, thriving in sheltered estuarine environments or protected by other habitats. A current (flow) velocity of 1.2 meters per second is considered as an upper threshold for salt marsh edge stability (van Loon-Steensma et al. 2012).

Salinity: Salt marshes have an average salinity of between 18 and 35 parts per thousand (Odum 1988). Different species exist across the salt spectrum, where the pioneer and low salt marsh zones are naturally species-poor and dominated by grasses, and the upper areas are increasing in species richness, bringing in salt-tolerant plants and herbs.

Sedimentation rate: More than 20 milligrams per liter concentration is necessary for marshes to keep up with conservative projections of sea-level rise (Kirwan et al. 2010). An ideal setting would balance enough sediment suspended in the marsh with transport potential through regular flooding to the upper parts of the marsh (EcoShape, n.d.). Local sediment budgets can be influenced by coastal protection structures, as well as by alterations in estuary morphology resulting from land reclamation, navigation dredging, and recurring flood defense works (JNCC 2008).

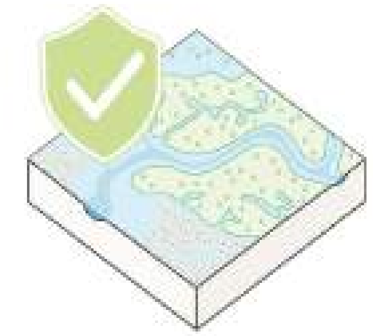
Soil: Salt marshes grow on various substrates, ranging from pure sand to clay and peat (Olff et al. 1997). The availability of silt and clay in the substrate increases the marsh's stability and ability to develop (Ford et al. 2016).

Slope: Salt marshes develop on slopes ranging from 0.2 to 2.0 percent. A new marsh would typically need to be set on a slope of 1.0 percent (Van Duin and Dijkema 2012). Slopes and tidal ranges determine three zones in a salt marsh: the pioneer zone, 40 centimeters below mean high tide (MHT); the low marsh, which is inundated during mean spring tides (100–400 floods per year); and the middle or high marsh, with fewer than 100 floods per year.

Outer Banks, North Carolina, United States
Photo by Neal Easterling on Unsplash

NBS INTERVENTIONS

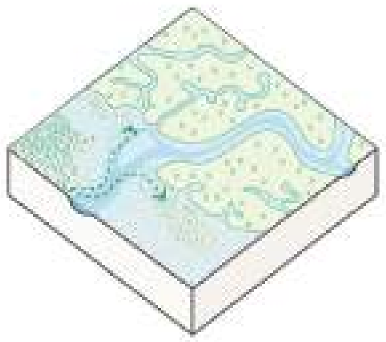
PROTECTION MEASURES



The protection of salt marshes can include establishing marine protected areas (MPAs). Protecting existing marshes is essential to ensure that they remain healthy, thereby continuing to provide their vital services such as resource production, carbon storage and sequestration, flood protection, biodiversity, and improving water quality. Effective protection must first identify potential threats that could lead to the degradation of the marsh areas. Polluted stormwater runoff, invasive species, and land-use changes are among the main threats to existing marshes (Warnell et al. 2023). Measures to alleviate stresses on the ecosystem—such as improving wastewater and stormwater management—can enhance nutrients entering the marsh and reduce pollution and unwanted algal blooms. Furthermore, salt marshes can be protected, for example, by creating reserve areas (such as nature conservation areas) where habitat degradation that results from activity such as vegetation removal or unsustainable fisheries is forbidden. Measures for controlling invasive species, such as grazing or flooding the area, can help sustain a healthy salt marsh. Moreover, integrating these protection interventions into broader coastal management plans and climate adaptation strategies can support the long-term functionality and resilience of salt marshes.

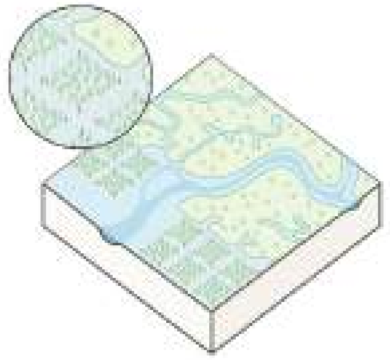
RESTORATION AND ENHANCEMENT MEASURES

Degraded salt marsh areas can be restored or healthy salt marsh areas can be enhanced by using one or more of the following techniques: natural regeneration, revegetation techniques, hydrological restoration, morphodynamic restoration, or managed realignment. The choice of measure(s) should be tailored to the specific causes of marsh disturbance.



Natural regeneration

Salt marsh formation can occur naturally, from the settling of fine sediments and arrival of seeds and propagules of established marshes. A key requirement for natural regeneration is therefore the availability of a well-developed marsh nearby for seed dispersal (Wolters et al. 2008). Transported by water, the seeds of certain salt-marsh species can travel large distances and establish new plants rapidly where conditions are optimal. Limitations to natural regeneration typically include poor or interrupted links to the natural system and processes; lack of clean, fresh and nutrient-rich waters and sediments—in the presence of these limitations there is little opportunity for seeding and colonization. Below-ground biomass (root biomass in the upper 30 centimeters of the soil profile) is a key indicator for marsh health (Turner et al. 2004) and therefore an important indicator for monitoring restoration progress.

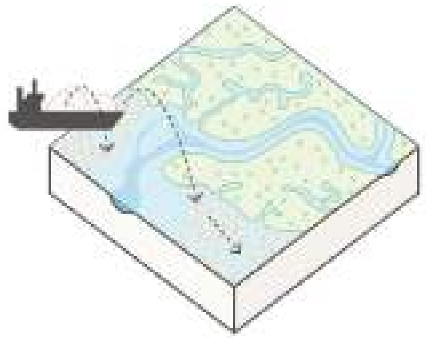


Revegetation

When natural regeneration is insufficient (or too slow) to restore ecosystem function within a required timeframe, revegetation techniques can be employed to boost the process. Among these techniques, planting is particularly important; methods such as using seedlings or planting mats are effective in jumpstarting marsh recovery. In planting mats, plants are grown on relatively dense coconut or hessian mats, where their roots are protected and grow safely. The mats are then placed in the salt marsh where the roots penetrate sediment and take hold. The mats continue to protect juvenile plants during their initial growth phases. Over time, the fibers of the mats degrade leaving the plants to propagate naturally. Revegetation efforts often benefit from complementary measures such as hydrological restoration or morphodynamic restoration.

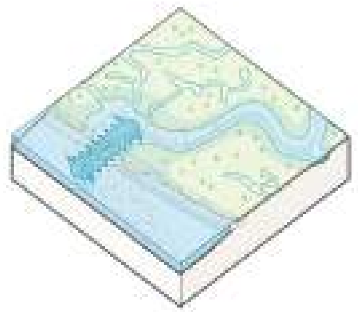
Hydrological restoration

Salt marsh meadows depend on tidal exchange and freshwater flows to maintain their intertidal character and support plant and sediment dynamics. In many degraded sites, these hydrological connections have been disrupted by infrastructure such as culverts or channel infill. Hydrological restoration focuses on re-establishing these flows without altering primary flood defenses. Typical measures include removing or modifying culverts, reopening blocked tidal creeks, and installing tidal gates to allow controlled water exchange. By restoring hydrological connectivity, these interventions promote nutrient delivery, restore tidal and freshwater flows, and support vegetation recovery.



Morphodynamic restoration

Morphodynamic restoration emphasizes restoring the natural processes and patterns that shape the environment. The salt marsh environment requires sufficient sediment supply to counter erosion and rising sea levels. To enhance natural sediment accumulation, brushwood fences can create sedimentation basins, facilitating new marshes. Artificial sediment supply or nourishment techniques are often effective in supporting salt marsh growth. Other techniques can place sediment strategically and create marsh mounds and other features for habitat complexity. For example, muddy sediment mounds can be placed in locations that allow river and coastal processes to redistribute it naturally, including in front of the levee as a protective measure. These mounds can slow flows, allowing sediment to accrete and providing optimal conditions for vegetation colonization and propagation, resulting in a fully functional marsh. Similarly, a "mud motor" technique spreads mud near and upstream of marshes in greater volumes, then allows flows to deposit sediment and mimic natural processes. This method helps marshes adjust gradually and can utilize locally sourced sediments, such as from port channel dredging maintenance (Baptist et al. 2019).



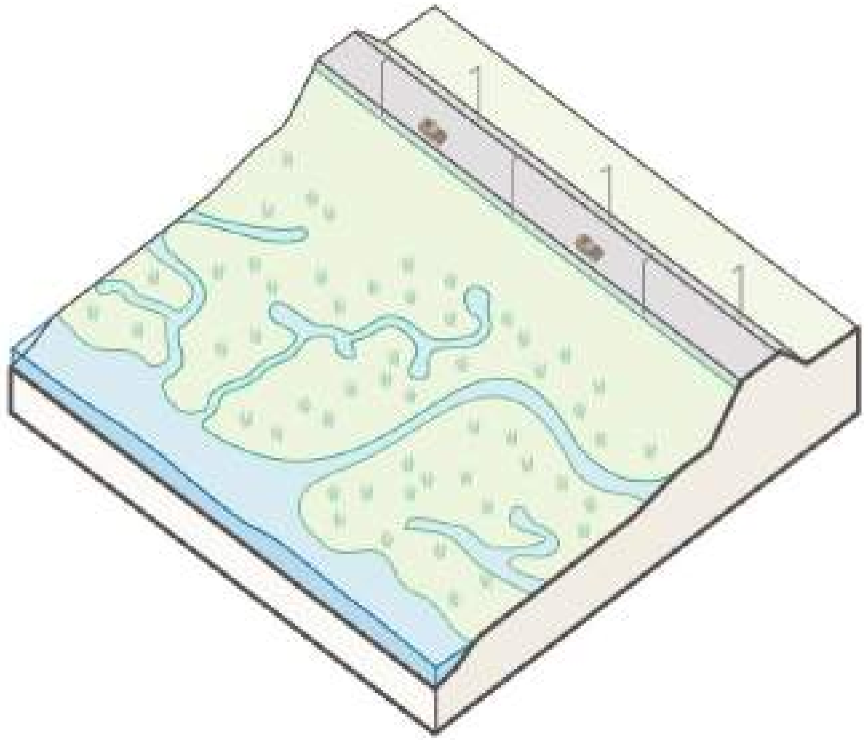
Managed realignment

Managed realignment involves the intentional modification or removal of flood defense structures, such as levees or embankments, to restore tidal flows and sediment delivery to previously disconnected areas. This approach enables the natural development or inland migration of salt marshes in response to sea-level rise. Measures may include breaching levees, installing regulators to control tidal inflow, or recreating tidal channels. These actions can restore sediment dynamics, reintroduce salinity gradients, which can allow natural conversion of low-lying land into marshes. In this way, managed realignment helps recover marsh areas that were previously lost.

HYBRID INTERVENTIONS

Salt marshes can be combined with levees (embankments) in the form of horizontal levees to reduce or control flood and wave action in priority risk locations and help retrofit existing hard infrastructure (Taylor Burns et al. 2022). Especially where surge levels are large, levees are required to withstand extreme conditions. The presence of salt marsh vegetation in front of these levees can reduce wave and surge height, leading to less load on the levees, less overtopping, and a reduction in costs of levees compared to traditional embankments.

The design of the hybrid intervention requires the salt marsh to have a minimum width to mitigate wave action effectively. Salt marshes of up to at least 6–10 kilometers wide are needed to reduce storm surges (Davy et al. 2009), and even longer marshes may be needed in areas with many drainage channels. Yet, for wave overtopping, horizontal levees can require substantially less width (Taylor-Burns et al. 2024). Depending on the marsh morphology (for example, the presence or absence of drainage channels) and vegetation characteristics, a width of at least 200 meters is required to achieve up to 40 percent wave mitigation (van Loon-Steensma 2015). Salt marshes under extreme events (high water levels and waves) are expected to have a decreased wave damping performance as the plants can deform and might break due to large wave forces (Vuik et al. 2019). Still, wave dissipation of around 20 percent was measured for a narrow marsh width of 40 meters (Möller et al. 2014). To these widths, extra margin should be added to enable salt marsh migration with sea-level rise (depending on the local slope and rate of the rise). Notably, marshes have the most effect at moderate water depths and are also more stable (experiencing no stem breakage) under these conditions; hence, relatively low dikes (with low protection levels, where the design standard is less than a 1-in-100 year flood event) can get the most benefit from salt marshes (Vuik et al. 2018).



Goldcliff, Newport, Newport, United Kingdom
Photo by Mike Erskine on Unsplash

BENEFITS

Flood risk reduction: By reducing wave heights and storm surge elevations, salt marsh meadows can reduce coastal flood risks (Vuik et al. 2018). For example, coastal wetlands in the northeastern United States provided ~16 percent risk reduction from Hurricane Sandy, valued at over US$625 million in reduced flood impacts (Narayan et al. 2016). In California, marsh restoration has also been found cost-effective to manage flood risks in areas of San Francisco Bay that can reach up to US$9 million per hectare in densely urbanized areas (Taylor Burns et al. 2024). Marshes are also more effective in offsetting the effect of storms than unvegetated mudflats (Barbier et al. 2011).

Erosion reduction: Marshes also reduce erosion by stabilizing the sediments (Davy et al. 2009; Morgan et al. 2009). Key salt marsh characteristics that are important for both wave attenuation and shoreline stabilization are vegetation density, biomass production, and marsh size (Shepard et al. 2011).

Resources production: Thanks to their complex structure, salt marshes provide safe and attractive habitat for young fish, shrimp, and shellfish that are inaccessible to larger predator fish (Boesch and Turner 1984). Therefore, salt marshes play a critical role in sustaining fisheries and aquaculture (Boesch and Turner 1984; MacKenzie and Dionne 2008). For example, salt marshes account for 66 percent of the shrimp and 25 percent of the blue crab production in the Gulf of Mexico (Zimmerman et al. 2002).

Tourism and recreation: Salt marshes are an important habitat for many species of birds and other wildlife, and therefore they also provide recreational and (eco)tourism opportunities such as recreational fishing and birdwatching activities. Furthermore, they also offer education and research opportunities (Barbier et al. 2011). For instance, students can engage in field-work activities in the salt marsh, such as those organized in Stamford, Connecticut, where students participated in ecological monitoring and restoration projects (Beldotti 2025).

Carbon storage and sequestration: Like mangroves, seagrass, and other wetlands, salt marshes are productive ecosystems that store and sequester significant amounts of carbon. On average, a salt marsh can store around 334 tons of organic carbon per hectare (Alongi 2020), mostly in the soil. A global estimation of sequestration rates for salt marsh ecosystems are between 167 and 250 grams of carbon per square meter per year. The sequestration rates for local/regional studies show a larger variation and can be between 16.5 grams of carbon per square meter per year (Spain) and 315 grams of carbon per square meter per year (regional estimate from Northern Europe) (Smeaton et al. 2024). The total avoided annual loss if salt marshes are protected or restored is expected to be US$6.4–US$97 million (Coverdale et al. 2014; Wang et al. 2022), looking at carbon emissions alone. Carbon benefits are often overlooked in existing salt marsh project evaluations, but cost recovery periods can be reduced and benefit-cost ratios increased when considering carbon benefits in marsh restoration projects (Wang et al. 2022).

Biodiversity: Salt marshes provide important habitat with a high diversity of plants, mammals, birds, and insects. They also offer crucial spaces for breeding, wintering, and feeding grounds for local and migratory species of birds (McKinley et al. 2018). Many salt marshes near urban areas have been designated Ramsar sites of international importance (UNESCO 1971).

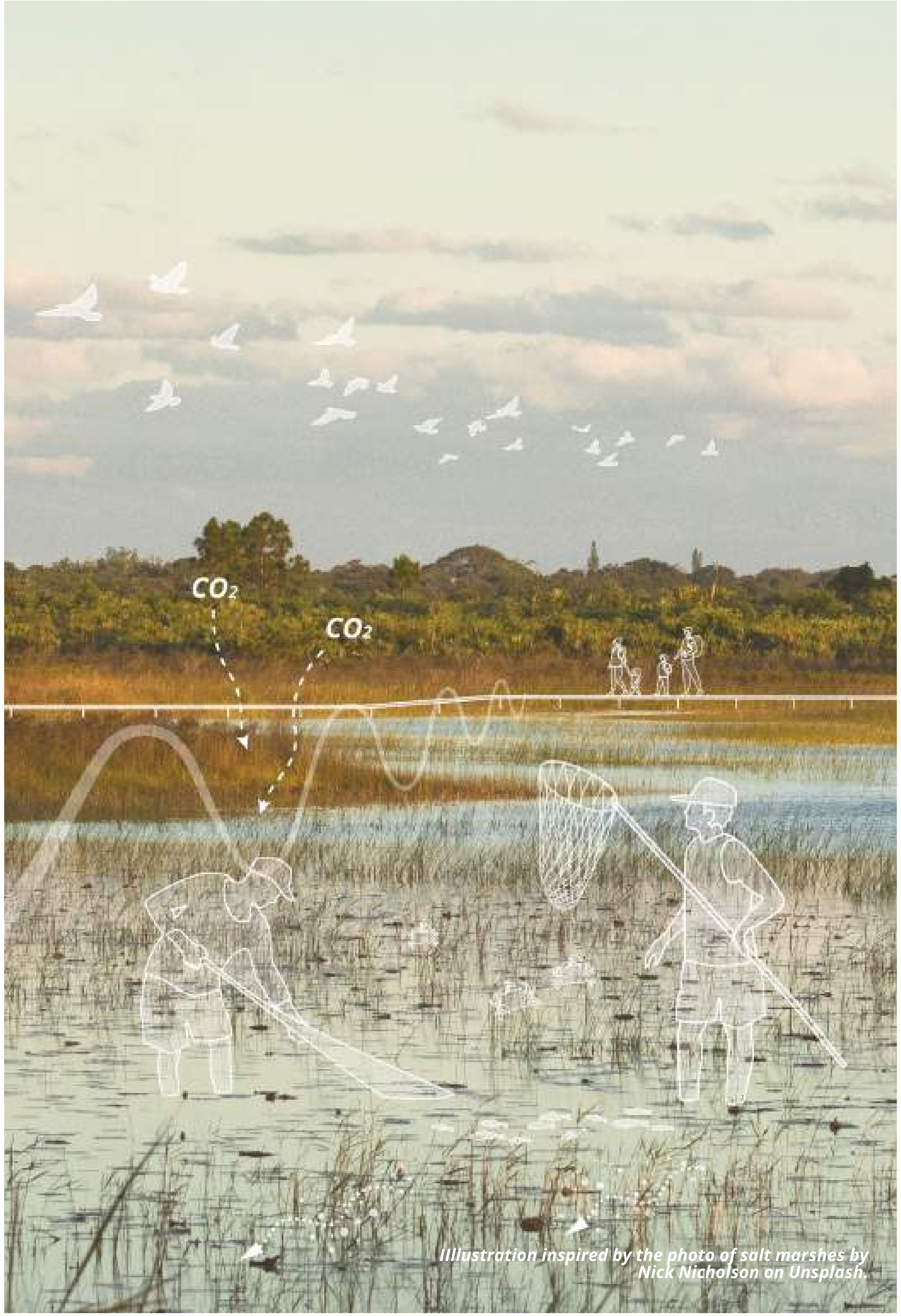


Illustration inspired by the photo of salt marshes by Nick Nicholson on Unsplash.

Water quality and sediment management: Salt marshes act as natural filters that purify water entering the estuary (Mitsch and Gosselink 2007). Tall grasses create friction that reduces the velocity of river or stormwater that passes through the marsh (Morgan et al. 2009), thereby also capturing and storing suspended, nutrient-rich sediments that nourish the marsh. The ability of salt marshes to filter water and remove pollutants benefits both adjacent ecosystems and people.

The multiple benefits of salt marshes on a qualitative scale

Westerhever Leuchtturm, Germany
Photo by Peter Steiner on Unsplash

COSTS

Implementation costs

Protecting salt marshes through MPAs can vary in cost depending on, for instance, the duration of the establishment and the size of the MPA (McCrea-Strub et al. 2011). In areas where there are invasive species, invasion control measures such as mowing, grazing, and flooding the area can be taken; the average costs are around US$100.000 per hectare (Wang et al. 2022).

Salt marsh restoration can be relatively expensive—on the order of tens of thousands of US dollars per hectare (Wang et al. 2022). Restoration or enhancement costs can include costs for planting, removing obstacles to hydrological flow, and supporting sedimentation by nourishment. The latter includes dredging and nourishment costs, which can vary depending on, for instance, the dredging strategy. An estimate is around US$3.6–US$10.4 per square meter to construct marshland out of a bare tidal flat (Vuik et al. 2019). Sedimentation can also be enhanced using permeable structures (such as bamboo or brushwood fences), which cost around US$16–US$160 per meter (Winterwerp et al. 2020). An example of a marsh restoration project is the Great Meadows Restoration Project in Stratford, Connecticut, which restored 34 acres of marsh through sediment elevation with dredged sediments, tidal channel construction, invasive species removal, and native vegetation planting (which included the help of volunteers). The total project cost was approximately US$4.65 million (Warnell et al. 2023).

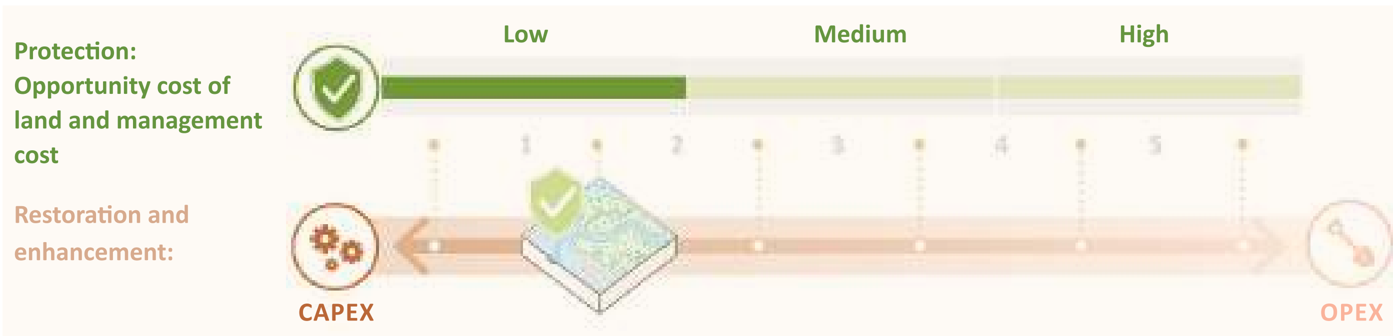
Hybrid interventions can include the above-mentioned costs and additional levee construction costs, generally a levee that is made from soft material (clay, sand, and grass), and avoid the use of hard elements, which are relatively more expensive (such as rock armor).

Operations & maintenance costs

In general, maintenance costs of wetlands can be around US$11,000 per hectare (at 2016 prices, considering a 50-year project life) (Aerts et al. 2018; USACE 2015). Permeable fences can require additional maintenance of US$20–US$80 per meter per year (Winterwerp et al. 2020). Operations and maintenance costs will also depend on how well the marshes are functioning, but, in general terms, maintenance costs for functional salt marshes are low. However, climate change, storm surges, and upstream processes on land may impact salt marsh functioning and health. To maintain the functions of the marsh (for example flood risk reduction and carbon storage), maintenance will include monitoring to identify plant health and may include additional restoration efforts.

Other cost considerations

Because the area required for salt marsh protection and/or restoration is often large, access to or ownership of land required can often represent an important cost factor. Land may be public or private and can increase costs and require engagement and collaboration with multiple landowners and stakeholders. Land-related costs may include land acquisition, land use (for example, payments to landowners), land protection costs (including managing and controlling access), and community resettlement.



CAPEX: Implementation costs
OPEX: Operations and maintenance costs

GUIDELINES AND RESOURCES

The resources listed provide guidance for designing standard levees, hybrid interventions, and restoring salt marshes, supporting their assessment, planning, and implementation as nature-based solutions. They also include information on creating suitable conditions for salt marshes, as well as guidance on monitoring approaches.

Levee design guidelines
CIRIA, USEACE, and MEDDE (CIRIA, US Army Corps of Engineers, and the French Ministry of Ecology). 2013. *The International Levee Handbook*. London: CIRIA. https://portal-miteco-stage.adobecqms.net/content/dam/miteco/es/agua/temas/gestion-de-los-riesgos-de-inundacion/2-the-international-levee-handbook_tcm30-518061.pdf

Hybrid infrastructure designs
Piercy, C. D., Pontee, N., Narayan, S., Davis, J., and Meckley, T. 2021. Coastal Wetlands and Tidal Flat. In *International Guidelines on Natural and Nature-Based Features for Flood Risk Managemen*t, edited by Bridges, T. S., King, J. K., Simm, J. D., Beck, M. W., Colins, G., Lodder, Q., and Mohan, R. K. Chapter 10. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center. https://issuu.com/poweroferdc/cs/nnbf-guidelines-2021/442?fr=sZTFiNjQyNjA2NDQ

Salt marsh restoration guides
Adapta Blues. 2023. *Catalogue of Adaptation Measures to the Effects of Climate Change in the Coastline*. https://lifeadaptablues.eu/wp-content/uploads/2023/04/Catalogue_EN.pdf

Hudson, R., Kenworthy, J., and Best, M., editors. 2023. *Saltmarsh Restoration Handbook: UK & Ireland*. Environment Agency, Bristol,UK. https://catchmentbasedapproach.org/wp-content/uploads/2021/10/ZSL00333_Saltmarsh_Restoration_Handbook__UPDATED_082023.pdf

Morris, R. L., Bishop, M. J., Boon, P., Browne, N. K., Carley, J. T., Fest, B. J., Fraser, M. W., Ghisalberti, M., Kendrick, G. A., Konlechner, T. M., Lovelock, C. E., Lowe, R. J., Rogers, A. A., Simpson, V., Strain, E., Van Rooijen, A. A., Waters, E., Swearer, S. E. 2021. *The Australian Guide to Nature-Based Methods for Reducing Risk from Coastal Hazards*. University of Tasmania. Report. https://hdl.handle.net/102.100.100/495361

World Bank. 2021. *A Catalogue of Nature-Based Solutions for Urban Resilience*. Washington, DC: World Bank Group. https://hdl.handle.net/10986/36507

In addition, the Nature-Based Solutions Opportunity Scan (NBSOS) is a tool that helps identify NBS investment opportunities,providing information on NBS types, suitable locations, costs, and coastal protection benefits and co-benefits. It supports decision-makers in integrating NBS into planning, and investment strategies for both urban and coastal areas.

SALT MARSHES CASE STUDIES

PROJECT #1
Jiangsu Yancheng Wetlands Protection Project, China (2011–19)

PROJECT #2
Marconi Salt Marsh Project, the Netherlands (2017–20)

PROJECT #3
Steart Marsh Restoration, United Kingdom (2014–ongoing)

PROJECT #4
Great Meadows Marsh Project, United States (2021–22)

PROJECT #5
Palo Alto Horizontal-Levee Project, United States (2017–25)

Unknown location
Photo by Hu Lei on Unsplash

PROJECT #1
Jiangsu Yancheng Wetlands Protection Project, China (2011–19)

The Yancheng coastal wetlands are home to milu deer, egrets, and other wildlife. Photo by Yang Guomei.
Source: Niu, Z. 2020. An Integrated Approach to Preserving the Wetlands of the PRC. East Asia Blog Series, August 12, 2020.
https://rksi.adb.org/publications/an-integrated-approach-to-preserving-the-wetlands-of-the-prc/

Location

Yancheng municipality, China

Approach

Salt-marsh restoration

Size

4,454 hectares *of salt marshes were restored and rehabilitated.*

Cost

US$81,480,000

Description

The coastal wetlands of Yancheng have suffered significant degradation over the past few decades, driven by land reclamation, habitat loss due to dehydration, invasive species, and pollution, leading to a 50 percent decline in wildlife between the 1980s and 2010s. The Jiangsu Yancheng Wetlands Protection Project sought to address these issues by safeguarding two natural reserves, managing two forest farms, and building capacity for more effective ecosystem management.

Benefits

The project significantly enhanced biodiversity, with notable improvements across various indicators. Bird populations increased by 24 percent, and the number of bird species in the wetland rose by 52 percent. The population of Milu deer, once near extinction, surged by 180 percent. Additionally, the project boosted forest biomass and carbon sinks. The ecosystem services related to carbon sequestration and oxygen release in Yancheng are now valued at approximately US$219 per hectare per year for wetlands.

Biodiversity enhancement

Carbon sequestration

Challenges

Improved grazing management increased the Milu deer population by 180 percent between 2012 and 2019, exceeding the carrying capacity of the ecosystem. Part of the deer population was therefore transferred to a larger wetland area beyond the borders of the managed reserve. Monitoring will be needed to continue tracking the deer population.

Lessons learned

The project provided a successful proof of concept for invasive species control, conversion of fishponds into wetland, and revegetation of forest habitats.

Source (reference)

China, People's Republic of. No date. Jiangsu Yancheng Wetlands Protection Project. Sovereign Project | 40685-013. ADB. https://www.adb.org/projects/40685-013/main#project-overview

PROJECT #2
Marconi Salt Marsh Project, the Netherlands (2017–20)

Bird's-eye view of the Marconi Salt Marsh Project, the Netherlands. Photo by Ecoshape.
Source: EcoShape (Building with nature: Solutions to adapt to climate change in City Port territories - AIVP).

Location

Delfzijl, Ems-Dollard Estuary, the Netherlands

Approach

Morphodynamic restoration
(Sediment augmentation and Adaptive management)

Size

***15 hectares** pioneer zone (coastal flood protection and nature development) and **13 hectares** of upper salt marsh zone (recreation area)*

Cost

~ €8.2 million

Description

The Marconi Salt Marsh Development Project aimed to enhance flood protection and ecological resilience along the Ems-Dollard estuary by constructing a new salt marsh using dredged sediment. The project involved raising intertidal elevations with sand and clay mixtures to promote vegetation growth; distributing seeds of glasswort plants of nearby salt marsh location; and monitoring hydrodynamics, bed level change, vegetation, and biodiversity.

Benefits

- *The 15-hectare pilot salt marsh served to attenuate wave energy and reduce flood risks.*
- *As the marsh accumulates fine sediments and keeps pace with sea-level rise, it also helps reduce coastal erosion.*
- *The salt marsh promotes biodiversity by creating habitats suitable for pioneer and lower salt marsh plant species. Early colonization was observed within the first year.*
- *The salt marsh development also contributes to water quality and the attractiveness of the coast, which enhances tourism and recreation, aligning with the goals of various stakeholders involved in the project.*

Challenges

- *Settlement and consolidation of the sediment base led to lower-than-anticipated bed levels, delaying construction and vegetation establishment. Additionally, sand used for the base layer was subject to wind erosion post-placement.*
- *Accurately mixing specific percentages of clay into the sandy base was challenging, requiring experienced contractors and specialized equipment. High mud content areas were particularly difficult to achieve and resulted in more surface disruption.*
- *The project's location outside the dikes exposed it to tidal and wave actions, requiring adaptive management and continuous monitoring to address unforeseen challenges.*

Lessons learned

- *Stakeholder engagement in the early stages of the project is crucial for creating balanced objectives.*
- *The added benefits provided by salt marshes—such as biodiversity enhancement—outweighed the higher initial costs compared to the traditional gray methods.*
- *Permeable brushwood fences or groins can be designed to create or to avoid tidal creek formation at specific locations.*
- *Salt marsh vegetation thrived best in areas with 20–50 percent mud content, indicating the importance of fine sediment for plant development.*
- *Seed treatment showed significant effect only in the first year (first growing season).*
- *Adaptive management was essential to address the uncertainties (such as achieving the correct elevation due to sediment settlement) related to the project by allowing timely adjustments.*
- *Salt marsh construction can lead to other morphological developments such as sandbars.*

Source (references)

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IKW Magazine. No date. Marconi Buitendijks. https://ikwmagazine.nl/marconi-buitendijks/

PROJECT #3
Steart Marsh Restoration, United Kingdom (2014–ongoing)

Bird's-eye view of the Steart Marsh Restoration Project, a wetland restoration scheme in the United Kingdom. Photo by Nick Turner. Source: WWT (Wildfowl & Wetlands Trust). No date. Steart Marshes and Bridgwater Bay NNR. WWT Wetland Centres, https://www.wwt.org.uk/wetland-centres/steart-marshes

Location

Steart, Somerset, United Kingdom

Approach

Salt-marsh restoration

Size

***480 hectares** of wetlands were restored, including tidal areas and salt marsh.*

Cost

***£20,700,000,** with **£7 million** allocated for land acquisition.*

Description

Steart Marshes was developed as a habitat creation scheme in response to rising sea levels and climate change, which threatened the upper saltmarsh areas of the Severn Estuary. The project aimed to compensate for the habitat loss by transforming intensively managed farmland into one of the UK's largest new wetland reserves. Jointly managed by the Wildfowl & Wetlands Trust (WWT) and the Environment Agency, the project began after five years of consultation with the local community. The site now serves multiple purposes, including supporting local agriculture, enhancing biodiversity, and providing a natural carbon sink.

Benefits

The Steart Marshes project has transformed the area into a biodiversity hotspot. The marshes now support otters, egrets, owls, waders, and wildfowl, alongside rare salt-tolerant plants and fish species such as sea bass and eels. Carbon sequestration is a significant benefit, with the wetlands storing up to 19 metric tons of carbon per hectare per year. The marshes also provide benefits to the local economy through sustainable grazing and tourism, employing 6 full-time staff and engaging 60 volunteers. Furthermore, the project has improved the mental health and well-being of the community by offering nature-based activities, especially through its Blue Prescribing Project.

Biodiversity enhancement

Carbon sequestration

Challenges

While Steart Marshes has been a success, the challenge lies in securing sustainable financial support. Currently, the site relies on government funding, grazing income, and tourism, but efforts are being made to include salt marshes in carbon markets, which could generate significant revenue.

Lessons learned

- *Transparent communication with the local community is essential for long-term success.*
- *Patience is key: allowing nature to take its course can yield better results than rushing.*
- *Focus on habitat restoration rather than individual species: a healthy habitat attracts the right species naturally.*

Source (reference)

ReWilding Britain. 2022. Case Study: Steart Marshes. https://www.rewildingbritain.org.uk/why-rewild/rewilding-success-stories/case-studies/steart-marshes

PROJECT #4
Great Meadows Marsh Project, United States (2021–22)

Creek construction to restore normal tidal flow in and out of Great Meadows Marsh. Photo by Jim Turek/NOAA Fisheries. Source: NOAA Fisheries. 2022. Great Meadows Marsh project is restoring salt marsh habitat and building resilience in coastal Connecticut. News Feature Story, NOAA Fisheries, May 16, 2022. https://www.fisheries.noaa.gov/feature-story/great-meadows-marsh-project-restoring-salt-marsh-habitat-and-building-resilience

Location

Stratford, Connecticut, United States

Approach

Salt-marsh restoration

Size

***34 acres** restored (ongoing efforts aim to cover **40 acres** in total).*

Cost

US$4.65 million

Description

Great Meadows Marsh, located along Long Island Sound, once covered 1,400 acres but has been reduced to less than 700 acres as a result of centuries of drainage, filling, and the invasion of non-native plants. In response to the ecological degradation and the threat of rising sea levels, a restoration project was initiated. This project restored 34 acres of salt marsh and adjacent habitats. The restoration included the removal of invasive species, elevation adjustments using re-graded soil, and the creation of tidal channels to restore natural water flow and ecological balance.

Benefits

- *The marsh now contributes to storm surge buffering and flood mitigation, helping reduce the impacts of rising sea levels and coastal storms.*
- *The project improved habitat for rare and endangered species. Local biodiversity was enhanced with over 270 bird species utilizing the marsh for nesting, feeding, and migration.*
- *150 volunteers and local students helped plant 165,000 native marsh grasses and other plants, reconnecting the community to the marsh through reopened trails and viewing platforms, highlighting its educational and cultural benefits.*
- *Re-graded land and better tidal flow minimized stagnant freshwater pools, significantly decreasing the mosquito population, enhancing local quality of life.*

Biodiversity enhancement | *Community engagement*

Challenges

*Continuous efforts are needed to control the spread of common reed (*Phragmites australis*), a highly invasive species that can outcompete native marsh plants.*

Lessons learned

- *Engaging local residents through active involvement can be critical to long-term project sustainability.*
- *Restoring ecological balance requires ongoing monitoring and the flexibility to adapt strategies based on emerging data, particularly in response to climate change.*

Source (references)

Munroe-Hutton, L. 2022. Making Great Meadows marshy again. U.S. Fish and Wildlife Service. October 26, 2022. https://www.fws.gov/story/making-great-meadows-marshy-again

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PROJECT #5
Palo Alto Horizontal-Levee Project, United States (2017–25)

Palo Alto shoreline in vicinity of proposed horizontal levee project. Photo by Ivan Parr.
Source: Okamoto, A. R. 2022. Half a Dozen Horizontal Levees in the Works. KneeDeep Times, February 25, 2022. https://www.kneedeeptimes.org/half-a-dozen-horizontal-levees-in-the-works/

Location

San Francisco Bay, California, United States

Approach

Restoration** (Managed realignment and Revegetation) and **Hybrid interventions

Size

*Horizontal levee of about **500 linear feet***

Cost

*Approximately **US$2.7 million***

Description

Locations in the San Francisco Bay, such as along Harbor Marsh, developed a horizontal levee to improve shoreline resilience by combining flood protection, waste water treatment, and wetland restoration.

Benefits

- *The marsh promotes sediment accumulation and counteracts coastal erosion.*
- *The horizontal levee attenuates waves and therefore reduces flood risk.*
- *The marsh helps wastewater purification, hence the water quality in the area.*
- *It protects species and enhances biodiversity.*
- *It provides recreational benefits to the community.*

Biodiversity enhancement | *Flood risk reduction* | *Coastal erosion reduction* | *Tourism and recreation* | *Water quality*

Challenges

- *Obtaining funds and permits for building within wetlands was a challenge.*
- *Passing large volumes of wastewater through levee systems was challenging.*

Lessons learned

- *Early and ongoing engagement is crucial.*
- *Ongoing staff training and compensation are important.*

Source (references)

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SEAGRASS MEADOWS

Burma, Myanmar
Photo by Benjamin l Jones on Unsplash

FACTS AND FIGURES

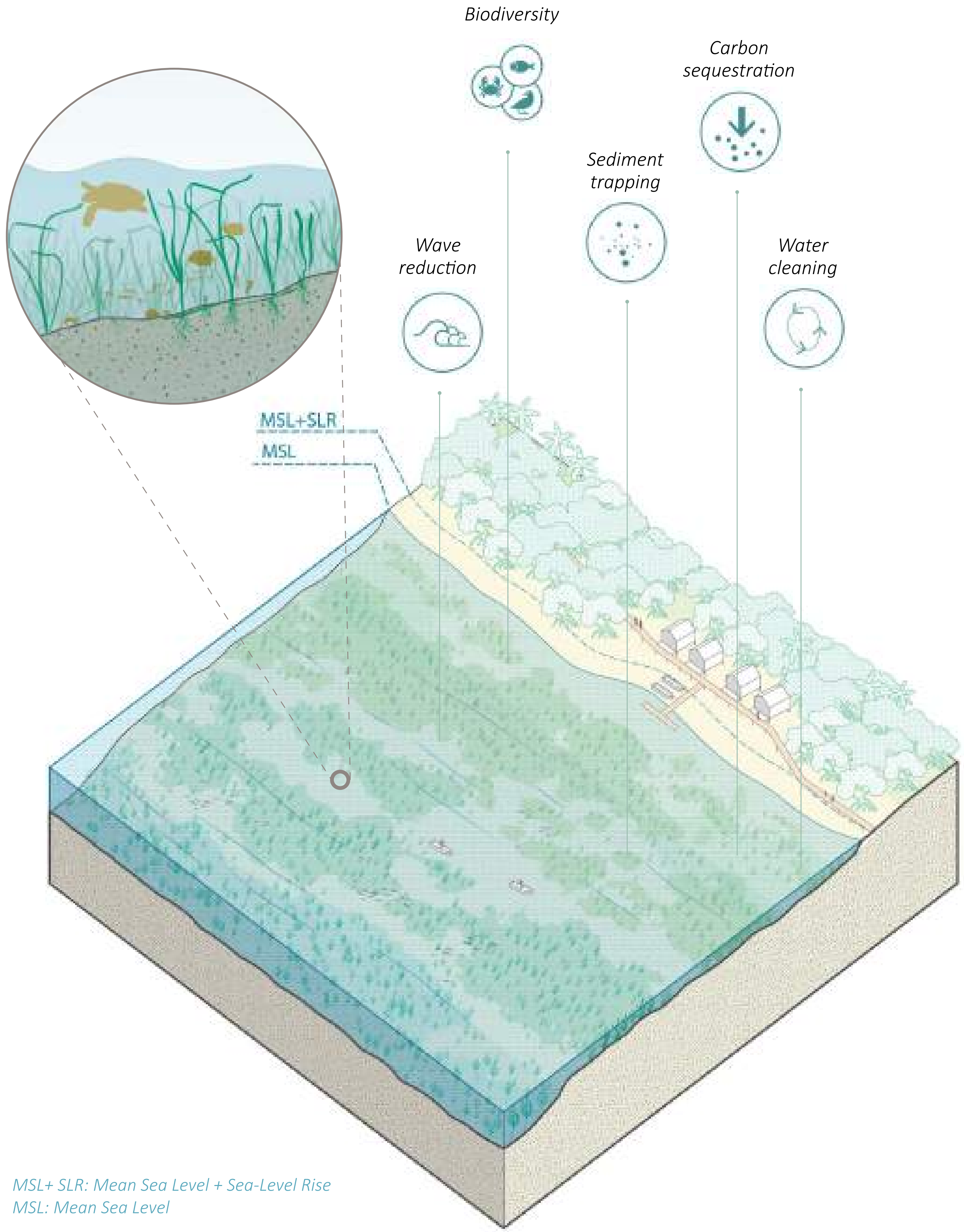
Seagrasses are marine flowering plants (aquatic angiosperms) that form dense, shallow meadows or beds in coastal and estuarine areas across temperate and tropical regions (Gamble et al. 2021). Seagrass can often be located inshore and adjacent to coral reefs (Ambo-Rappe 2022). These aquatic angiosperms use roots and rhizomes to anchor into sandy or muddy substrates; they play a foundational role in marine ecosystems. Four families of seagrass occur globally, with region-specific genera; these families are Zosteraceae, Hydrocharitaceae, Cymodoceaceae, Posidoniaceae (Hasim 2021).

The vast plant systems represent an important nature-based solution (NBS) for flood and erosion risk reduction both above ground and below ground. The root systems and undersoil stems (rhizomes) stabilize sediments while the flexible canopies of seagrass reduce current velocities and wave energy, all factors that contribute to shoreline protection (Ondiviela et al. 2014). Seagrass meadows can also enhance the resilience of adjacent gray infrastructure by limiting scour and wave loading (Infantes 2022; Jacob et al. 2023). Seagrasses can be integrated not only with engineered structures such as seawalls, but also with other nature-based features such as reefs and beach and dune systems. However, projects and design should take care to prevent damage to sensitive habitats, avoiding factors such as dredging and sediment nourishment projects that can impact seagrass meadows.

Seagrass meadows rank among the world's most productive habitats and are considered keystone ecosystems alongside mangroves and coral reefs (see the chapters on these families for details) (Duffy 2006). These meadows support global fisheries by offering nursery, spawning, and feeding grounds for commercially valuable fish and shellfish (Unsworth et al. 2019). Seagrass meadows also provide carbon sequestration, water purification, nutrient cycling, and cultural services such as recreation and tourism and are vital to human well-being (Hasim 2021; Gamble et al. 2021; Green et al. 2018; Whitfield 2017). An estimated 1 billion people live within 100 kilometers of seagrass meadows and benefit from the services they provide (de los Santos et al. 2020). Seagrasses also play a role in mitigating ocean acidification and support biodiversity including endangered dugongs, turtles, and other grazers (de los Santos et al. 2020; Ricart et al. 2021).

However, seagrass meadows are rapidly being lost. Seagrass ecosystems are under increasing threat from pollution (eutrophication), smothering (turbidity, sedimentation), coastal development, destructive fishing practices, and climate change (Waycott et al. 2009). Rising sea temperatures, sea-level rise, storms, and increased runoff degrade habitat quality and limit the available light needed for photosynthesis (Orth et al. 2006; Short and Neckles 1999). An estimated 29 percent of the known global seagrass area has been lost since 1879 (Waycott et al. 2009); over 10 species of seagrasses are at risk of extinction and 3 are endangered (Short et al. 2011).

Conserving and restoring seagrass meadows helps maintain their roles in flood protection, biodiversity, food security, and climate regulation, while also supporting progress toward environmental and sustainability goals (e.g., the United Nations Sustainable Development Goals) (Unsworth et al. 2022a). Understanding the temporal and spatial changes in the habitat and the local triggers driving seagrass loss are two essential factors to plan management and restoration strategies and investment. Large-scale restoration of seagrass meadows can be technically challenging and costly, but many other interventions—such as eco-moorings that reduce disturbance of the seabed), water quality improvements, and planting and reseeding—exits that have also been demonstrated to be effective and can support recovery (Gamble et al. 2021; van Katwijk et al. 2016).



Visualizing the processes and benefits of seagrass meadows.

SUITABILITY CONSIDERATIONS

To function effectively as a coastal NBS, seagrass meadows require a combination of environmental conditions that support growth, stability, and ecosystem service delivery. These include adequate light, suitable substrates, appropriate hydrodynamic exposure, and balanced sediment and nutrient dynamics. Site suitability must be assessed before implementing protection, restoration, or hybrid interventions, especially given the sensitivity of seagrasses to physical disturbances and water quality stressors. This section outlines the main environmental criteria necessary for sustaining healthy, resilient seagrass meadows.

Location and climate: Seagrasses are globally distributed across temperate and tropical coastlines, occurring on all continents except Antarctica (Green and Short 2003). They inhabit shallow marine environments up to 50 meters deep, with optimal temperature ranges differing by climate zone: 11.5–26°C for temperate species and 23–32°C for tropical species (Hemming and Duarte 2000; Lee et al. 2007). Rising seawater temperatures can disrupt metabolism, alter distribution, and shift seasonal dynamics, as observed in *Zostera* species across Europe (Short and Neckles 1999). These shifts may reduce above-ground biomass, shoot density, and leaf length, thereby diminishing their coastal protection functions. However, responses to warming vary by species based on thermal tolerance.

Hydrodynamics: Seagrass meadows typically occupy intertidal and subtidal zones in estuaries and coastal waters, usually within a depth of 10 meters but occasionally reaching down to 70 meters (Grech et al. 2012). Growth requires sufficient light penetration—approximately 11 percent of surface irradiance—to support photosynthesis, making turbidity a critical limiting factor (Duarte 1991). Tides, waves, and currents shape the distribution, structure, and productivity of seagrass meadows. While high hydrodynamic energy can restrict seagrass density and shoot length (Schanz and Asmus 2003), moderate water movement promotes nutrient exchange and photosynthetic efficiency (Koch 1994; Thomas and Cornelisen 2003). Large waves during storms can also damage seagrass meadows through burial and unburial of shoots, fragmentation, and detachment (e.g., 10–80 percent of meadow cover being buried under 7 centimeters of sediment is considered a survival threshold for *P. oceanica*), although exposed and patchy meadows are more vulnerable than sheltered and continuous meadows (Marco-Méndez et al. 2024).

Salinity: Most seagrass species are adapted to grow at salinities ranging between 20 and 40 practical salinity units, although they can tolerate short-term fluctuations in high and low salinity conditions given the nature of coastal and estuarine systems (Touchette 2007). Nevertheless, sustained deviations outside this range may impair physiological processes and limit meadow persistence.

Sedimentation rate: Seagrass blades slow water flow and trap suspended sediment, enhancing deposition on the seabed (Barcelona et al. 2021). Reported sedimentation rates range from 1.5 to 500 grams per square meter per day, depending on season and environmental context (Gacia and Duarte 2001). While this can help build elevation and reduce erosion, excessive sediment loads can limit light availability and smother shoots. Burial by just a few centimeters can reduce seagrass density, while catastrophic burial events, such as the 50-centimeter sediment deposit from Hurricane George in Florida, can lead to complete vegetation loss (Cruz-Palacios and van Tussenbroek 2005).

Soil: Seagrasses generally prefer fine to medium sediment substrates such as sand, silt, or mud, though some species adapt to coarser or mixed sediments including coral rubble and shell fragments (Ruju et al. 2018). Sediment composition influences root anchorage, nutrient cycling, and resilience to wave or current-driven disturbances. Soft, organic-rich sediments are typical of sheltered estuaries, while coarser substrates dominate more exposed bays.

Slope: Gentle to moderate seabed slopes offer the most stable conditions for seagrass establishment by maximizing light penetration and minimizing erosion. Although seagrasses can occur on both flat and steep slopes, steep gradients can reduce light availability and substrate stability, resulting in poorer anchorage and diminished productivity (Duarte 1991; Gross et al. 2019). Slope should therefore be carefully evaluated when selecting restoration or hybrid intervention sites.

Burma, Myanmar
Photo by Brian Sumner on Unsplash

NBS INTERVENTIONS

PROTECTION MEASURES

Seagrass meadows are among the most threatened coastal ecosystems globally. Seagrass beds naturally regenerate in favorable conditions, where light penetration allows for photosynthesis and there is a degree of sheltering by the local geology or other habitats. Conservation and protection measures are vital to maintain structural integrity and resilience, and to reduce costly restoration. Protecting these habitats can also sustain their ecosystem services such as coastal protection, carbon storage, and fisheries support.

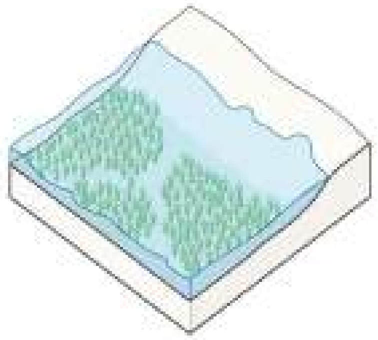
Protection strategies can help mitigate and prevent causes of degradation, such as poor water quality, damage from moorings, and invasive species. These pressures disrupt the seagrass canopy and rhizome structure, which are critical for sediment stabilization and wave dampening. Due to the widespread loss of seagrass and the immediate threats these habitats face, conservation and restoration models that drive global net recovery of ecologically functioning seagrass are essential for habitat recovery (Unsworth et al. 2022b).

Management strategies include regulatory zoning, eco-engineering, and enforcing marine spatial planning. Establishing marine protected areas (MPAs), implementing boating and fishing exclusion zones (Gamble et al. 2021), and using eco-moorings can reduce physical disturbance. For example, mooring designs that prevent anchor chains from dragging on the seabed help preserve the integrity of seagrass beds. Additional tools—such as water quality improvement programs and watershed-based pollution controls—are essential to limit eutrophication and turbidity, which reduce light availability and hinder seagrass growth. Direct interventions can include caged or fenced areas to protect areas of the seagrass from overgrazing, particularly when in flower or seed.

Protecting existing meadows can also strengthen their natural resilience by allowing natural adaptation processes such as inland migration and sediment accumulation to continue. Conservation can be cost-effective and help maintain habitats for threatened and endangered species.

RESTORATION AND ENHANCEMENT MEASURES

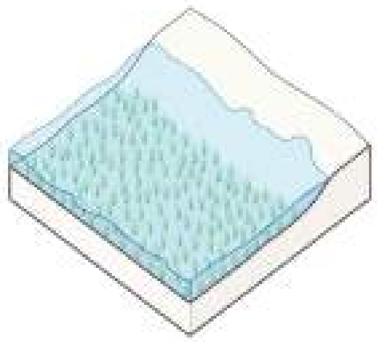
The ongoing degradation and loss of seagrass meadows poses a threat to the many benefits these ecosystems provide. A variety of active measures can offer promising ways to decrease these trends. These measures can be applied both to restore degraded sites (restoration) and to enhance the condition and resilience of existing healthy seagrass habitats (enhancement).



Planting units

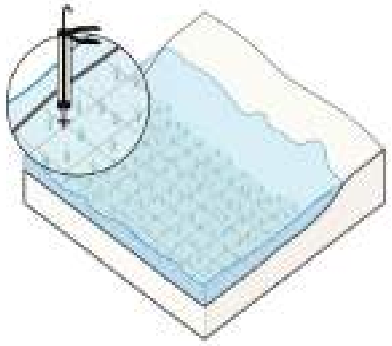
Seagrass habitat recovery may be aided by human intervention through restoration using planting. Although global restoration efforts are ongoing, success remains mixed because of insufficient stakeholder engagement, poor understanding of site-specific stressors, and limited knowledge of local hydrodynamics. Experiments in controlled tank environments have shown that individual planting units are vulnerable to scour and erosion under the action of waves and currents. However, when planting units were connected in groups, survival rates improved significantly, particularly under realistic field conditions. Therefore, restoration approaches should avoid uniform spacing across large areas and, instead, cluster planting units into interlinked patches that can provide mutual protection, reduce exposure to hydrodynamic stress, and enhance establishment. Managers must also choose native species suited to local conditions, avoid planting during periods of high tourism and storm activity, and ensure long-term monitoring is built into restoration plans.

Restoration success is especially challenging for large, slow-growing seagrass species such as *Posidonia oceanica*, a foundation species in the Mediterranean Sea of significant ecological, economic, and cultural value. Even under ideal conditions, natural recolonization can take up to 30 years. Therefore, planting design must factor in the growth traits and reproductive ecology of target species, particularly when aiming to restore long-term coastal protection functions.



Replanting

Replanting is currently the most common seagrass restoration method. This involves either transplanting adult shoots from existing meadows or planting nursery-grown seedlings. Field-collected shoots should only be sourced from robust and healthy donor beds that can recover from partial harvesting. Once collected, the shoots can be hand-planted directly into the seabed, tied to biodegradable substrates such as shells for boat-based deployment, or inserted using mechanical planting equipment. The shoots must be securely anchored to prevent displacement by waves and currents and to ensure that roots establish in the substrate. A global meta-analysis demonstrated the effectiveness of scale on seagrass restoration. The study reported average restoration success rates of 37 percent, with success increasing by 20 percent in projects deploying more than 100,000 units (shoots or seeds), highlighting the importance of scale (van Katwijk et al. 2016). Larger planting projects are also more likely to overcome ecological feedback loops and trap small patches in degraded states. However, costs, logistics, and long-term maintenance remain challenges, particularly in remote or dynamic environments. Careful site selection, timing, and post-restoration monitoring are essential to achieving sustainable outcomes.



Reseeding

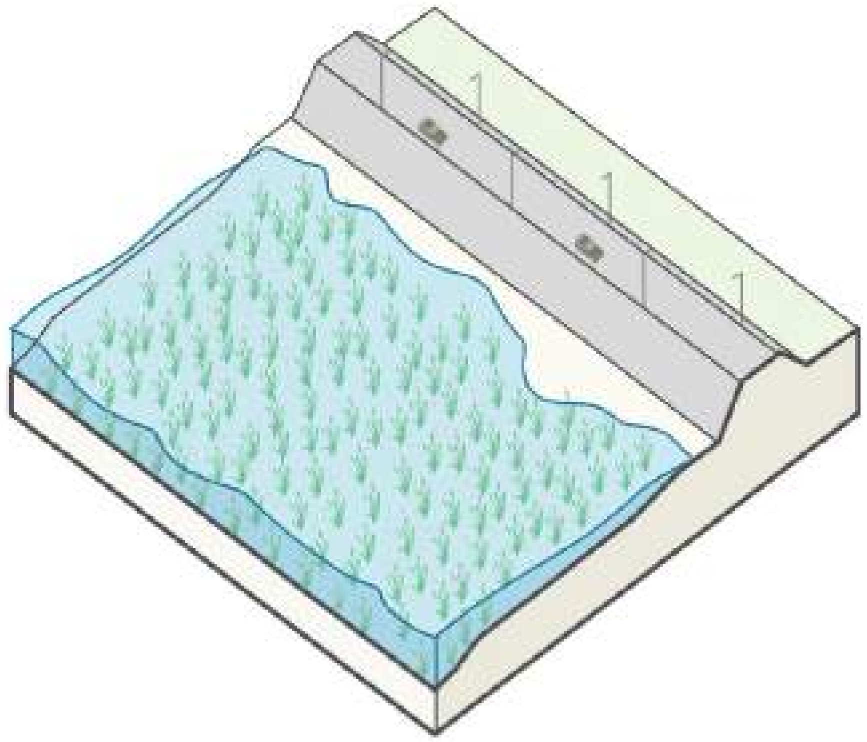
Reseeding involves the collection, storage, and strategic deployment of wild seagrass seeds and is increasingly used to enhance restoration scale and genetic diversity. Seeds must first be harvested from donor meadows, then transported and stored under controlled conditions to preserve viability. Deployment options vary and include scattering seeds directly from boats, placing them manually in the seabed, or embedding them in hessian seed bags or biodegradable mats. In some cases, the bags must be anchored using weights or pegs to ensure contact with the substrate and prevent drift. Emerging technologies such as Buoy-Deployed Seeding (BuDS) suspend mature shoots above restoration sites, allowing seeds to fall naturally onto the seabed. In the Dutch Wadden Sea, another technique injects seed–sediment slurry directly into the substrate (Tan et al. 2020). Tested on Zostera marina species, this method was shown to be more effective for sites with strong currents and fine-grained sediments than the BuDS or hand-casting methods (Tan et al. 2020). Furthermore, laboratory simulations suggest that free-deployed seed bags and scattering methods may perform better under wave stress than fixed planting methods, as fixed units can be more susceptible to erosion. However, success depends heavily on timing, local sediment conditions, water clarity, and predation pressures. While reseeding can be less labor-intensive than replanting, it often requires large volumes of seed and still carries risks of low germination or loss due to environmental variability.

HYBRID INTERVENTIONS

Seagrass meadows can be integrated with coastal engineering structures to form hybrid systems that enhance shoreline protection. By combining ecological and engineered elements, these interventions aim to reduce wave energy, stabilize sediments, and improve the resilience of hard defenses such as seawalls and revetments. In areas of moderate environmental stress, well-designed hybrid systems can reduce maintenance needs for hard structures while preserving the ecological services provided by seagrasses. The dense rhizome and root systems of seagrass meadows anchor sediments and help prevent scouring at the toe of built infrastructure, contributing to long-term structural stability.

However, caution is needed: placing hard infrastructure within existing seagrass beds is not recommended, as physical disruption, burial, and erosion caused by construction and altered hydrodynamics can lead to habitat degradation. Instead, hybrid solutions should be designed to maintain or enhance natural processes, avoid shading or smothering effects, and accommodate ecological function.

To support hybrid functioning, seagrass meadows should be located in shallow, low to moderate energy environments where they can maintain stable biomass. While they are found in both open coasts and estuaries, they are more persistent in sheltered areas such as estuaries or lagoons protected from storm conditions (Marco-Méndez et al. 2024). The placement of engineered structures must allow for adequate water flow and sediment dynamics to sustain seagrass health. However, they can also exist in other sedimentary shorelines and can be combined with beach and dune systems and solutions. Where possible, hybrid designs should also anticipate future sea-level rise by allowing for landward habitat migration.



BENEFITS

Flood risk reduction: Seagrass meadows contribute to flood risk mitigation by attenuating wave energy and stabilizing sediments in coastal zones. In the northeast Pacific, studies show that eelgrass (Zostera marina) can attenuate current speeds by 40–70 percent, though this declines as current speed increases (Lacy and Wyllie-Echeverria 2011). Seagrass meadows' effects on hydrodynamics depend on their stiffness, plant density, submergence, wave climate, and species, among other factors. Therefore, seagrass meadows cannot support shoreline protection in every situation (Ondiviela et al. 2014). Optimal conditions for enhancing the protection supplied by seagrasses may be achieved in shallow waters and low wave energy environments. Research shows that when plant length matches water depth, wave energy reduction can reach up to 40 percent per meter of meadow, a performance comparable to that of salt marshes (Fonseca and Calahan 1992). Likewise, the most favorable protection might be provided by large, long-living, slow-growing seagrass species, with biomass being largely independent of seasonal fluctuations and with the maximum standing biomass reached under the highest hydrodynamic forcings (Ondiviela et al. 2014). However, performance may decrease under storm conditions as a result of increased wave setup and surge, particularly in deeper or more exposed sites. Storms can also produce damage on seagrass beds from wave induced stress. When compared with hard infrastructure solutions, the cost-effectiveness of protecting or restoring seagrass meadows depends on local conditions, implementation scale, and opportunity costs.

Resources production: Seagrass meadows support coastal fisheries. Globally, around 20 percent of the world's largest fisheries rely on seagrass ecosystems (de los Santos et al. 2020). In the United Kingdom, temperate eelgrass beds support fish densities 4.6 times greater than adjacent sand flats and provide habitat for at least 10 commercially important species (Gamble et al. 2021). The economic value of these services is evident in sites such as Trang Province, Thailand (where it is valued at US$1.2 million per year; Praisankul and Nabangchang-Srisawalak 2016) and Gran Canaria (valued at €600,000 per year; Tuya et al. 2014). In the Mediterranean, seagrasses contribute US$65–103 million annually to commercial fisheries and €126 million to recreational fisheries (Jackson et al. 2015).

Erosion reduction: Although research on the coastal protection benefits of seagrass is less extensive than for other ecosystems, evidence suggests that large, dense seagrass beds near shorelines can buffer wave and tidal energy, but, most importantly, retain and stabilize (Ondiviela et al. 2014). In turn, these effects affect the shoreline profile and contribute to its stability, preventing erosive processes. Seagrass blades flex with wave motion, absorbing energy and reducing its impact on shorelines. Root and rhizome systems bind sediments, protecting against storms and gradual erosion (Gamble et al. 2021). Studies also show that vegetated foreshores with seagrass can reduce wave loads on coastal infrastructure (Timmerman et al. 2013). In the Wadden Sea, meadows reduced current velocity and wave height by up to 30 percent in deeper waters and over 90 percent in shallows (Jacob et al. 2023). Seagrass meadows may also adapt to sea-level rise through sediment accretion and inland migration (Duarte et al. 2013). Laboratory tests further indicate that dense root mats can reduce wave-driven cliff erosion in sandy seabeds (Infantes 2022). However, their effectiveness for erosion control ultimately depends on plant density, stiffness, and submergence (Bouma et al. 2005), as well as tidal and current regimes (Paul et al. 2012).

Tourism and recreation: Seagrass beds offer opportunities for ecotourism and recreation, including snorkeling, diving, and wildlife viewing. In Marsa Alam, Egypt, tourists visit seagrass beds to swim with dugongs (de los Santos et al. 2020). In some coastal communities, seagrass meadows also hold cultural significance, reflecting traditional ways of life and fostering local identity. For example, in Trang Province, Thailand, the recreational value of seagrass meadows has been estimated at US$5 million per year (Praisankul and Nabangchang-Srisawalak 2016).

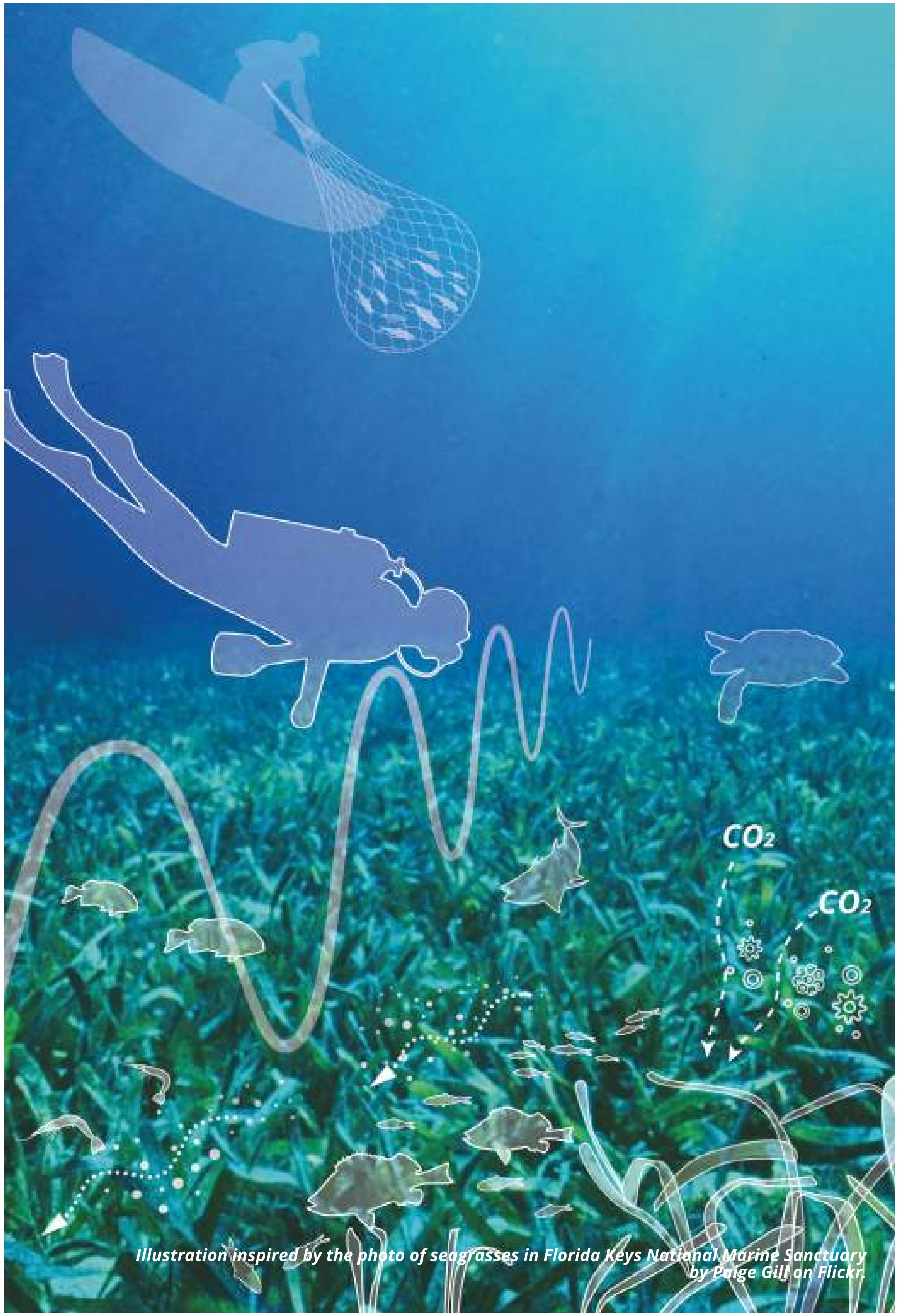
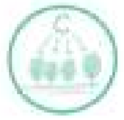


Illustration inspired by the photo of seagrasses in Florida Keys National Marine Sanctuary by Paige Gill on Flickr.



Carbon storage and sequestration: Seagrasses play an important role in mitigating climate change through carbon sequestration. They absorb atmospheric CO_2 and store carbon in belowground biomass and sediment as "blue carbon" (Duarte et al. 2013; Gullström et al. 2018; Lyimo 2016; Potouroglou et al. 2017). Although they cover just 0.1 percent of the ocean floor, seagrass meadows account for 10–18 percent of oceanic carbon burial and sequester carbon up to 35 times faster than tropical forests (Kennedy et al. 2010; Mcleod et al. 2011). Long-term storage rates range from 25–132 grams of Carbon per meter per year (Duarte et al. 2013; Fourqurean et al. 2012). For example, in Trang, Thailand, annual carbon sequestration services are valued at US$65 million (Praisankul and Nabangchang-Srisawalak 2016). In the United Kingdom, sediment-based carbon stocks were valued at US$3.5–7.3 million (Green et al. 2018).

Biodiversity: Seagrasses are among the most biodiverse shallow marine habitats, offering shelter, food, and nursery grounds for marine species. They support a range of commercial fish, crustaceans, and megafauna, including dugongs, manatees, and green turtles—all of which are threatened with extinction (de los Santos et al. 2020). Seagrass beds connect with other ecosystems such as salt marshes, kelp forests, and shellfish reefs, enabling animal movement and nutrient transfer across habitats (Gamble et al. 2021).

Water quality and sediment management: Seagrass meadows improve water quality through nutrient filtration, sediment trapping, and chemical cycling. They capture excess nitrogen, microplastics, and trace metals, improving clarity and supporting adjacent habitats (de los Santos et al. 2020; Gamble et al. 2021). Their ability to reduce suspended sediment also enhances light availability for photosynthesis. Moreover, the pH of seawater surrounding the meadow can be raised up to 30 percent, which can help to counter ocean acidification (Ricart et al. 2021). The nutrient cycling function alone has been valued at US$19,000 (in 1994 US dollars) per hectare annually (Costanza et al. 1997).

The multiple benefits of segrass meadows on a qualitative scale

Burma, Myanmar
Photo by Brian Sumner on Unsplash

COSTS

Implementation costs

The cost of seagrass restoration is highly variable and context-specific, depending on the technique, scale, location, and equipment used. Restoration is significantly more expensive and uncertain than conservation. A success rate above 40 percent for restoration is considered notable, and only half of projects reviewed by Fonseca (2006, 2011) achieved this. Key cost components include feasibility assessments, pilot trials, permitting, seed sourcing, nursery or aquaria facilities, and securing stakeholder support.

Implementation costs can vary largely between regions and techniques. In Western Australia, mechanical plantation using an ECOSUB system to cut and plant large sods costs around US$641,520 per hectare, including equipment design, testing, and site preparation (Paling et al. 2009). By contrast, manual planting ranges from US$10,263 to US$21,809 per hectare with volunteers and US$55,000 to US$100,000 per hectare using professional contractors (Paling et al. 2009). Amphibolis restoration in Southern Adelaide reported costs of US$11,887–US$16,320 per hectare (Wear et al. 2006; Wear et al. 2010). A global estimate places the average cost of seagrass restoration at approximately US$700,000 per hectare. Under favorable scenarios, seagrass interventions can yield a cost-benefit ratio of 1 to 7 and an internal rate of return of 3 percent, demonstrating that benefits can outweigh costs (de Groot et al. 2013). These benefits include not only flood attenuation but also co-benefits such as fisheries support, carbon storage, and improved water quality.

In Indonesia's Spermonde region, a multi-species restoration across 600 square meters cost approximately US$100,000 over three years, covering preparation, installation, and monitoring. Measurable success, in terms of increased coverage, biodiversity, and erosion control, was observed after seven years (Asriani et al. 2019). The United Kingdom's ReMEDIES project highlights that innovation in mechanization and scaling can reduce unit costs and labor requirements, though restoration remains capital-intensive and demands a multi-benefit valuation approach to justify investment.

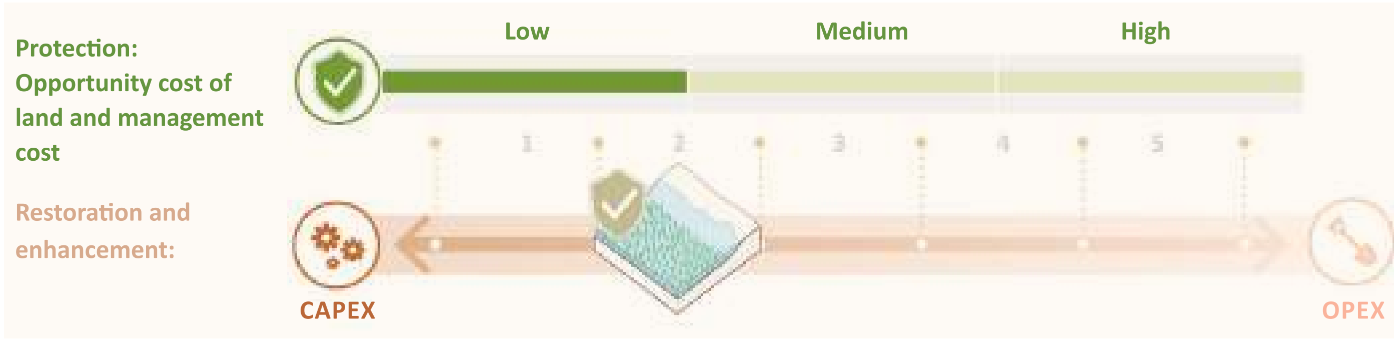
Operations & maintenance costs

Long-term monitoring and adaptive management are critical to the success of seagrass restoration but often underfunded. Maintenance costs include managing invasive species, preventing anchor or boat damage, monitoring ecological health, and replacing failed transplants. Projects may also require regular engagement with stakeholders to maintain compliance with no-disturbance zones and support continued behavioral change.

Other cost considerations

Land access and tenure represent important cost components. While seagrass meadows typically occur in marine environments, adjacent land access is often necessary for launching boats, maintaining nurseries, or facilitating monitoring. Costs may include land acquisition, lease payments, or compensation to private landowners. Effective restoration or protection may require coordination across multiple jurisdictions, further increasing transaction costs.

Costs vary by subtidal or intertidal location, restoration method, and required permitting. Restoration in deeper, more dynamic waters tends to be more expensive because of its additional technical and logistical complexity. Significant time and resources must also be allocated to stakeholder engagement, given the importance of buy-in from local communities and marine users. Furthermore, seagrass recovery can be slow and requires trained capacity as well as adequate and adaptive designs and planning. Evidence suggests that larger-scale restoration projects can improve cost-effectiveness and future resilience through ecological thresholds that boost survival and ecosystem functions. Stacked valuation approaches that account for biodiversity, carbon sequestration, and coastal protection services also offer a promising pathway to assess investments and align diversified funding sources.



CAPEX: Implementation costs
OPEX: Operations and maintenance costs

GUIDELINES AND RESOURCES

The resources listed provide guidance for protecting, and restoring seagrass meadows, supporting their assessment, planning, and implementation as nature-based solutions. They also include information on creating suitable conditions for seagrass meadows, as well as guidance on monitoring approaches.

Altman, S., Cairns, C., Whitfield, P., Davis, J., Finkbeiner, M., and McFall, B. 2021. Plant Systems: Submerged Aquatic Vegetation and Kelp. In International Guidelines on Natural and Nature-Based Features for Flood Risk Management, edited by Bridges, T. S., J. K. King, J. D. Simm, M. W. Beck, G. Collins, Q. Lodder, and R. K. Mohan. Vicksburg, MS: U.S. Army Engineer Research and Development Center, chapter 13. https://ewn.erdc.dren.mil/nnbf-guidelines/13-plant-systems-submerged-aquatic-vegetation-and-kelp/

Gamble, C., Debney, A., Glover, A., Bertelli, C., Green, B., Hendy, L., Lilley, R., Nuuttila, H., Potouroglou, M., Fagazzola, F., Unsworth, R., and Preston, H., eds. 2021. Seagrass Restoration Handbook. London: Zoological Society of London, UK. https://catchmentbasedapproach.org/learn/seagrass-restoration-handbook/

Green Guide to Anchoring and Moorings https://thegreenblue.org.uk/wp-content/uploads/2024/11/The-Green-Guide-to-Anchoring-Moorings.pdf

Morris, R. L., Bishop, M. J., Boon, P., Browne, N. K., Carley, J. T., Fest, B. J., Fraser, M. W., Ghisalberti, M., Kendrick, G. A., Konlechner, T. M., Lovelock, C. E., Lowe, R. J., Rogers, A. A., Simpson, V., Strain, E. M. A., Van Rooijen, A. A., Waters, E., nd Swearer, S. E. 2021. . Earth Systems and Climate Change Hub Report No. 26. NESP Earth Systems and Climate Change Hub, Australia. University of Melbourne. https://www.researchgate.net/publication/351655220_The_Australian_guide_to_nature-based_methods_for_reducing_risk_from_coastal_hazards

Natural England. 2024. Reducing and Mitigating Erosion and Disturbance Impacts affecting the Seabed (ReMEDIES). Record published by Natural England October 29, 2024l https://publications.naturalengland.org.uk/publication/6041956655038464

UNEP-Nairobi Convention/WIOMSA. 2020. Guidelines for Seagrass Ecosystem Restoration in the Western Indian Ocean Region. UNEOP: Nairobi. https://www.unep.org/resources/report/guidelines-seagrass-ecosystem-restoration

In addition, the Nature-Based Solutions Opportunity Scan (NBSOS) is a tool that helps identify NBS investment opportunities, providing information on NBS types, suitable locations, costs, and coastal protection benefits and co-benefits. It supports decision-makers in integrating NBS into planning, and investment strategies for both urban and coastal areas.

SEAGRASS MEADOWS CASE STUDIES

PROJECT #1
Badi Island Seagrass Restoration, Indonesia (2016)

PROJECT #2
Seagrass Restoration in Florida, United States (1981–85)

PROJECT #3
Seagrass Ocean Rescue, West Wales, United Kingdom (2019–20)

PROJECT #4
Posidonia Andalusia Project, Spain (2011–16)

Wakatobi, South East Sulawesi, Indonesia
Photo by Benjamin L. Jones on Unsplash

PROJECT #1
Badi Island Seagrass Restoration, Indonesia (2016)

UC Davis researchers monitor seagrass in South Sulawesi, Indonesia. Photo by Christine Sur, Taken from UC Davis College of Biological Sciences.
Source: Seagrass Project Highlights New Paradigm for Marine Ecosystem Restoration. https://basc.ucdavis.edu/news/seagrass-project-highlights-new-paradigm-marine-ecosystem-restoration

Location

Badi Island, South Sulawesi, Indonesia

Approach

Seagrass restoration

Size

600 square meters

Cost

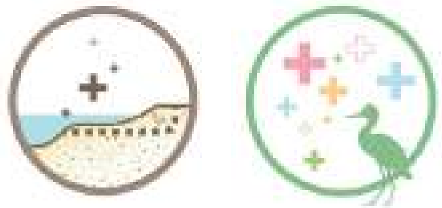
US$100,000

Description

A long-term seagrass restoration project was conducted in the Spermonde archipelago using multiple seagrass species to counter degradation due to complex anthropogenic pressures. The 600-square meter project area began with approximately 10 percent seagrass coverage and aimed to restore and monitor seagrass meadows. The substrate was sand; depths range from 1 to 1.5 meters. After 7 years, the project achieved success, evidenced by increased seagrass cover, more diverse faunal communities, and enhanced coastal protection from erosion. A positive relationship was found between seagrass species richness, transplant survival, and increase in seagrass coverage. On average, when at least four seagrass species were planted together, seagrass cover increased. Change in cover varied for different seagrass species. Half of the species (Halodule uninervis, Syringodium isoetifolium, Thalassia hemprichii) increased in cover while other species (Enhalus acoroides, Cymodocea rotundata, Halophila ovalis) lost coverage over time.

Benefits

- *Seagrass restoration increased biodiversity in the area over areas without seagrass.*
- *Erosion was reduced through sediment trapping and stabilization.*



Coastal erosion reduction

Biodiversity enhancement

Challenges

- *The restored seagrass bed supported fewer species than natural seagrass beds.*
- *Limited understanding of specific site conditions may affect the success of restoration.*

Lessons learned

- *Transplanted seagrass meadows support a wider variety of organisms than bare substrates.*
- *Restoration efforts must consider species-specific requirements and environmental conditions to ensure success.*

Source (references)

Ambo-Rappe, R. 2022, The success of seagrass restoration using Enhalus acoroides seeds is correlated with substrate and hydrodynamic conditions. *Journal of Environmental Management*, 310:114692. https://doi.org/10.1016/j.jenvman.2022.114692

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PROJECT #2
Seagrass Restoration in Florida, United States (1981–85)

Taking data at Key Biscayn. Image courtesy of Resource Environmental Solutions (RES).
Source: RES. No date. USACE, Key Biscayne 145-Acre Seagrass Assessment, Resource Environmental Solutions, LLC. https://res.us/projects/usace-key-biscayne-145-acre-seagrass-assessment/

Location

Biscayne Bay, Florida, United States

Approach

Seagrass restoration

Size

114.1 hectares

Cost

*The project restored **US$9 million** worth of seagrass, while the planting costs amounted to less than 10 percent **(less than US$900,000)** of this value.*

Description

This project focused on the large-scale restoration of seagrass in Biscayne Bay, Florida, where human activities over 80 years caused severe degradation. The restoration effort involved planting three species of seagrass (Thalassia, Halodule, and Syringodium) at different depths (from 1.6 to 2.8 meters) across multiple phases in 114 hectares of silted, sandy seabed. The project tested different planting techniques and timings to ensure success. The restored areas have since seen the rapid recolonization of marine life, including commercially significant species, and significant improvements in seagrass coverage. The initiative aimed to rehabilitate critical ecosystems in Biscayne Bay, enhancing biodiversity and supporting fisheries.

Benefits

- *The project restored over 100 hectares of seagrass, supporting biodiversity and enhancing the ecological productivity of Biscayne Bay.*
- *It provided habitat for commercially important species such as lobster, shrimp, crabs, and fish, supporting local fisheries.*
- *Seagrass restoration increased the bay's capacity for carbon sequestration and nutrient cycling, improving water quality.*
- *The project enhanced resilience of coastal ecosystems to environmental disturbances and contributed to shoreline stabilization.*

Biodiversity enhancement

Carbon sequestration

Coastal erosion reduction

Challenges

- *Severe weather conditions negatively impacted plant survival rates.*
- *Winter planting efforts had little success.*
- *Some restoration areas suffered from recolonization challenges, particularly in regions affected by historical dredging and filling activities.*

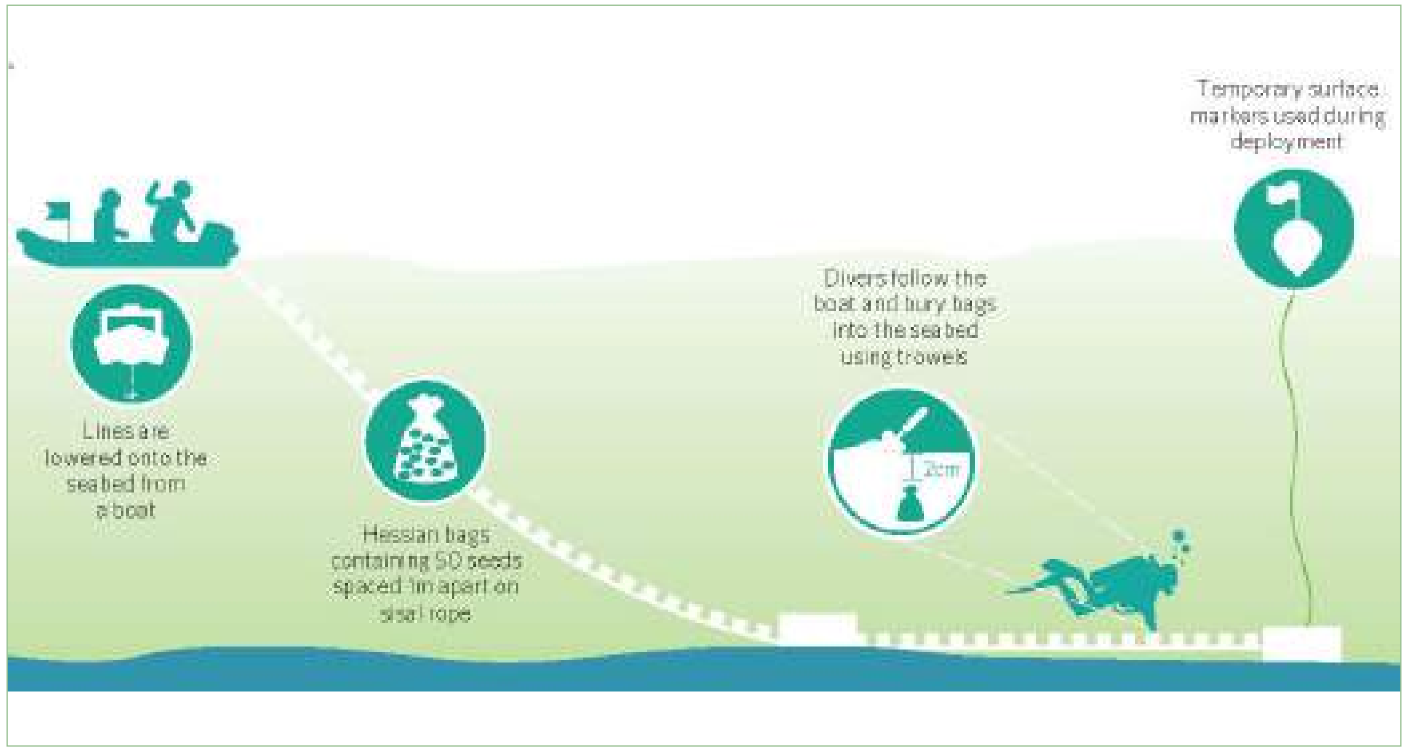
Lessons learned

- *Winter planting is not suitable for all seagrass species.*
- *Mechanized planting methods improved speed and reduced costs, making large-scale restoration more feasible.*
- *Areas with existing seagrass had higher survival and regrowth rates, indicating the importance of selecting optimal restoration sites.*
- *Ongoing monitoring and adaptive management are crucial to address challenges such as severe weather to improve restoration success.*

Source (references)

Thorhaug, A. 1987. Large-scale restoration in a damaged estuary. *Marine Pollution Bulletin*, 18(8):442–46. https://doi.org/10.1016/0025-326X(87)90621-7

PROJECT #3
Seagrass Ocean Rescue, West Wales, United Kingdom (2019–20)



How seagrass seeds are planted using the hessian bag BoSSLines method.
Source: Gamble, C., Debney, A., Glover, A., Bertelli, C., Green, B., Hendy, L., Lilley, R., Nuuttila, H., Potouroglou, M., Fagazzola, F., Unsworth, R., and Preston, H., eds. 2021. Seagrass Restoration Handbook. London: Zoological Society of London, UK. https://catchmentbasedapproach.org/learn/seagrass-restoration-handbook/

Location

Dale Bay, Pembrokeshire, West Wales, United Kingdom

Approach
Seagrass restoration

Size
2 hectares

Cost
Unpublished. Funded by the World Wildlife Fund and the Sky Ocean Rescue program.

Description
The United Kingdom has suffered large-scale loss of historic seagrass meadows due to issues such as land reclamation and water contamination. In 2019, a partnership between Swansea University, Project Seagrass, and Pembrokeshire Coastal Forum undertook the United Kingdom's first major seagrass restoration project, named "Seagrass Ocean Rescue." Building on years of experimentation into seagrass planting methods and site suitability studies, over 1 million seagrass seeds of common eelgrass (Zostera marina) were collected and planted across a 2-hectare area in Dale Bay (the restoration site is approximately 1.5 meters below the chart datum, with a spring tide range of 7.9 meters). Twenty thousand hessian bags were deployed in total across the project lifetime.

Benefits
- *In 2021, monitoring estimated that restoration resulted in between 5,600 to 9,119 mature seagrass shoots across an area that had been devoid of seagrass prior to the project. This expansion is expected to continue over the coming years.*
- *Some biodiversity benefits were recorded, including the presence of juvenile Pollack fish.*

Biodiversity enhancement

Challenges
- *Initial delays in licensing were encountered due to concerns raised by local stakeholders.*
- *Seagrass shoot density remains much lower than expected. The overall conversion rate of seeds to mature plants in the field study was less than 5 percent.*
- *Anchoring activity and the presence of drift algae impacted seagrass survival.*

Lessons learned
- *Restoration activities rely on the close support of the local community.*
- *Observed restoration successes may have been aided in part by the COVID-19 pandemic lockdown in 2020, when almost no recreational boating activity took place.*
- *The use of hessian bags protects the enclosed seeds from predation by green shore crabs (Carcinus maenas).*

Source (references)

Gamble, C., Debney, A., Glover, A., Bertelli, C., Green, B., Hendy, L., Lilley, R., Nuuttila, H., Potouroglou, M., Fagazzola, F., Unsworth, R., and Preston, H., eds. 2021. Seagrass Restoration Handbook. London: Zoological Society of London, UK. https://catchmentbasedapproach.org/learn/seagrass-restoration-handbook/

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PROJECT #4
Posidonia Andalusia Project, Spain (2011–16)

Photo by Benjamin L. Jones on Unsplash.

Location

Andalusian Region, Spain

Approach
Protection measures

Size
27,022 hectares

Cost
US$4,020,710

Description

In Andalusia, Spain, Posidonia oceanica seagrass meadows are a management and conservation priority to secure the socioeconomic and ecosystem benefits of seagrass. However, since the 1960s, the extent of Posidonia seagrass in the Mediterranean has declined by around 50 percent. Some of the threats affecting this ecosystem include bottom trawling, water pollution, competition with invasive species, and seabed sand extraction.

The EU LIFE+ Posidonia Andalusia project's key objective was to improve the conservation status of Posidonia oceanica meadows in Andalucia and inform effective management plans. Initial research was undertaken to map the extent and current condition of the seagrass meadows. Posidonia oceanica meadows typically thrive in clear, shallow waters up to about 40 meters, but are most robust in the 5- to 15- meter depth zone. The project implemented multiple protection measures, including surveillance of fishing activity and the creation of artificial reefs to reduce illegal trawling.

Benefits

- *A total of 27,022 hectares of Posidonia seagrass meadows were mapped and received protective measures for conservation and restoration purposes. A socioeconomic study revealed that the seagrass meadows in Andalusia support commercial fish species, protect the coastline from erosion, improve water quality, and enhance underwater landscapes, boosting tourism (outreach tours reached over 20,000 participants, and 5,000 people attended three "Seas of Posidonia" festivals).*

Water quality

Tourism and recreation

Resource production

Challenges

- *Implementing measures to control the spread of invasive seaweed species proved challenging and ultimately unsuccessful although the project did generate data on their distribution.*

Lessons learned

- *The education of habitat user groups and community outreach were key components to project success.*
- *Collecting data prior to taking protective actions is important to ensure that management decisions are well-informed.*
- *Efforts to eradicate alien species are only worthwhile at the early stages of detection and invasion, when it is of a limited size.*

Source (references)

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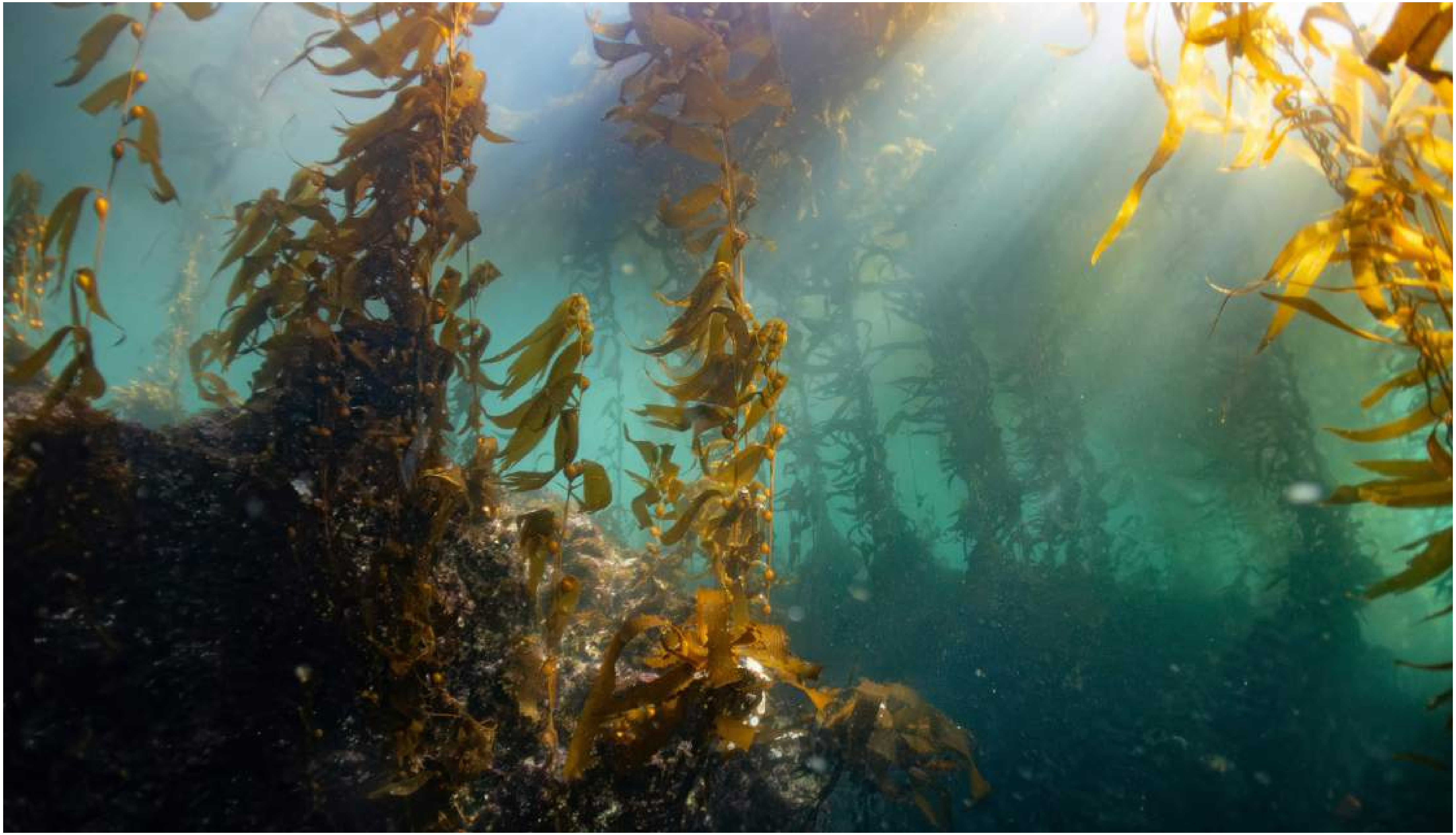


KELP AND OTHER SEAWEEDS

Anacapa Island, California, United States
Photo by Erick Morales Oyola on Unsplash

FACTS AND FIGURES

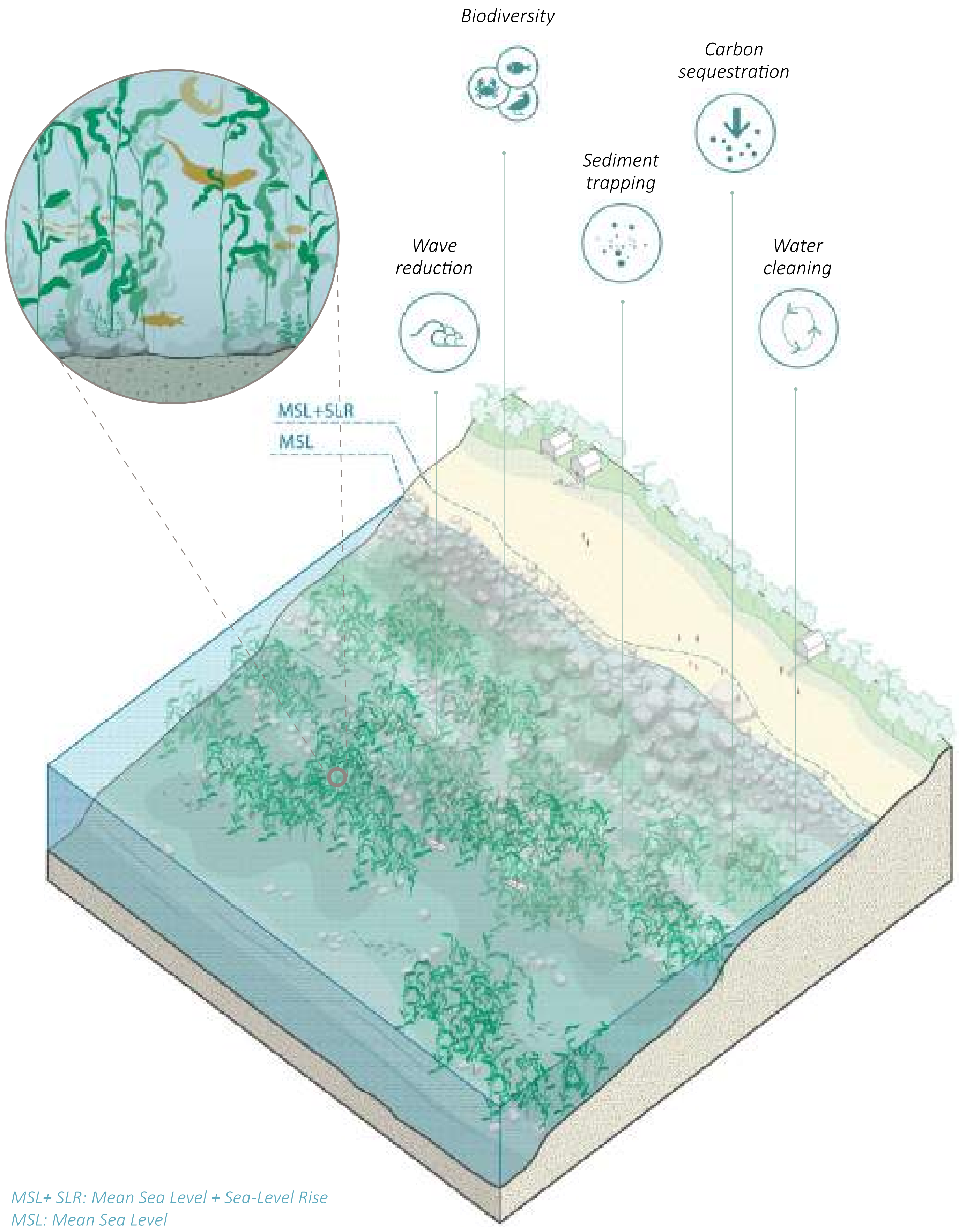
Seaweeds are a group of non-flowering, photosynthetic marine macroalgae. Kelp (a group of brown macroalgae genera) forms structurally complex habitats (kelp forests), in contrast to most other seaweeds that typically create simpler microhabitats. Kelp forests are abundant in rocky, nearshore waters of the temperate and polar zones (Steneck et al. 2002). Kelp requires a hard substrate (usually rocky surfaces) for attachment, high-nutrient conditions for survival, and light for growth. Kelp and other seaweeds form some of the world's largest and most productive coastal ecosystems (Duarte et al. 2020), with some species being more productive per unit area than tropical rainforests (Reed and Brzezinski 2009).

Seaweed beds are important coastal habitats that provide a range of ecological and socioeconomic benefits. They enhance water quality, cycle nutrients such as nitrogen, and sequester carbon in their biomass and soils. They also create feeding grounds, shelter, and nursery grounds for other species.

Socioeconomically, both wild and aquaculture seaweed sustain livelihoods, supporting food production (such as edible seaweed) and agriculture (such as by providing raw materials for biofertilizers), and providing materials for pharmaceutical and cosmetics industries. Kelp forests also perform important ecological functions, including influencing hydrodynamic (Morris et al. 2020), nutrient, and light conditions within the water column (Hondolero and Edwards 2017). Kelp forests form the basis of a complex food web: their canopies provide habitat, nursery areas, and food for a host of mobile and benthic organisms.

Kelp forests are threatened by a variety of human coastal activities, including overfishing, direct harvest, pollution from nearby urban areas (Krumhansl et al. 2016), and climate change (Eger et al. 2022b). Kelp forests can further degrade from overgrazing (often linked to overfishing, which results in the decline of urchin predators from the ecosystem), despite the rapid growth of kelp (Williams and Davies 2019).

The role of Kelp in coastal protection is secondary compared to other coastal ecosystems, But in large densities, and with significant complexity in the morphology, they can help reduce wave action (especially high-frequency components) and combat coastal erosion, particularly if combined with substrate stabilization and restoration. Kelp forests are also important for coastal communities, with an estimated total value worldwide of US$500 billion per year (from fisheries production, nitrogen removal, and carbon sequestration) for the approximately 740 million people living within 50 kilometers of a kelp forest (Eger et al. 2023).



Visualizing the processes and benefits of kelp forests.

SUITABILITY CONSIDERATIONS

To deliver benefits such as erosion reduction and biodiversity enhancement, kelp and other seaweeds must be located in areas where conditions allow them to remain stable and functional.

Location and climate: Kelp forests are abundant. They are found along approximately one-third of the world's coastlines in polar, subpolar, and temperate latitudes (Eger et al. 2022a). Most kelp species inhabit areas where water temperatures are between 5°C and 20°C, although there are instances of kelp in intertropical regions where temperatures do not exceed 22°C–24°C (Becheler et al. 2022). Water temperature is often the best indicator of kelp distribution at a large scale (Wernberg et al. 2019).

Hydrodynamics: Kelp species are found in the intertidal and subtidal zones in nutrient-rich waters where sunlight can penetrate for photosynthesis, typically in water up to 30 meters deep for some species. Kelp is flexible and strong, anchoring to rock with holdfasts and high tensile strength. The root, stem, and blades all stretch and absorb energy without breaking, bending and aligning with flows. These features reduce drag and shear forces during extreme wave events, enabling kelp to experience meter wave heights greater than 10 meters and large surge events. Kelp forests, especially those formed by large brown algae such as *Macrocystis pyrifera* (giant kelp) and *Laminaria spp*., are therefore remarkably resilient to high-energy environments, including strong wave action and coastal currents. Their morphology, anchoring systems, and biomechanical properties have evolved specifically to withstand exposure.

In general, kelp species grow best in waters moderately exposed to waves and currents as low water motion can inhibit photosynthesis and growth. They can tolerate high wave exposure and display morphology adaptations in high-energy environments. However, extreme waves can damage or dislodge them from the seabed and can inhibit in-water restoration activity (Morris et al. 2021). Kelp forests also require a moderate current to circulate water and distribute nutrients, which they can withstand by anchoring to a strong substrate by holdfasts. In high-velocity or strong currents, kelp can become dislodged and result in scattered distributions. Large areas are typically needed to achieve wave attenuation effects. During storm events, its effectiveness in attenuating waves may also diminish as changes in coastal water levels reduce its buffering capacity.

Salinity: Kelp are marine species and are not found to inhabit fresh water. They typically grow in salinities of around 35 practical salinity units and are unable to survive in high-salinity environments over 40 practical salinity units. Reduced salinity associated with flooding events is known to negatively impact kelp growth, survival, and photosynthetic yield. The exact tolerances of kelp to reduced salinity depends on the species and life stage, as well as on related factors such as water temperature (Davis et al. 2022).

Sedimentation rate: Kelp species require clear water conditions for photosynthesis. Although they can tolerate a high degree of sediment load (turbidity), excessive sedimentation can smother kelp and prevent the settlement, growth, and reproduction of juvenile kelp. Increased turbidity is an uncommon cause of decline of established mature kelp forests. Kelp provides some cobble and sand bed stabilization by dampening flow.

Soil: Kelp is found predominantly along rocky shorelines, as they require a hard substrate to anchor. Kelp forests form by attaching to cobbles and rocks and rocky seabed features. The appropriate substrate availability is a fundamental constraint to seaweed distribution. Substrate preferences and tolerances are highly species-specific.

Slope: Kelp abundance has been found to be greater in flat areas where stable substrates (such as cobbles and boulders) are plentiful for attachment. Steep terrain can pose challenges for attachment, particularly to lose rocky substrate, resulting in reduced kelp abundance (Bekkby et al. 2019).

Natural regeneration: Natural regeneration of kelp forests occurs when individual suitability conditions and tolerance levels of a particular species are met in a given area. To facilitate natural regeneration, damaging activities—such as trawling or overfishing—should be limited or prohibited entirely. Overexploitation of predators may result in too many sea urchins, a factor recognized as contributing to the rapid decline of kelp.

Lynmouth, United Kingdom
Photo by bizzyspace_images on Unsplash

NBS INTERVENTIONS

PROTECTION MEASURES

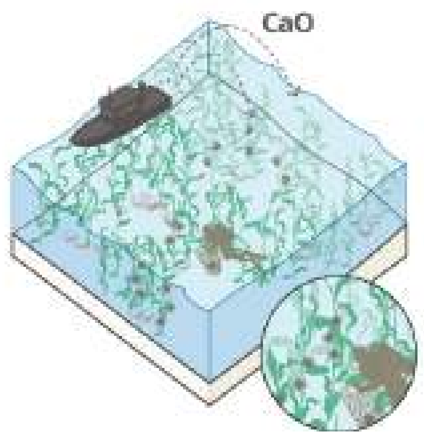
Kelp forests are declining as a result of a wide range of human-made and environmental stressors (Wear et al. 2023). These include land-use practices, degraded water quality, increased temperatures, and sediment loading, as well as direct impacts from destructive fishing and boating and dredging (Williams and Davies 2019). Kelp forest loss is driven by a variety of physical development factors such as overgrazing and overharvesting, pollution, coastal development, and ocean warming and other climate-related stressors (Krumhansl et al. 2016; Smale et al. 2013; Steneck and Johnson 2013; Wernberg et al. 2019). Some stressors can be managed at local and/or regional scales.

Kelp canopies can recover quickly following physical disturbance (Hawkins and Harkin 1985). Many types of kelp are extremely fast growing, with some species growing up to 50 centimeters per day and to lengths of up to 60 meters, maximizing the breadth and scalability of benefits delivered (Schiel and Foster 2015). However, persistent stressors must be managed or removed for successful restoration (Eger et al. 2022a).

Overcoming such stressors can require regulatory, policy, and multi-jurisdictional support, among other protection and management actions. For example, in New Zealand, marine protected areas have led to long-term kelp forest recovery and ecosystem stability (Peleg et al. 2023).

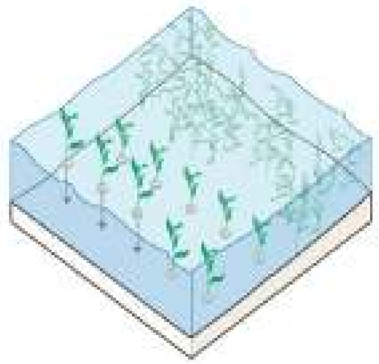
RESTORATION AND ENHANCEMENT MEASURES

Kelp forests and seaweeds beds may be restored or enhanced to support coastal resilience and climate adaptation. Kelp presents rapid growth rates. Approaches to kelp restoration vary considerably, as highlighted in the *Kelp Restoration Guidebook* (Eger et al. 2022a). Kelp forest restoration or enhancement has occurred since the 1700s in Japan, with more consistent global adoption since the 1950s (Eger et al. 2022b). Experience in restoring kelp forest has also grown since then: for example, around 200 recorded restoration projects are presented at kelpforestalliance.com (Eger et al. 2022b). Low-cost pilot projects and method comparison are also recommended before engaging in large-scale efforts (Eger et al. 2022a).



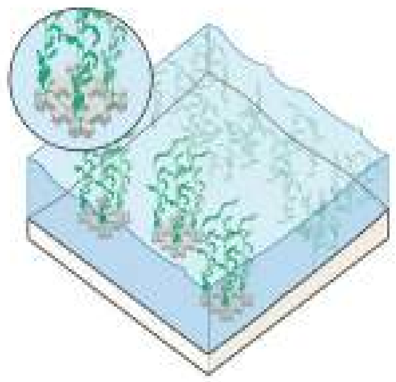
Grazer management

Grazing of kelp by herbivorous marine species is a natural part of ecosystem interactions. Changes to grazer populations are a key driver of kelp forest loss, recovery, and growth (Reeves et al. 2022). Overabundance of grazers that results from the removal of predators, whether by overfishing or disturbance, can impact kelp health. Therefore, the management of overgrazing by herbivores—such as sea urchins, herbivorous fish, and marine snails (gastropods)—is often a successful measure to employ to restore kelp forests, if there are parent populations of kelp nearby. Grazers can be removed from the ecosystem by harvesting, hand culling, mechanical culling, and translocation (Eger et al. 2022).



Seeding

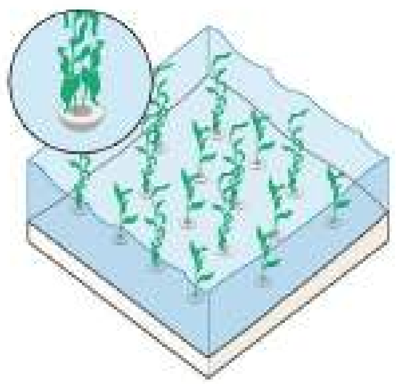
Seeding involves dispersing "seeds" or gametophytes into the ocean (Conservation South Africa 2024; Eger et al. 2022a). Seed material can either be released directly from the surface or underwater; dispersed via seed lines or spore bags, or on substrata such as rocks (Eger et al. 2022a).



Transplanting

The most frequently applied method of restoration has been *transplanting*, which involves introducing mature kelp to a site (Eger et al. 2022a). Transplanting is advantageous because kelp at older life stages is typically more resistant to environmental stressors, resulting in higher survival rates. By using mature kelp, a protective canopy is introduced immediately; this facilitates the successful recruitment of a second generation. Mature kelp must be secured to the seabed, either using mesh mats, gravel, or tiles—even through the low-cost and simplified use of glue or rubber bands (Eger et al. 2022a). Artificial reefs can also be used for seabed anchoring and substrate stability.

Kelp material for both seeding and transplanting can be sourced from wild stocks and/or by lab culturing. Sourcing wild material is cost-effective and more time-efficient; however, collecting wild material can lead to stressing (dislodging) in the doner fields, applying additional pressure to natural populations. Cultured materials from a laboratory ease pressure on wild stocks and means that restoration activities are not constrained by the reproductive timings of natural forests. This approach, however, may require more equipment, resources, and technical knowledge (Eger et al. 2022a).

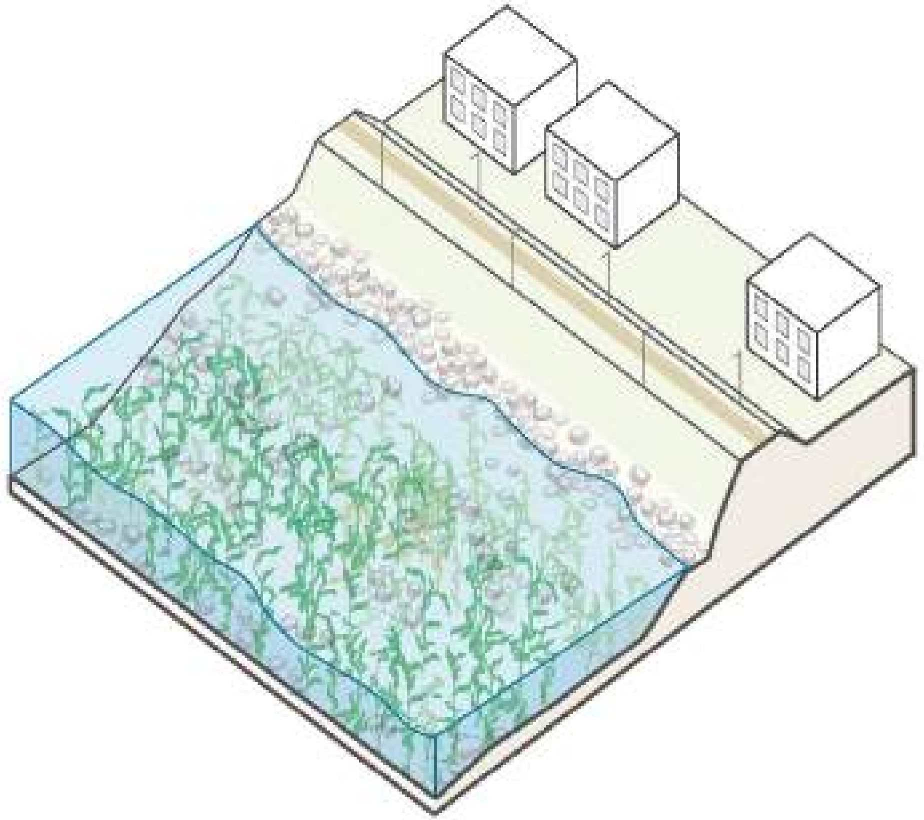


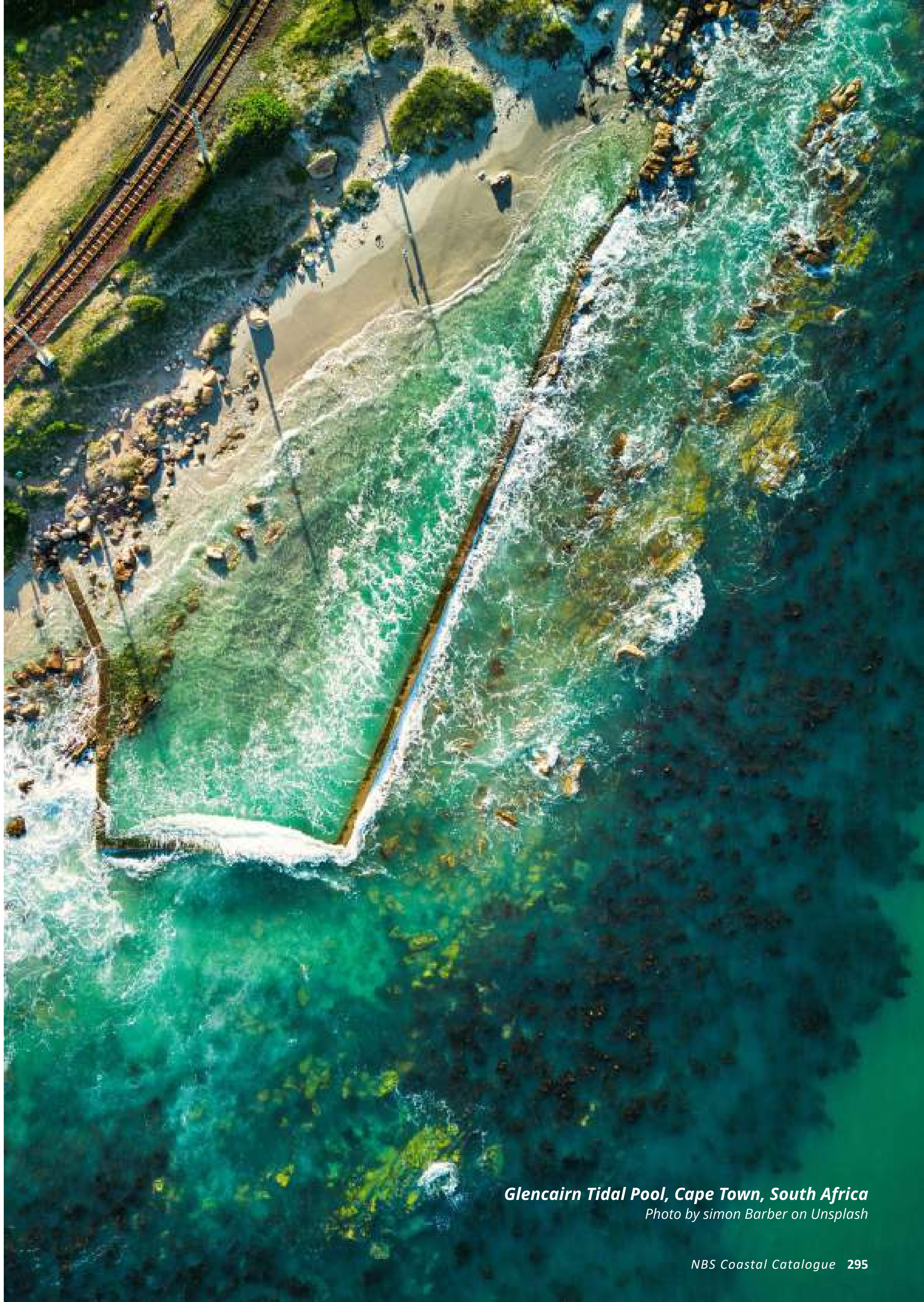
Green gravel and other innovative technologies

Green gravel is a new restoration technique that adds kelp spores to substrates, such as gravel or cobbles, in controlled conditions (Fredriksen et al. 2020). When the spores are grown into seedlings, the substrate is released into the field site. Green gravel is a relatively cheap and simple technique compared to other restoration methods that may require other underwater installations and scuba divers.

HYBRID INTERVENTIONS

The direct wave attenuation of kelp is smaller than other coastal ecosystems. However, the combination of kelp forests with other measures and substrate restoration (e.g., artificial reefs) can help integrate them into hybrid systems that can provide various benefits. The design of coastal protection systems should also avoid damaging kelp beds during construction and maintenance, as sediment movement can harm kelp ecosystems and compromise their long-term viability.





Glencairn Tidal Pool, Cape Town, South Africa
Photo by simon Barber on Unsplash

BENEFITS

Erosion reduction: Marine plants can influence currents and surface waves by exerting drag in the water column (Dalrymple et al. 1984; Kobayashi et al. 1993). The capacity of vegetation to provide wave attenuation depends on their ability to exert drag, which in turn depends on vegetation characteristics such as height, density, and individual stiffness, as well as wave parameters such as wave height and period, wave–current interactions, and water depth (Cotas et al. 2023; Maza et al. 2015). These effects can also modify sediment transport processes (López and García 1998). Kelp forests act as a filter of high-frequency wave energy, particularly in rocky coastlines with short wave periods. However, there are relatively few species of kelp that can provide this benefit, and the wave dampening capacity varies spatially and temporally (Lindhart et al. 2024). For instance, Giant Kelp, *Macrosystis pyrifera*, often occupies the entire water column and forms a dense surface canopy in summer periods during low tide conditions, which can dampen short waves to an extent comparable to floating ice (Lindhart et al. 2024). Conversely, other studies report only modest to no significant wave height reduction by kelp forests (e.g., Elsmore et al. 2023; Morris et al. 2020). In addition, large quantities of seaweed washed up on the shoreline, known as *wrack*, can result in dune erosion reduction during usual daily conditions (Innocenti et al. 2018). Therefore, the risk reduction capability of kelp and seaweed should be considered limited, but these habitats can support coastline stabilization (mostly during daily conditions) while providing many other ecosystem benefits. For example, coastal protection from kelp forests in Sussex, in the United Kingdom, was estimated to be worth US$2.38 million per hectare per year, while restoring kelp forests to their full potential extent was estimated to have a coastal protection value of US$164 million per hectare per year (Williams and Davies 2019).

Tourism and recreation: Seaweed and kelp forests also have cultural, religious, and traditional significance, including for indigenous populations in Australia, Canada, South America, New Zealand, and the United States (Cotas et al. 2023; Pérez-Lloréns et al. 2023). These forests are celebrated in folklore, art, and poetry, and contribute to local economies through tourism and recreational activities such as animal sightseeing, fishing, snorkeling, diving, and even pick-your-own seaweed excursions (Cotas et al. 2023). For example, in Sussex, United Kingdom, the tourism and recreation value of the kelp forest was valued at US$540,600 per hectare per year (Williams and Davies 2019), while in South Africa, the value of kelp in supporting ecotourism is estimated at US$113 million per year (Blamey and Bolton 2018).

Resources production: Kelp and other seaweeds are commercially important resources. They are important food sources and contribute to producing nutritional supplements, cosmetics, and pharmaceuticals. Seaweed is important in producing agricultural and aquaculture products, including fertilizer, livestock feed, and dried pellets for abalone feed.

Seaweed has have pharmaceutical applications, providing a sustainable resource for drug manufacturing (Pereira and Cotas 2024). In Chile, kelp harvesting has a present economic value of US$409.5 million, and the value of associated fisheries is US$82.2 million discounted over a 10-year period (Vásquez et al. 2014). In the United Kingdom, the value of kelp beds in provisioning fisheries is valued at US$275,000 per hectare per year and direct kelp harvesting generates US$1.3 million per hectare per year (Williams and Davies 2019). In South Africa, kelp harvesting is valued at US$0.9 million per year and the value of three key fisheries supported by kelp forests is nearly US$175 million per year (Blamey and Bolton 2018). Global estimates of the economic value of various kelp species across different regions suggest fisheries production values ranging from US$780–US$28,068 per hectare per year, and potential harvest values (based on variable harvest rates of 20 to 70 percent) of between US$4,420 and US$114,150 per hectare per year (Eger et al. 2023). This substantial variation in estimated value encourages a cautionary approach in estimating benefits and developing a business case that is site- and species-specific.

Biodiversity: Seaweed beds, particularly of large canopy-forming seaweeds, benefit biodiversity by providing three-dimensional habitat structure as well as protection and nutrition for many species. This leads to increased abundance and diversity of invertebrates, fish, mammals, and seabirds (Conservation South Africa 2024). Various studies in Australia have found over 350 species located on the holdfasts alone of *Ecklonia radiata*, commonly known as “golden kelp” (Anderson et al. 2005; Smith 1996). In the United Kingdom, kelp forests provide essential habitat for otters and nursery grounds for valuable commercial fish and shellfish species, including scallops, lobsters, and sea bass. The value in providing nursery habitats for commercial fish species is valued at US$0.95 million per hectare per year in West Sussex ports (Williams and Davies 2019).

Illustration inspired by the photo of kelp forests by Daderot on Flickr.

Carbon storage and sequestration: Seaweed is recognized as an important carbon sink that reduces atmospheric levels of carbon dioxide, and it can fix carbon at rates of between 1,000 and 3,400 grams per meter per year (United Nations Global Compact 2021). The dominant pathway is deep sea export, while some seaweed biomass feeds other marine species or is buried in coastal sediments. A significant proportion of seaweed biomass from wild and aquaculture sources is exported to open water by currents where it sinks to the deep sea (United Nations Global Compact 2021). As much as 90 percent of carbon sequestered is exported to the deep sea by seaweed species (Krause-Jensen and Duarte 2016), estimated at between 61 and 268 (average 173) megatons of carbon per year. Yet the ability of seaweed to sequester carbon is uncertain and consensus of its effectiveness remains poor. By some estimates, sequestration rates of kelp forests can range from 5 to 30 grams of carbon per square meter to the deep ocean every year (Eger et al. 2025). Globally, kelp forests could sequester 8.6 million metric tons (2.6–14.7 metric tons) of carbon every year, equating to approximately 32 million metric tons of CO_2 (Eger et al. 2025).

Water quality and biogeochemical services: Both wild seaweed beds and aquaculture provide nutrient cycling services (Forbes et al. 2022) and improve water quality by removing excess nutrients (United Nations Global Compact 2021). Seaweed can be effective in tackling eutrophication and reducing the instances of harmful algal blooms, which rely on excess nutrients (Jiang et al. 2020). In a 127,922-hectare study site in China, seaweed aquaculture was found to provide significant environmental benefits, including the removal of around 75,563 metric tons of nitrogen per year and 9,592 metric tons of phosphate per year from coastal waters. The provision of clean coastal waters was further supported by the annual prevention of approximately 29,313 metric tons of chemical fertilizers and 1,873 metric tons of pesticide when compared to the alternative of vegetable cultivation on land (Zheng et al. 2019). In Sussex in the United Kingdom, the water quality maintenance value of the kelp forest is valued at US$760,600 per hectare per year (Williams and Davies 2019). In South Africa, the nutrient cycling value of kelp is estimated at US$144 million per year (Blamey and Bolton 2018). The global value of kelp forests to remove nutrients is estimated at US$36,109 (*Ecklonia spp*.) to US$113,681 (*Laminaria/Saccharina spp.*) per hectare per year (Eger et al. 2023), where a small fraction of these combined estimates is carbon sequestration.

The multiple benefits of kelp and other seaweeds on a qualitative scale

Ucluelet, BC, Canada
Photo by Kieran_wood on Unsplash

COSTS

Implementation costs

Kelp forests support fisheries by providing habitat for commercially important species, enhance biodiversity, and contribute to carbon sequestration, all of which have direct and indirect economic value. However, restoring kelp ecosystems can be costly and time-consuming. Recovery periods may take years, depending on the extent of degradation and the restoration techniques employed. Restoration costs associated with seaweed often include performing a comprehensive feasibility study, running pilot studies, complying with licensing and permitting requirements, sourcing seeds or mature samples, and providing laboratory or aquaria space. Kelp forest restoration is in its infancy in comparison to the restoration of other habitats, and reporting outputs of active projects is important for refining the cost-effectiveness of restoration approaches.

In the Mediterranean, urchin removal and restoration by seeding was approximately US$62,000 per hectare (Medrano et al. 2020). The cheapest method of restoration is urchin culling by quicklime, estimated at US$1,500 per hectare, then manual removal at US$67,800 per hectare (in 2020 US dollars) (Eger et al. 2022b). Other restoration and adaptation measures are more costly: seeding was estimated at US$526,000 per hectare, transplanting at US$616,000 per hectare, and building artificial reefs at US$707,300 per hectare (Eger et al. 2022b).

Pilot study revegetation efforts of *Phyllospora comosa* in Sydney also estimated that scaling-up restoration efforts will cost around US$46,250 per hectare, including materials, transport, and personnel but excluding project management and monitoring, and excluding also the initial and ongoing scientific research required (Vergés et al. 2020).In contrast, large-scale government-level supported projects in Japan and the Republic of Korea (see FIRA 2019) have achieved successful restoration at a cost of approximately US$10,000 per hectare (Eger et al. 2022a), with reported survival rates of around 50 percent in the Republic of Korea (Eger et al. 2025).

Operations & maintenance costs

Operation and maintenance costs include the costs of a long-term monitoring program, which is critical for assessing a project's effectiveness and allowing for adaptive management. Monitoring protocols and costs may include surveys of the restoration site in addition to a healthy reference site and/or a barren control site that represents the pre-restoration conditions (Eger et al. 2022a). Citizen science monitoring programs can help reduce monitoring costs while also facilitating public engagement. Monitoring methods include in-water surveys, remote sensing, and on-water or coastal surveys. Maintenance costs of a restoration project may also include the periodic removal of grazers, area clean-up, and supplemental kelp transplants to ensure project success (Eger et al. 2024).

The costs of monitoring and maintenance of kelp forests are rarely reported. Layton et al. (2020) estimate that the ongoing project management and monitoring of Operation Crayweed sites in Sydney totaling six sites of 2 square meters each to be about US$18,500 per year

Other cost considerations

Access to or ownership of space in coastal and marine areas and seabeds is required for the conservation and restoration of seaweed. This space may be publicly or privately owned. The water and seabed surface areas required for seaweed conservation and/or restoration may be large, depending on objectives, which increases costs associated and makes engagement and collaboration with multiple landowners and stakeholders necessary. Land-related costs include land acquisition, land use fees (e.g., payment to landowners), and protection costs such as managing and controlling access. For example, Coleman et al. (2022) quantify lease rent in Maine, the United States, as US$100,000 per year for a baseline site of 405 hectares. Many countries do not yet have the mechanisms to lease seabed for restoration, highlighting governance challenges that must be addressed to scale seaweed restoration and conservation.

CAPEX: Implementation costs
OPEX: Operations and maintenance costs

GUIDELINES AND RESOURCES

The resources listed provide guidance for protecting, and restoring seaweed, supporting their assessment, planning, and implementation as nature-based solutions. They also include information on creating suitable conditions for seaweed, as well as guidance on monitoring approaches.

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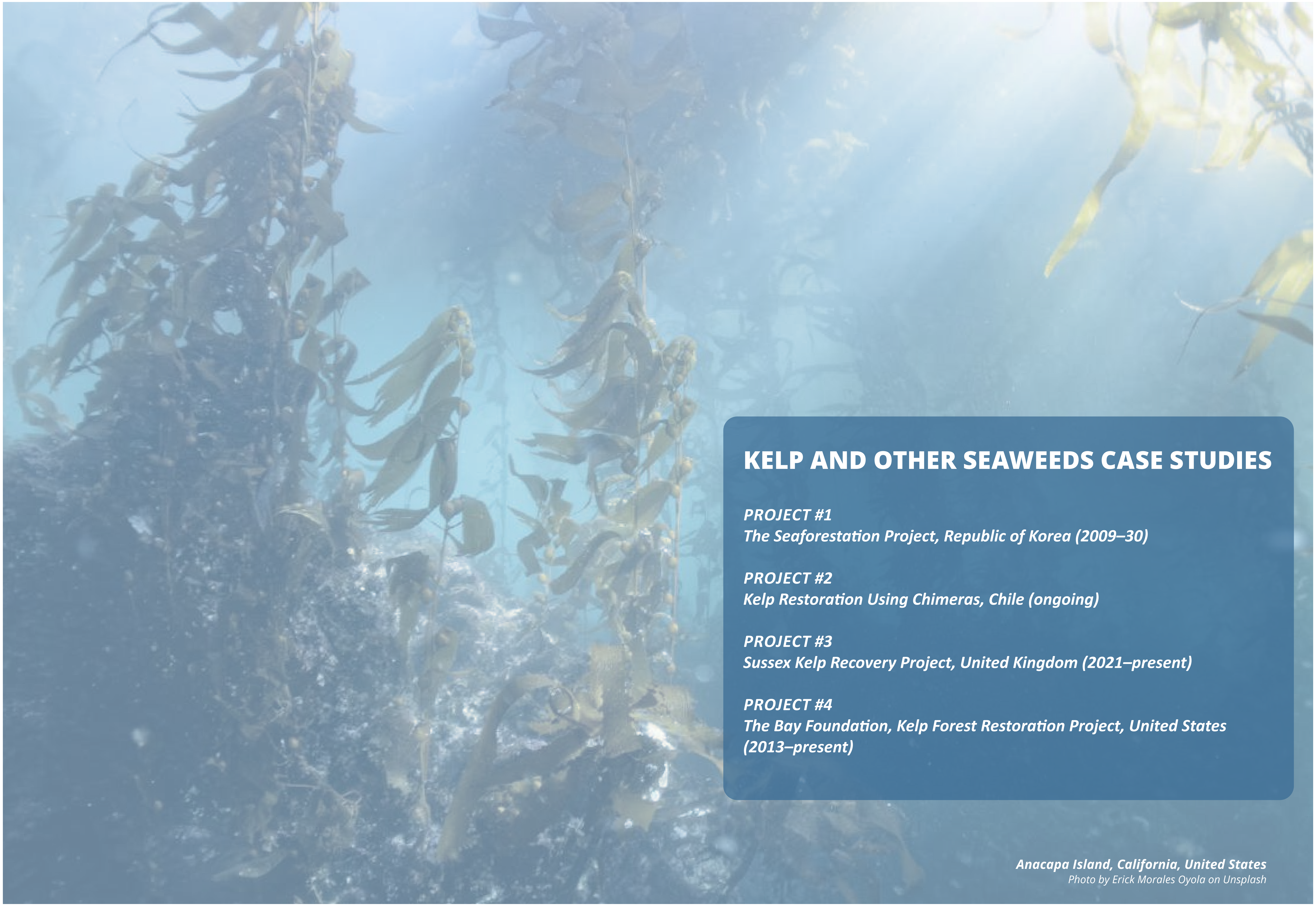
In addition, the Nature-Based Solutions Opportunity Scan (NBSOS) is a tool that helps identify NBS investment opportunities, providing information on NBS types, suitable locations, costs, and coastal protection benefits and co-benefits. It supports decision-makers in integrating NBS into planning, and investment strategies for both urban and coastal areas.



KELP AND OTHER SEAWEEDS CASE STUDIES

PROJECT #1
The Seaforestation Project, Republic of Korea (2009–30)

PROJECT #2
Kelp Restoration Using Chimeras, Chile (ongoing)

PROJECT #3
Sussex Kelp Recovery Project, United Kingdom (2021–present)

PROJECT #4
The Bay Foundation, Kelp Forest Restoration Project, United States (2013–present)

Anacapa Island, California, United States
Photo by Erick Morales Oyola on Unsplash

PROJECT #1
The Seaforestation Project, Republic of Korea (2009–30)

Photo by Ben Wicks on Unsplash.

Location

Republic of Korea

Approach

Monitoring and seaweed restoration

Size

50,000 hectares

Cost

US$29 million *(2019 value)*

Description

Seaweed abundance along the coastal waters of Korea has declined in recent decades as a result of climate change, sedimentation, and other threats. This has had serious ecosystem and economic impacts, impacting marine fisheries resources. In response, the Korea Fisheries Resources Agency has developed monitoring tools and restoration techniques. Actions have included the removal of grazing species, transplanting ropes with juvenile plants attached to artificial seaweed reefs, and anchoring bags containing mature seaweeds to the seabed to aid regeneration. Established in 2009, the project is running until 2030 and aims to restore a total of 50,000 hectares of kelp forests with an annual budget of US$29 million.

Benefits

- *The project has strengthened the cultural benefits of seaweed and is widely supported by the public through public events and thereby fostering social cohesion.*
- *Various seaweed species restored using artificial reefs on Jeju Island are estimated to sequester 11.01 – 26.42 metric tons of CO_2 per hectare.*
- *Furthermore, seaweed restoration contributes to sustainable aquaculture practices.*

Tourism and recreation | *Resource production* | *Carbon sequestration*

Challenges

- *Cloth transplanting ropes used in initial restoration attempts were mostly damaged or destroyed in instances of strong tides and waves.*
- *There was concern regarding the widespread use of artificial reefs. The development of restoration activities has since shifted to restoring kelp forests on existing rocky reefs.*

Lessons learned

- *Restoration projects showing the greatest success are those located near existing kelp forests. Successful growth of kelp at the restoration sites and production of sporelings in adjacent areas were achieved.*
- *The federal government–led project has benefitted greatly from collaboration with the aquaculture industry and local universities.*
- *Utilizing cultured stocks of kelp can lead to successful restoration while reducing pressure on wild stocks.*
- *A national framework for seaweed restoration connects multiple projects across Korea to share learnings and ensure consistency in evaluation.*

Source (references)

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PROJECT #2
Kelp Restoration Using Chimeras, Chile (ongoing)

Each row, left to right from top: Chimeric individuals of Lessonia spicata in the laboratory and installed in the field for intertidal restoration trials. (a) Details of holdfast from chimera. (b) Substrate with chimeras, one month after installation. Juveniles reached between 10-15 cm long. (c) Three months after substrate installation, with numerous chimeras reaching 25-30 cm in length. (d) Five months after installation, chimera formed an intertidal belt of juveniles (data obtained from FONDEF IDeA ID17I10080). Photos by Alejandra González. with associated captions from the Kelp Restoration Guidebook.
Source: Eger, A. M., Layton, C., McHugh, T. A, Gleason, M., and Eddy, N. 2022. Kelp Restoration Guidebook: Lessons Learned from Kelp Projects Around the World. The Nature Conservancy, Arlington, VA, USA. https://www.scienceforconservation.org/assets/downloads/TNC_Kelp_Guidebook_2022.pdf

Location

Various, Chile

Approach

Laboratory chimera trials and restoration

Size

Small-scale pilot study

Cost

US$355,118

Description

Kelp harvesting represents the main benthic fishery in Chile, where over 340,000 metric tons are harvested annually, providing 10 percent of the total global alginate/extracted raw material. Overexploitation and illegal harvesting have led to kelp forest declines and habitat fragmentation, impacting biodiversity and associated fisheries. To address this, the Chilean government has put in place extraction management measures and supports the restocking of kelp populations. Despite incentives, restocking uptake has been low and restoration activities have experienced limited success. The University of Chile is cultivating resilient multi-species individuals or "chimeras" of kelp to aid restocking, improve the effectiveness of planting efforts, and facilitate the restoration of rocky coastal ecosystems.

Benefits

- *Chimeras displayed approximately 5 times greater genetic diversity relative to homogeneous plants; hence showing an increase in biodiversity and greater resilience to stressors.*

Biodiversity enhancement

Challenges

- *Trials of planting substrate types have shown low success rates.*

Lessons learned

- *The pilot study results showed improved survivorship (1–3 times greater) and growth in chimeras than monospecific individuals.*
- *Plantings that took place in early spring led to the highest survival rates of Lessonia spp.*
- *Adhesive-back Velcro and AlgaeRibbon were the most effective planting substrates trialed, showing survivorship six months post-planting.*

Source (references)

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PROJECT #3
Sussex Kelp Recovery Project, United Kingdom (2021–present)

Photo by Our aims and highlights | Sussex Kelp Recovery Project.
Source: Sussex Wildlife Trust taken from Sussex Kelp Recovery Project: Rewilding the Sussex marine environment. https://www.rewildingbritain.org.uk/rewilding-projects/sussex-kelp-restoration-project

Location

West Sussex, United Kingdom

Approach

Protection and natural recovery

Size

304 square kilometers *of marine habitat protected under the Sussex Nearshore Trawling Byelaw*

Cost

Unreported.

Description

The Sussex Kelp Recovery Project (SKRP) was established to monitor and support the natural recovery of kelp forests along the West Sussex coastline. This followed the introduction of Sussex Nearshore Trawling Byelaw (2021) by Sussex Inshore Fisheries and Conservation Authority, which received strong support from a public campaign leading to a trawling ban across 304 square kilometers of sea to protect kelp beds and marine life. Unlike most kelp restoration initiatives that involve active planting, SKRP aims for a "rewilding" approach, monitoring natural recovery while assessing whether active restoration (such as seeding or planting) may be required in the future.

Benefits

- *Although significant kelp regrowth is yet to be observed, there are early signs of ecological recovery. These include increased algae cover and changes in marine species populations.*
- *The project is expected to lead to biodiversity and coastal resilience benefits.*
- *Fishers using static gear have reported increased job and income satisfaction following the trawling ban.*
- *The project has also boosted tourism, with local and international outreach through events like the Kelp Summit and educational programs in schools and universities.*

Biodiversity enhancement | *Carbon sequestration* | *Coastal erosion reduction*

Challenges

- *Kelp ecosystems can take years, if not decades, to fully recover.*
- *Marine ecosystems are inherently harder to study than terrestrial ones, leading to uncertainty in measuring outcomes such as carbon sequestration.*
- *Research on kelp habitats, especially in the English Channel, is limited compared to other regions such as the Pacific Coast of North America.*

Lessons learned

- *The project uses an adaptive, science-led approach, continually reassessing whether additional interventions like active planting are necessary. This approach allows for flexibility based on real-time data and environmental changes.*
- *Community engagement is central to success, promoting long-term support for marine conservation.*

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PROJECT #4
The Bay Foundation, Kelp Forest Restoration Project
United States (2013–present)

Kelp Forest at low tide, Crescent Bay Beach (USA), where the floating kelp canopy reflects ongoing restoration and regeneration of coastal ecosystems. Photo by Shane Stagner on Unsplash.

Location

Palos Verdes Peninsula, California, United States

Approach

Kelp restoration

Size

***~60 acres** of kelp forest restored*

Cost

Unreported.

Description

The Kelp Forest Restoration Project aims to restore degraded kelp forests off the Palos Verdes Peninsula, which have suffered an 80 percent loss in canopy cover. By reducing the sea urchin population, the project seeks to encourage the natural regrowth of giant kelp (Macrocystis pyrifera), creating a more resilient ecosystem. In addition to the physical restoration efforts, The Bay Foundation's Kelp Forest Hydrodynamics Study investigates how restored kelp forests influence coastal processes such as wave attenuation, sediment movement, and water chemistry.

Benefits

- *Vital marine habitats have been restored for over 700 species, including fish, invertebrates and marine mammals.*
- *The resilience of coastal ecosystems increased, potentially protecting against coastal erosion and wave damage.*
- *The density of purple sea urchins has dropped from 30 per square meter to ~2 per square meter, improving the health and size of remaining urchins.*
- *Economic benefits from healthier sea urchins (increased gonad weight by 168 percent) are seen for fisheries. Over eight commercial urchin fishers have been employed.*
- *The project provides a sustainable tourism attraction for SCUBA divers.*

Biodiversity enhancement | *Carbon sequestration* | *Coastal erosion reduction* | *Tourism and recreation*

Challenges

- *There is high variability in kelp restoration success as a result of local oceanographic conditions, weather, and topography.*
- *Continuous urchin culling is needed to maintain appropriate population levels and prevent the return of areas barren of kelp.*
- *Monitoring biological, chemical, and physical parameters to understand the full impact of restored kelp forests is very complex.*

Lessons learned

- *Collaboration with local fishers and researchers is essential for success.*
- *Active management of urchin populations accelerates the restoration process.*
- *Site-specific conditions must be considered in the restoration strategy for optimal results.*
- *Ongoing monitoring of hydrodynamic processes helps inform the broader impact of restoration on coastal resilience.*

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GLOSSARY

ACTIVE COASTAL ZONE refers to the cross-shore region of the beach over which sediment is actively exchanged under hydrodynamic forcing (e.g., waves), extending from the landward limit of sediment mobility (e.g., dunes) to the offshore limit (closure depth).

CHENIERS refer to ridges composed of coarse-grained sediments often lying on top of muddy sediment, detached from the shoreline by a mudflat (Otvos and Price 1979; Tas 2002).

CLOSURE DEPTH refers to "the most landward depth seaward of which there is no significant change in bottom elevation and no significant net sediment transport between the nearshore and the offshore for a given or characteristic time interval." (Wise 1998). It is the seaward boundary of the active coastal zone.

CREST FREEBOARD refers to the difference between the crest elevation height of a coastal defense structure and the water level (van der Meer et al. 2018). The crest freeboard limits overflow and overtopping.

COASTAL PROFILE refers to a cross-section taken perpendicular to the shoreline.

GRAY (OR HARD) INFRASTRUCTURE refers to built structures, such as seawalls, breakwaters, and embankments.

NATURE-BASED SOLUTIONS (NBS) is an umbrella term referring to "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (UNEP 2022).

NBS FAMILIES (or typologies) are groupings of nature-based solutions based on the coastal ecosystem type.

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