Tides of change: greening the gray toward coastal resilience

By William Nardin, Julia C. Mullarney, Pieter Rauwoens and Davide Vettori

Increasing climate-driven threats to coastlines are necessitating a new approach to coastal protection. The use of coastal nature-based solutions offers a timely and transformative response, harnessing the resilience of ecosystems to protect human settlements, economies, and biodiversity, and recognizing the intricate relationships between land, sea, and human well-being. Due to a lack of empirical evidence and societal resistance, this approach is yet to be fully embraced in coastal engineering. Through close collaborations with stakeholders, long-term monitoring, and data sharing, nature-based solutions can provide a crucial framework for mitigating climate risks with a sustainable and cost-effective alternative to hard engineering.

Exploring Coastal Nature-based Solutions

Coasts worldwide are under increasing physical and ecological pressures due to the accelerating impacts of climate change, including sea level rise (SLR), and coastal erosion. In the European Union alone, these challenges result in an estimated €350 billion in annual damages, highlighting the urgent need for effective solutions. Traditional gray infrastructure has long been the primary response to these threats. While these solutions effectively provide immediate protection against erosion and flooding, these approaches come with long-term environmental costs, such as habitat fragmentation or destruction, and high maintenance costs. Using habitat-forming species such as seagrass, salt marshes, mangroves, or marram grass, it is possible to provide coastal protection, preserve biodiversity, and contribute to a more sustainable, resilient blue economy. This approach, termed 'Nature-based Solution' (NbS), integrates the natural and built environments, leveraging ecosystems' protective and restorative powers to create resilient coastal communities. Depending on the setting, NbS can be implemented as a new natural system, or integrated into existing gray infrastructure in a hybrid configuration[5].

Lessons learned in Coastal NbS implementation

Seagrass meadows

Seagrasses are marine plants that form dense meadows in shallow waters across the intertidal and subtidal zones these species are present on many coastlines and play an invaluable part in providing ecosystem services. Seagrasses are very efficient at sequestering carbon and are estimated to bury organic carbon at a global rate comparable to that of all terrestrial forests combined[1]. Moreover, seagrass ecosystems enhance marine biodiversity through the provision of habitat for a large variety of marine species, from sea turtles to seahorses. From a physical point of view, seagrass meadows can contribute to coastal protection by damping waves and stabilizing sediments. In the last century, more than 30% of seagrass areas have been lost due to pollution, wasting disease, and human activities. To recover lost meadows, since 2000 many initiatives have been undertaken, including in Chesapeake Bay in the USA, and off the coasts of Bergeggi (Italy), in Holyhead Bay (Wales), and the Firth of Forth (Scotland) in Europe. Seagrasses are particularly sensitive to abiotic and biotic stressors, so pre- and post-restoration monitoring represents a crucial part of the process.

Biogenic reefs

Biogenic reefs, formed by living organisms like corals and mollusks, serve as effective nature-based solutions by enhancing coastal protection, promoting biodiversity, and mitigating the impacts of climate change. As an example, Chesapeake Bay is the largest estuary in the USA, and the relative SLR is rapid with impacts especially pronounced along the low-lying Eastern Shore. Protecting the local communities from increased inunda-

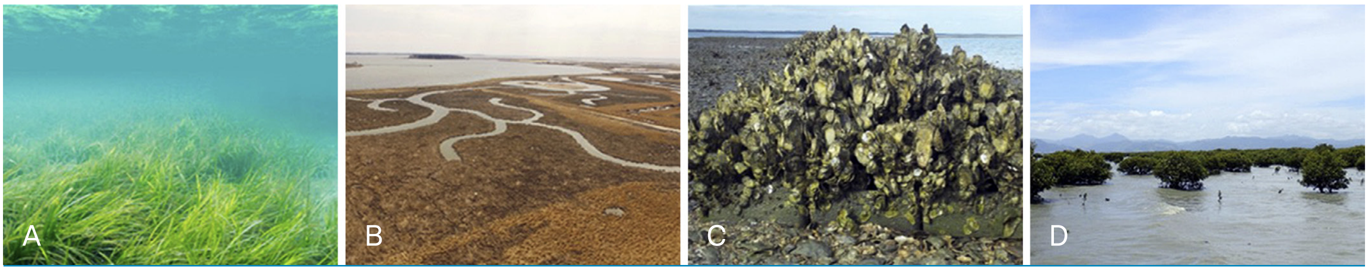

Figure 1 | Examples of ecosystems used as NbS in various implementations: A) a natural seagrass meadow; B) an example of a restored wetland at Poplar Island (Maryland, USA) in Chesapeake Bay; C) an oyster castle within a restored oyster reef, and D) a fringing mangrove forest.

tion and shoreline erosion requires repair of aging infrastructure, such as breakwaters. Consequently, there are growing calls for NbS to not only be the basis of shoreline armoring projects in the future, but also to improve the performance of existing infrastructure. Oyster reefs have gained attention recently, as these ecosystems create a complex habitat that attenuates wave energy and can fortify coastlines. These rough structures can be used in high-energy environments, in which other techniques may be ineffective. Moreover, the biogenic nature of reefs allows for accretion and keeping pace with SLR. Optimizing oyster integration with grey infrastructure requires balancing both biological and physical constraints. While most research has focused on oysters, interest is spreading to other bio-builder species or structures, such as aquaculture mussel lines and reefs built by sand mason worms.

Salt marshes

Restored salt marshes are an example of NbS aimed at addressing environmental challenges, such as climate change, biodiversity loss, and coastal flooding. Salt marshes act as natural buffers, absorbing excess nutrients and pollutants from runoff, while their dense vegetation stabilizes shorelines, protecting coastal communities from storm surges and rising sea levels. These ecosystems also offer a habitat for various species, supporting biodiversity and helping to maintain ecological balance.

An example of a study for coastal wetland restoration is the Paul S. Sarbanes Ecosystem Restoration Project at Poplar Island in Chesapeake Bay (Figure 1). This low-energy tidal marsh is a demonstration site, where scientists, practitioners, and agencies work together to study how the interactions between tides, channel morphology, and vegetation affect sediment dynamics. Poplar Island is an active restoration site, in which fine grained material dredged from navigation channels in the upper Chesapeake Bay is being used to restore remote tidal marsh habitat toward the middle bay.

Mangrove forests

Mangroves (salt-tolerant trees) are one of the key species for use as NbS in tropical and subtropical areas. While different species are characterized by a wide variety of geometries (e.g heights, foliage styles, root structures), mangrove forests have nonetheless demonstrated the ability to attenuate swell and infragravity waves, in addition to long waves such as tsunamis and storm surges. However, the extent of the energy dissipation depends on the species and forest settings. For example, wide forests are needed to reduce long-wave heights, and the presence of channels can weaken the energy-dampening effects. Moreover, these ecosystems also can trap and prevent the resuspension of sediment, thus allowing land elevations to keep pace with SLR in some locations. Mangrove coverage is declining worldwide owing to resource pressures (e.g. conversion to aquaculture ponds), threatening both biodiversity and protective capabilities. To restore systems, pioneer species first need to be established, and to be provided with 'windows of opportunity' to establish and expand. Hybrid green/gray systems may offer a solution, whereby small shrubs are protected by gray infrastructure to allow initial establishment and growth. Limited long-term studies examining the success of replanting mangroves exist; however, one such recent case study from Bangladesh found stabilization of lands (with an estimated value of ~18 billion USD) following mangrove planting[2].

Coastal Dune systems

On the most upward part of the sandy coastal zone, natural dunes emerge, forming a buffer of sand against storm erosion. These ecosystems are shaped by the complex interplay between aeolian sand transport and deposition, and vegetation growth. In many places, dune habitat has deteriorated as a result of management activities. These actions have resulted in fully fixated static dunes, or even the complete disappearance of dunes through replacement with sea walls and a built environment. However, the absence of a natural ecosystem has reduced natural seasonal fluctuations in sand transport and led to a transition to an erosive coastline state. Consequently, much recent attention has focussed on re-initiating natural dynamics for example to remobilize fixed dunes by digging notches to allow transport of sand again. A recent technique has involved dunes being built in front of engineered coastlines. This so-called dune-in-front-of-a-dyke approach is seen as a valid alternative to typical hard-engineered structures to cope with increased sea levels and storminess. Examples are Prins Hendrik Zand Dijk (Texel, Netherlands), Hondsbossche Duinen (Hondsbossche-Pettemer, Netherlands), Raversijde (Ostend, Belgium) and Oosteroever (Ostend, Belgium)[4]. In the latter scenario, marram grass was planted in front of an existing dyke, firstly to prevent nuisance by sand transport blocking roads and rail infrastructure, but secondly to explore the efficacy of dunes as NbS to increase resilience and cope with SLR. An intensive monitoring program already reveals the capacity of eco-engineering species to capture sand and build a natural defense against coastal flooding[4].

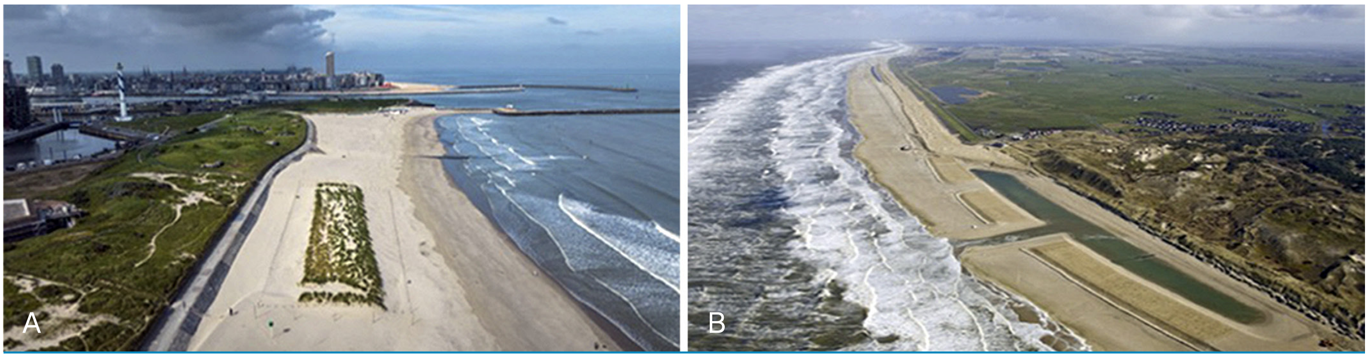

Figure 2 | Successful dune implementation projects for coastal safety instead of hard-engineered measures at (A) Ostend (BE) and (B) Hondsbossche-Pettemer (NL).

Challenges and opportunities in coastal NbS implementation

Historically, coastal engineering has been dominated by hard-built structures such as sea walls, breakwaters, and groins. NbS offers a more sustainable approach than traditional gray infrastructure as it can adapt to changing environmental conditions. For instance, wetlands and dunes can naturally accrete or migrate horizontally in cases where sufficient accommodation space exists. Further, NbS offers ecosystem services, such as enhancing carbon sequestration and fostering biodiversity.

So far coastal NbS have not been implemented extensively because of a lack of quantifiable performance in the medium-long run and because of the interdisciplinary and public perception challenges they involve. The data gap makes it difficult for engineers and policymakers to confidently recommend NbS for coastal protection at large scales. In addition, coastal ecosystems show extreme variability across the globe due to a combination of different climates and soil types (e.g. mangroves only live in tropical areas with muddy/sandy substrates), therefore a wide range of solutions may be used, making it harder to have references for each specific case.

A key challenge of implementing NbS in coastal areas is the need for effective collaboration between ecology and engineering. Engineers tend to focus on the technical and structural aspects (e.g. to prioritize immediate protection against waves), while ecologists focus on the biological and environmental elements (e.g. to ensure biodiversity is preserved). However, both perspectives are essential to creating effective and sustainable NbS as the optimal solution likely involves finding a compromise between the two viewpoints. Another key challenge is the approval of NbS from local communities, which may perceive NbS as too experimental, or less effective compared to traditional gray infrastructure. For example, landowners may view the restoration of natural shorelines as a threat to the aesthetics or function of their property, particularly if this restoration means sacrificing areas to flooding or plant growth.

Given the lack of long-term performance data for NbS, increasing efforts to monitor how these solutions evolve is crucial. To this end, collaboration and transparency across sectors are key to openly sharing not just the successes but also the failures of nature-based projects. Further, societal aspects must be accounted for in the design process. With increasing awareness of climate change and its impact on coastal zones, there is an opportunity to shift public perception and promote the co-benefits of NbS. In this respect, Indigenous communities represent a model of how we can employ a holistic, long-term perspective on the environment by complementing traditional knowledge with modern scientific understanding. Collaboration and working with indigenous communities mean respecting different cultural perspectives, governance structures, and land rights, to co-create culturally appropriate solutions that benefit both ecological health and social welfare, in addition to fostering a sense of ownership and stewardship among local populations[3].

In conclusion, coastal NbS offers promising alternatives to gray infrastructure in the face of climate change. However, they come with their own set of challenges, including data limitations, multidisciplinary collaboration, and societal and ecological complexities. By promoting better monitoring, sharing of both successes and failures, and working collaboratively with various stakeholders, coastal engineering can evolve toward more adaptive, sustainable, and resilient practices for coastal risk management.

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