

Policy Brief

Rewilded coasts

Mainstreaming biodiversity in Nature-based Solutions for coastal management.



DuneFront



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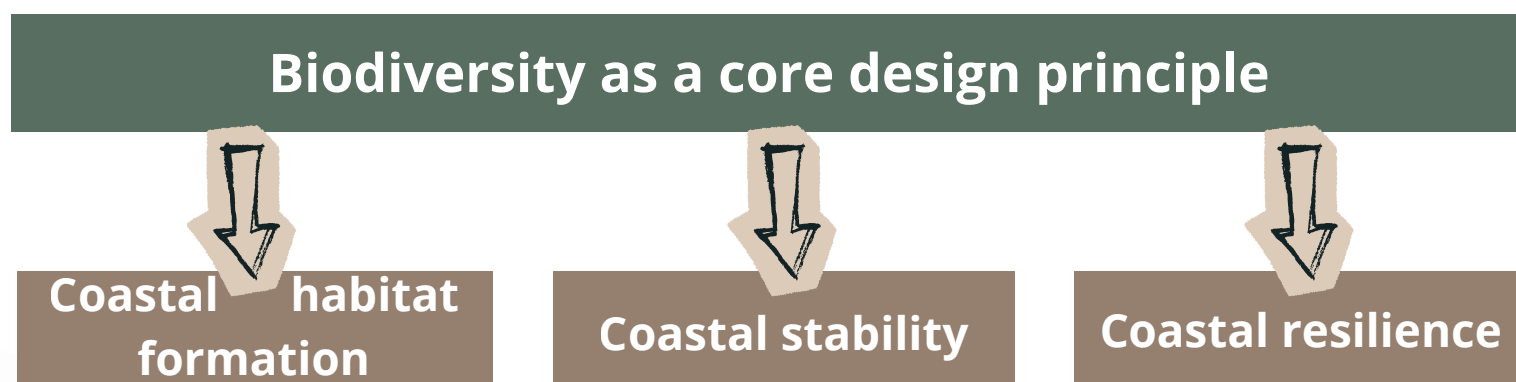


Executive Summary

Coastal management strategies require urgent transformation as traditional hard infrastructure proves ecologically harmful and increasingly inadequate to deliver sustainable solutions under accelerating climate change. Sandy coastlines are among the world's most economically valuable and densely populated regions and experience severe degradation due to urbanization, hard structures, and climate-driven pressures, eroding their natural adaptive capacity.

Nature-based Solutions (NbS) offer a promising pathway to climate-resilient, multifunctional coastal landscapes. However, their potential is often undermined by limited process understanding, unilateral technical designs, and widespread confusion between true NbS and superficial nature-inclusive design (NID). Current practices frequently treat vegetation as aesthetic rather than as a functional driver of dynamic ecological processes, thereby limiting adaptive capacity and long-term resilience.

This policy paper advocates for mainstreaming biodiversity as a core design principle in coastal NbS. Biodiversity-driven dynamics through bio-geomorphological feedbacks and species-specific engineering traits are essential for creating regenerative, self-organizing systems that safeguard coastal communities while enhancing ecosystem integrity. We present evidence that biodiversity underpins dune formation, stability, and resilience, and outline a framework for biodiversity-led design, spatial planning, integrated coastal zone management and multilateral governance. These recommendations align with EU policy frameworks, including the Nature Restoration Law, the EU Biodiversity Strategy 2030, and the Floods Directive, and aim to enable coastal landscapes that adapt to climate uncertainty while supporting socio-economic objectives.



Key highlights



1 COASTAL MANAGEMENT STRATEGIES NEED TRANSFORMATION

Sandy coastlines, among the world's most economically valuable and densely populated regions, are degrading rapidly due to urbanization, coastal squeeze, and rising seas. Under climate change, traditional hard infrastructure (dikes, seawalls, and groins) has proven ecologically harmful and increasingly inadequate to deliver sustainable management solutions.

Without effective adaptation, up to half of the world's sandy beaches could disappear by 2100, exposing hundreds of millions of people to flooding and severe economic losses.

2 PRIORITISE NATURE-BASED SOLUTIONS OVER HARD DEFENCES

Nature-based Solutions offer a promising alternative, creating multifunctional, climate-resilient coastal landscapes that combine protection, biodiversity, and socio-economic benefits.

However, their full potential remains unrealised when they are implemented as unilateral technical (static) interventions rather than as dynamic systems capable of adapting to changing coastal conditions



3 DISTINGUISH TRUE NbS FROM NATURE-INCLUSIVE DESIGN

Widespread confusion between true NbS and superficial nature-inclusive design (NID) undermines overall credibility and resilience potentials.

Many current approaches treat vegetation as an aesthetic feature rather than as a functional component of dynamic ecological systems. This limits adaptive capacity and weakens long-term coastal protection



BIODIVERSITY IS THE CORNERSTONE OF EFFECTIVE NbS

Biodiversity influences dune formation, their stability, and ability to recover after storms through the functional roles of different plant species and their interactions with dynamic coastal processes. When these processes are disrupted, dunes lose resilience and collapse.

Evidence shows that vegetation can reduce dune erosion by 30–40%, while species such as marram grass and sand couch create contrasting dune morphologies with major implications for storm protection. Climate-driven range shifts and non-native species further reinforce the need for adaptive, biodiversity-led design.

4

POLICY ALIGNMENT AND GOVERNANCE ARE CRITICAL.

Effective coastal NbS require alignment with EU policy frameworks, including the Nature Restoration Law, EU Biodiversity Strategy 2030, and the Floods Directive.

Coastal NbS should be understood as a continuum, from static, minimally biodiverse designs toward dynamic, regenerative systems that embed ecological processes. This shift requires adaptive governance, continuous monitoring, integrated and multilateral standards that prioritize functional performance over rigid species lists

ENABLE BIODIVERSITY-LED NbS THROUGH DESIGN, PLANNING, AND MANAGEMENT.

Actionable steps to enable biodiversity-centered coastal management include restoring natural dynamics through design principles that prioritize functional species traits and anticipate disturbance cycles; implementing coastal zone management to prevent coastal squeeze and maintain ecological connectivity for dune dynamics and species movement; integrating adaptive management into governance and permitting frameworks; engaging stakeholders to balance safety, recreation, and biodiversity through transparent trade-offs; and investing in research and innovation such as predictive models (e.g., Digital Twins), long-term monitoring, and trait-based restoration



SHIFT TOWARD REGENERATIVE, SELF-ORGANISING COASTAL SYSTEMS.

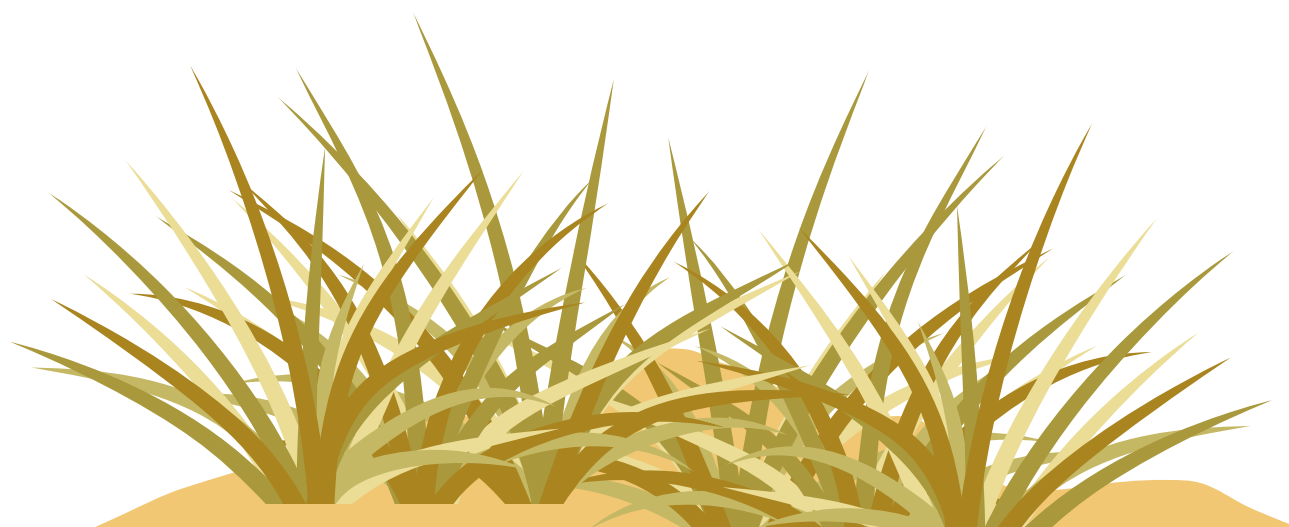
Resilient coastal zone management must move beyond unilateral technical designs toward biodiversity-led, regenerative NbS.

Embedding ecological processes into planning and governance enables dynamic, self-organizing systems that safeguard coastal communities, enhance ecosystem integrity, and deliver co-benefits for climate resilience and socio-economic well-being



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List of definitions and abbreviations

Term	Explanation
Adaptive Capacity	A coastal system's ability to adjust and recover under changing climate conditions
Bio-geomorphological Feedbacks	In the case of coastal environment, the interactions between vegetation, sand movement, and hydrodynamics.
Dune-Dike Hybrid Systems	A type of coastal NbS integrating both soft (nature) and hard (traditional) infrastructure. A blue-grey infrastructure.
Hard Coastal Protection Structures	Traditional grey infrastructure for coastal protection that includes dikes, seawalls, revetments and groins.
Nature-based Solutions (NbS) for coastal protection	Interventions inspired and supported by nature that use <i>natural processes</i> to reduce coastal risks <i>while delivering co-benefits</i> for biodiversity, climate resilience, and socio-economic value.
Nature-Inclusive Design (NID)	Design that adds natural elements to hard infrastructure without restoring dynamic ecological processes.
Regime Shift	A sudden, lasting change in ecosystem structure and function after crossing critical thresholds.
Resilience	A coastal system's ability to withstand, absorb, and recover from storms, flooding, sea-level rise, and other disturbances <i>while maintaining its essential functions</i> .



1 | Setting the scene

1.1 Sandy coasts under pressure

Sandy coasts are among the world's most valuable and densely inhabited regions, with population densities of ± 80 people per square kilometer, roughly twice the global average (Burke et al., 2001). These areas host major infrastructure, transport routes, and tourism economies, making them critical contributors to national and regional prosperity. Beyond their economic importance, sandy beaches and dunes provide essential ecosystem services including **coastal management against flooding, storm-damage reduction, recreational opportunities, and biodiversity support**.

Despite their **economic-, social and ecological values**, these ecosystems are under accelerating pressure, leading to their systematic degradation reaching critical proportions. Model-based estimates indicate that a substantial proportion of sandy beaches may retreat significantly by 2100 under current emission scenarios (Vousdoukas et al., 2020; see also Cooper et al. 2020) Under high-emission scenarios (SSP5-8.5), up to 26% of the world's sandy coastline ($\pm 52,100$ km) may experience severe beach loss by 2100, with high-income regions particularly affected (Vousdoukas et al., 2020). Without effective adaptation measures, the number of people exposed to coastal flooding could increase from about 250 million today to around 630 million by 2100, and global economic losses could rise from 0.008% to more than 5% of GDP under extreme sea-level rise scenarios (Vousdoukas et al., 2017; Lomborg, 2020).

1.2 Urbanisation and coastal squeeze

Today, much of the natural dune landscape has been urbanized or replaced by **hard coastal protection structures** such as dikes, seawalls, revetments, groins, and embankments. **To maintain their protective function, dunes rely on sediment transport, landward migration, and ecological succession**. In many urbanized areas, hard infrastructure blocks this movement, causing **coastal squeeze** and preventing dunes from adapting to changing climate conditions.

Globally, one third of sandy shorelines (33%) are already hardened by human infrastructure, limiting sediment movement and undermining its natural **resilience** (Lansu et al., 2024). This fundamentally compromises their **actual adaptive capacity** (their ability to adjust and recover under changing climate conditions) and reduces their natural ability to respond to storms and sea-level rise. Sandy shorelines in urban contexts also face added pressures: **invasive species** often establish more easily, and heavy recreational use alters vegetation and sand dynamics. Evidence-based thresholds for these pressures and their contribution to diminished resilience remain poorly defined.

1.3 Nature-based solutions for coastal protection

Nature-based solutions utilise natural processes and ecosystems to address societal challenges such as climate adaptation and coastal flood risk. The European Commission considers NbS as actions "inspired and supported by nature", that are cost-effective, provide environmental, social and economic benefits and help build resilience (European Commission, 2024).

In practice, this means introducing or restoring natural features and processes in landscapes and seascapes through resource-efficient, and locally tailored interventions. In coastal settings, NbS encompass systems such as vegetated dunes, hybrid dune-dike structures, and other interventions that rely on natural dynamics to maintain or strengthen protective functions against flooding and storm impacts.

1.4 Situating NbS within EU policy frameworks

Across EU policy, NbS are embedded in major frameworks including the **EU Biodiversity Strategy for 2030**, the **Nature Restoration Law**, the **Birds and Habitats directives**, and the **Marine Strategy Framework Directive**. These policy instruments collectively promote infrastructure that is multifunctional, resilient, and enhances biodiversity. Maintaining and restoring the resilience of sandy coasts is therefore not only an environmental priority along these EU directives, but also an explicit requirement for fulfilling the objectives of the **EU Floods Directive**, which mandates risk reduction across Member States.

1.5 Misuse and misunderstandings of coastal NbS

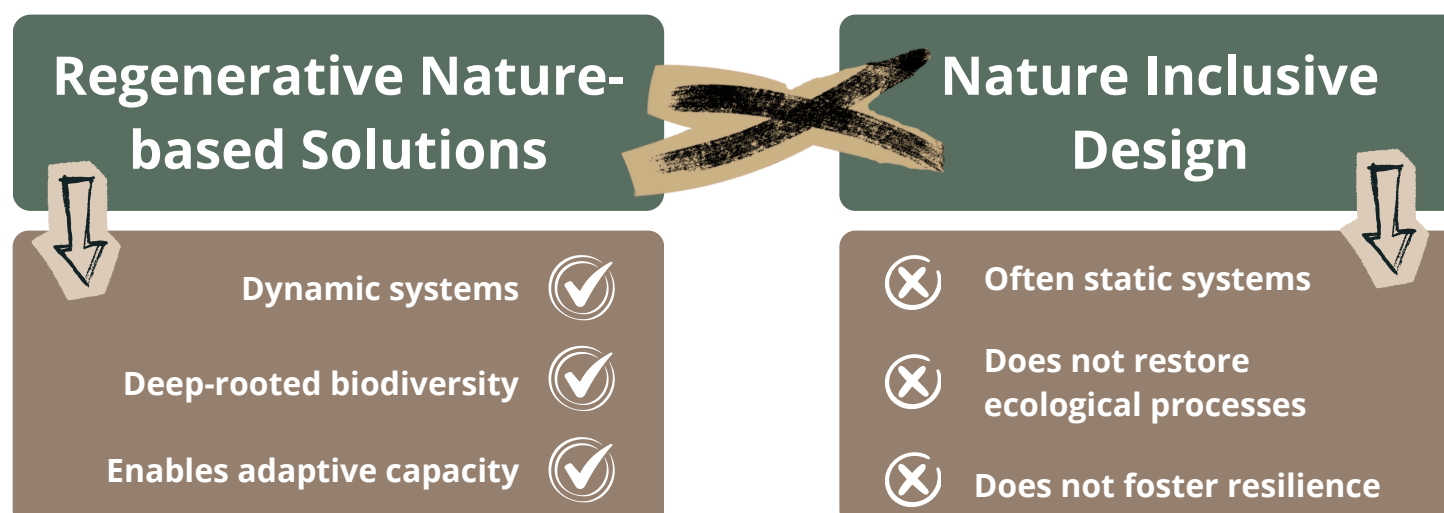
Many projects labelled as "Nature-based Solutions" do not function as true NbS because they misunderstand or oversimplify how nature itself contributes to coastal protection. In practice, vegetation within NbS for coastal protection is often treated as aesthetic planting rather than as part of a functional system.

A related misconception arises in **Nature-Inclusive Design (NID)**, where green elements are added to **hard coastal protection structures** without reactivating the ecological processes that create resilience. While NID represents an improvement over hard coastal protection structures, unilateral designs such as fixed dune shapes or sand drift dikes often fail because they prevent natural dynamic feedbacks between wind, sand, and vegetation, which are essential for dunes to adjust and recover during storms and floods.

Dune-Dike hybrid NbS systems can resemble protected dune habitats in appearance, yet may lack the natural species diversity, ecological processes, and successional dynamics that underpin its functional resilience. Such systems may technically comply with the species-lists in the **Annex I Habitat Criteria** but still fail to deliver the functional processes required for **self-organization** and **long-term adaptation**. **Habitat replication is not the same as restoring ecological processes.** Restoration projects often prioritise rapid stabilisation over long-term resilience, introducing species without consideration for their functional traits or adaptability under changing climate conditions.

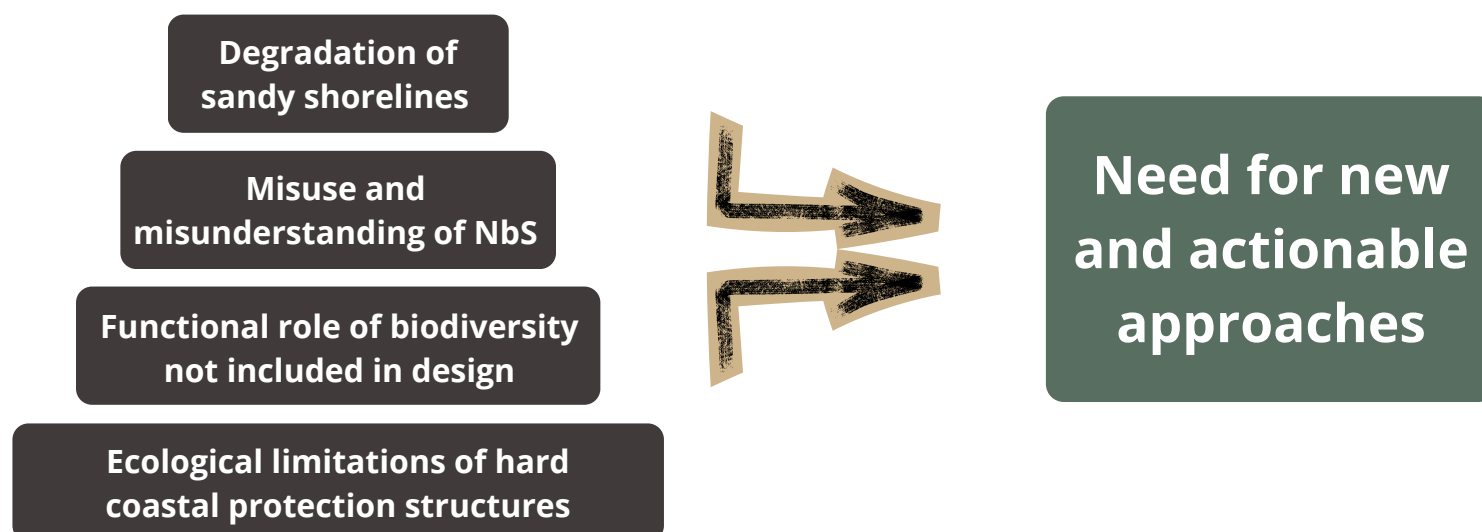
Effective **NbS for coastal protection** requires native species with proven dune-building capacity (e.g., sand-trapping ability, robust root systems) and must anticipate natural successional pathways to maintain protective functions over time. Importantly, NbS may be particularly relevant in degraded coastal ecosystems, where targeted interventions can impose a positive regime shift that would otherwise be difficult to achieve under the current conditions.

A critical distinction therefore exists between regenerative NbS for coastal protection, which restore or enhance ecological processes, and NID, where biodiversity is added superficially without enabling adaptive capacity. **Only the former can deliver the long-term resilience envisioned in EU policy.**



1.6 Why it matters

The functional role of **biodiversity** in dune-based coastal management remains **insufficiently integrated into planning and decision-making** towards a more resilient coastal zone management. When space constraints (e.g. due to coastal squeeze), connectivity, human pressures, or invasive species are not addressed, biodiversity cannot perform its engineering role of trapping sand, stabilizing dunes, and regenerating after storm events. The accelerating degradation of sandy coastlines worldwide, combined with the ecological limitations of hard coastal protection structures, and the widespread misuse or misunderstanding of NbS, underscores the need for new approaches.



This policy paper examines how **biodiversity forms a fundamental cornerstone for regenerative system design, enabling resilient and multifunctional landscapes that support ecological integrity and human well-being.** It argues that many current NID and NbS approaches for coastal protection, while progressive, are insufficient in the face of climate change, biodiversity loss, and socio-economic pressures. This policy paper calls for a shift toward biodiversity-led design **frameworks that move beyond inclusion and towards regeneration.** Biodiversity is framed not as a constraint but as a strategic asset that can drive innovation in spatial planning, infrastructure, and governance and support cross-sector collaboration to integrate ecological principles - next to technical, economic and social aspects - into more sustainable policy and management practices. into policy and practice.

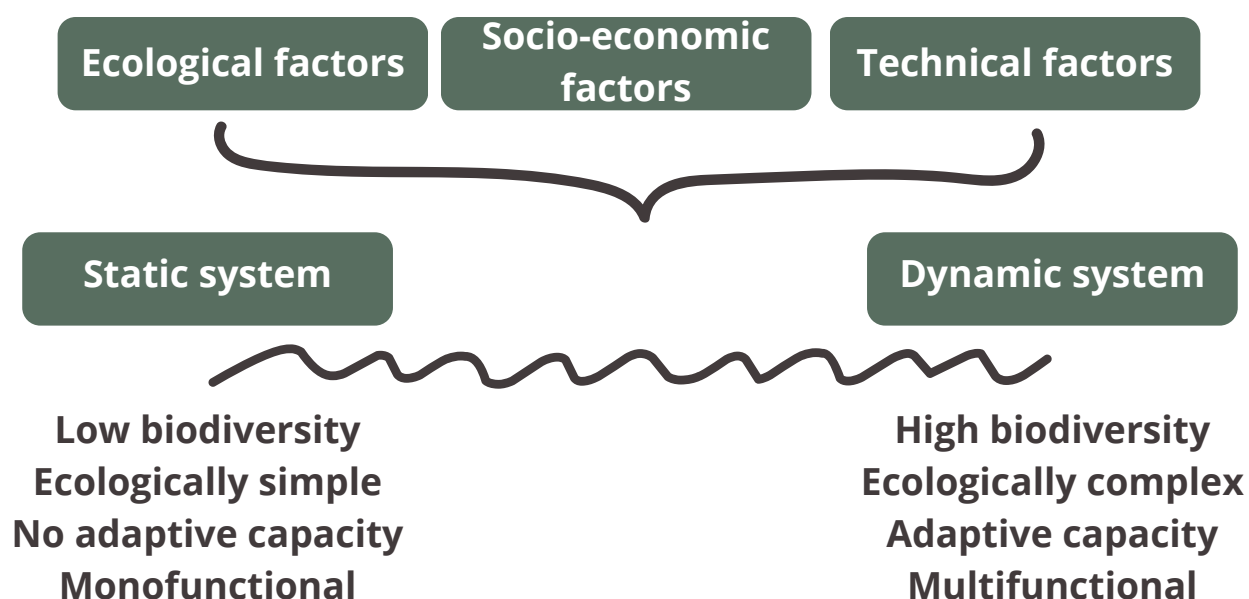
Guiding question: How can biodiversity-led, regenerative NbS be effectively integrated into coastal management to ensure long-term adaptive capacity under climate change?



2 | Policy Recommendations

2.1 Policy options: From static to dynamic coastal protection.

Coastal NbS management strategies can be positioned along a continuum from static, minimally biodiverse designs to fully dynamic, biodiversity-driven systems. This spectrum reflects increasing ecological complexity, adaptive capacity, and multifunctionality. **Across all approaches, smart design must integrate ecological, socio-economic and technical dimensions.**



For example, introducing non-native species for rapid stabilisation may undermine native biodiversity, while large-scale sand nourishments can disturb benthic ecosystems and affect water quality. Balancing such trade-offs requires integrated planning that prioritises native species, maintains ecological connectivity, optimizes technical engineering, develops operational efficiency and aligns coastal protection goals with biodiversity outcomes. When designed thoughtfully, **NbS can deliver co-benefits** for coastal protection, recreation, and biodiversity as an economically valuable solution, but they demand an active adaptive multilateral management but they demand **adaptive management and stakeholder engagement** to minimize unintended impacts (Gutierrez et al., 2025).

2.2 Actionable Recommendations

To transition from static, nature-inclusive designs toward dynamic, biodiversity-driven coastal NbS we propose the following recommendations:

1. Design principles

Designing effective coastal NbS requires **embracing the natural dynamism of coastal systems**. This means designing interventions that restore natural ecological processes rather than imposing fixed, static forms. Bio-geomorphological feedbacks, the interactions between vegetation, sand movement, and hydrodynamics, should be imbedded in every stage of design.

Species selection must focus on functional traits that enhance dune building and climate resilience. Anticipating storm and overwash scenarios allows such events to become opportunities for system renewal rather than system failures. This implies that traditional evaluations based solely on species counts must be abandoned, and that **blue-grey rating systems and life-cycle analyses should integrate functional, process-based ecological assessments** rather than static biodiversity metrics.

Effective coastal resilience requires **sufficient space**. Without available space, dunes cannot migrate landward or maintain sand exchange under rising seas.

Strategic spatial planning should consider and prioritize measures to prevent coastal squeeze. Beyond physical space, both cross- and alongshore ecological **connectivity** is essential: corridors that enable species movement and gene flow make long-term adaptation and post-storm recovery possible. These measures ensure that coastal NbS function as components of a larger resilient coastal zone network.

2. Spatial planning

3. Governance and policy integration

Policy frameworks must evolve **from static compliance toward adaptive governance**. Aligning NbS with the EU Nature Restoration Law requires functional compliance that **restores ecological processes and connectivity**, not just meeting species lists. Regulatory instruments should mandate adaptive management, continuous monitoring, and flexible responses to ecological thresholds.

Embedding these principles into governance will align EU Floods Directive safety requirements with the EU Biodiversity Strategy for 2030, ensuring that NbS for coastal protection remain robust and responsive under changing climate conditions.

Coastal landscapes are multifunctional spaces where safety, recreation, tourism, and biodiversity intersect. NbS for coastal protection must be designed to balance these without compromising their coastal protection function or the ecological processes that support it.

Transparent trade-off negotiations and stakeholder engagement are essential as NbS may require limiting access, reallocating space, or accepting more dynamic landscape behavior. Communicating them with **co-benefits**, such as reduced sand nuisance along urban infrastructure, improved freshwater retention, enhancing carbon sequestration, and cultural and educational value can build **shared ownership of adaptive solutions**.

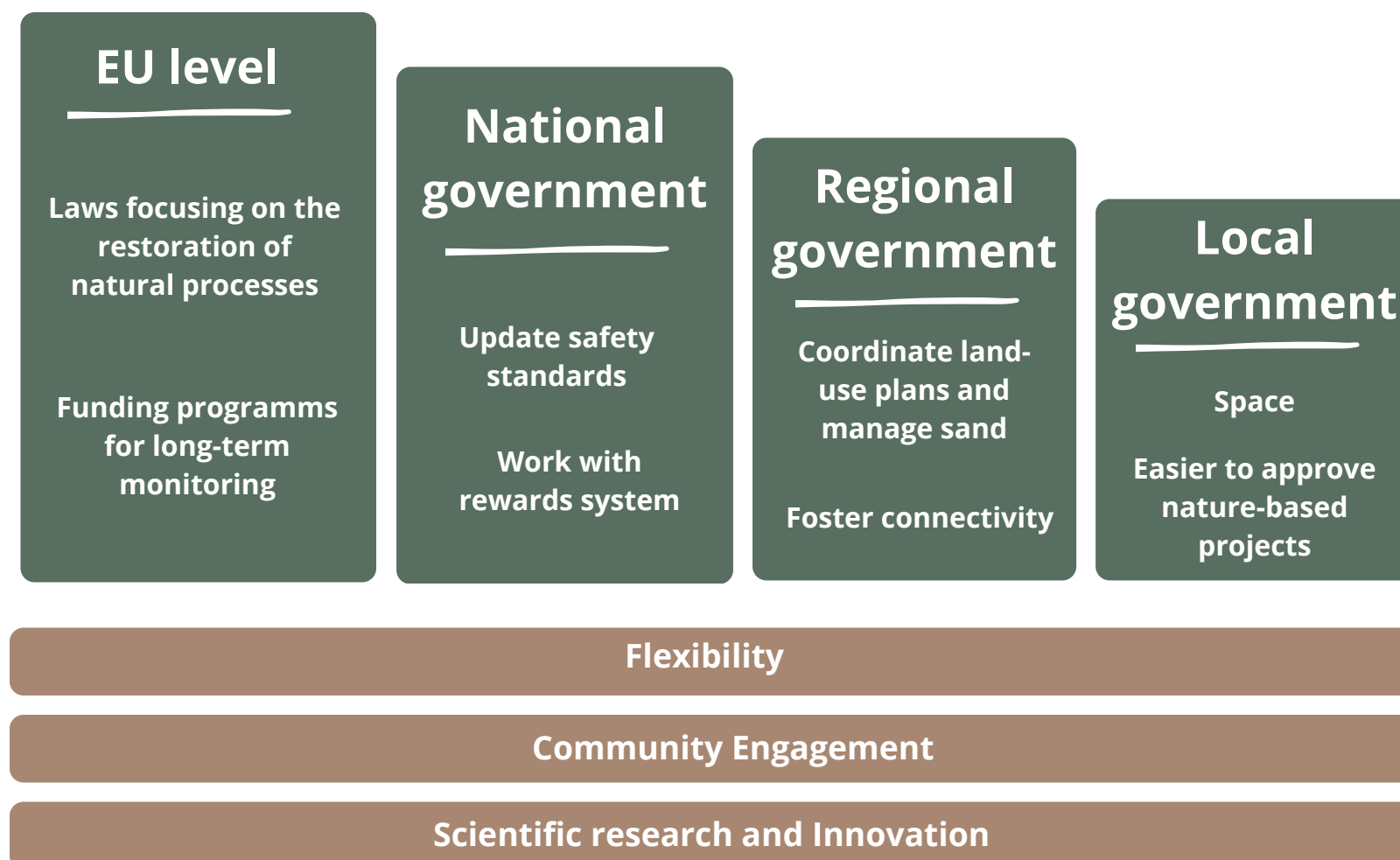
4. Socioeconomic and stakeholder engagement

5. Research and innovation

Scientific research and innovation provide the backbone of effective and future proof NbS for coastal protection. Predictive models (e.g. Digital Twins) integrating disturbance regimes (e.g. storm events), biodiversity, and climate scenarios, **can support evidence-based design and risk assessment**.

Long-term field experiments and monitoring are needed to understand species interactions, successional dynamics, and hybrid NbS performance under changing climate conditions and guide necessary adjustments to design over time. Investing in this research priorities will close knowledge gaps and accelerate the transition toward regenerative coastal protection.

In summary, to make nature-based coastal management, we need more than good ideas, we need supportive rules and planning at every level. **Local governments** should set aside space for dunes and beaches to move naturally and make it easier to approve nature-based projects. **Regional authorities** must coordinate land-use plans and manage sand, so beaches and dunes stay connected. **National governments** should update safety standards to include hybrid solutions that mix natural and engineered defenses, and reward land uses that store carbon and reduce flood risk. At the **EU level**, laws should focus on restoring natural processes, not just planting species, and funding programs must support long-term monitoring. Across all levels, policies should allow flexibility, encourage innovation, and involve communities, thereby facilitating frontrunning pilot projects at full scale.





3 | Evidence and analysis

3.1 Functional role of biodiversity in dune-based coastal NbS

Biodiversity shapes dune-building systems through strong bio-geomorphological feedbacks (Hesp 1989; Walker & Zinnert 2022; Moore et al. 2025). Vegetation zonation and the traits of dune-building species control dune-height, sand storage, storm resilience, and adaptability to changing climate conditions (Durán & Moore, 2013). **Ecological engineers** are species which modify their environment, drive dune formation by trapping sand, and stabilize the sand through their above- and below-ground structures (Bonte et al. 2021; Walker & Zinnert 2022).

When these organism–environment interactions are disrupted, dunes may undergo **regime shifts** from stable, accreting systems to eroding, fragmented landscapes.

Ecological engineers **reduce physical stresses** such as wind and salinity, creating conditions for other species to establish and drive successional dynamics. Their functional traits such as rooting depth, rhizome architecture, and sand-trapping efficiency shape dune morphology and resilience.

Maintaining this functional diversity is critical for adaptive capacity under climate change. Restoration strategies must therefore go beyond species counts, focusing on reactivating these feedbacks to prevent collapse and enable long-term resilience.

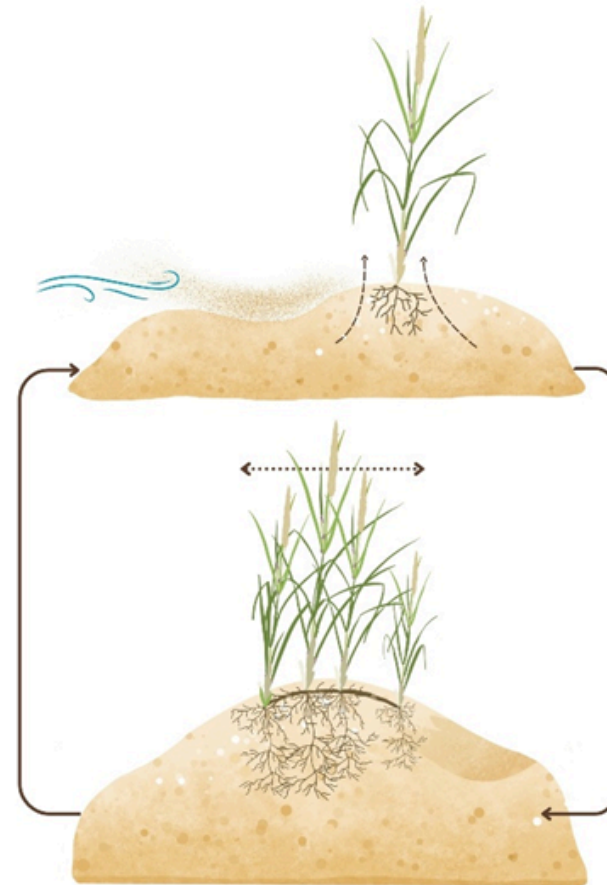


Fig.1: a schematic representation of engineering processes for dune building. Once plants establish (upper panel), sand is trapped, making the dune grow. This feeding of sand stimulates plant vertical and lateral growth, further facilitating sand capture. This process is eventually bounded by physical limits, when erosion balances accretion (adapted from Bonte et al. 2021).

3.2 Functional role of plant roots in erosion control

Below-ground biomass significantly boosts a dunes' ability to resist erosion by waves. European marram grass (*Ammophila arenaria*) can reduce erosion by up to 36% compared to bare sand, while annual pioneers such as European sea rocket (*Cakile maritima*) and prickly saltwort (*Salsola kali*) also provide protection in early successional stages (De Battisti & Griffin 2020). Collectively, **evidence shows that vegetation can reduce dune erosion by 30– 40%, depending on species traits, maturity, and sand conditions**. The most effective erosion control is achieved when both biological traits (e.g. root biomass, buried shoots) and physical factors (e.g. sediment grain size) are considered and optimized.

3.3 Species-specific dune-building outcomes

In Europe, **different dune-building species** create contrasting dune morphologies with major implications for storm protection and resilience. **Sand couch** (*Elytrigia juncea*) typically forms low, wide dunes, while European marram grass (*Ammophila arenaria*) builds taller, faster growing dunes (Reijers et al. 2020; Lammers et al. 2023, 2024). These structural differences influence how dunes store sand and buffer storm surges. Similar patterns occur elsewhere: in North America, **American beachgrass** (*Ammophila breviligulata*) produces wide, resilient foredunes, whereas sea oats (*Uniola paniculata*) generate narrower, steeper dunes. Their species-specific traits such as shoot density, rhizome architecture, and growth strategy shape dune morphology and thus determine its adaptive capacity under climate change.

3.4 Importance of cross-shore connectivity

The connectivity of marine and terrestrial ecosystems is expected to strongly influence dune growth and resilience, although empirical evidence remains limited. Wrack, organic material deposited by tides, interlinks marine and terrestrial ecosystems. Faunal decomposition of wrack enriches the sand with organic matter, providing nutrients that support vegetation growth and can initiate **embryo dune formation** (e.g., Ulaski et al., 2023; Hyndes et al., 2022; Colombini & Chelazzi, 2003). While wrack-mediated nutrient transfer can initiate dune formation and enhance resilience, its benefits are undermined by coastal squeeze: when space for landward migration is blocked by hard infrastructure, dunes cannot expand or regenerate, limiting the effectiveness of these natural connectivity processes under rising seas.

3.5 Impact of non-native species on dune formation

The introduction of **non-native plant species** by humans has fundamentally altered coastal dune systems worldwide. Their profound implications for both biodiversity and coastal protection services highlight the risk of using non-native species in NbS for coastal management.

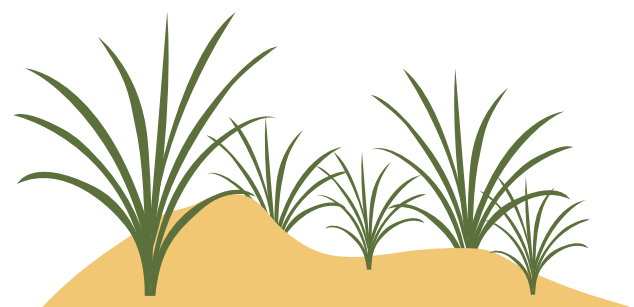
In northern Europe, the introduction of **Japanese rose** (*Rosa rugosa*) has significantly altered coastal dune ecosystems. Originally planted for dune stabilization, it forms dense thickets that outcompete native vegetation, reduce habitat heterogeneity, and hinder natural dune dynamics (Elleriis et al. 2015; Woch et al. 2023). Its persistence and soil modification complicate restoration efforts, making it a priority species for removal in many conservation programs. In the Mediterranean regions of Europe, the introduction of **sour fig** (*Carpobrotus edulis*) has changed the local sediment, by changing the microbial community and preventing the growth and germination of native dune plants even after the invasive species has been removed (de la Peña et al. 2010). This **soil legacy effect** complicates restoration efforts.

In North America, **European marram grass** (*Ammophila arenaria*) has altered dune morphology by rapidly stabilizing sand but outcompeting the native **American beachgrass** (*Ammophila breviligulata*) (Hacker et al., 2012; Zarnetske et al., 2012). Their dominance has hereby suppressed native biodiversity, altered habitat availability for native fauna, and reduced the functional resilience of these dune ecosystems to changing climate conditions (Seabloom et al., 2013).

3.6 Climate-driven range shifts

Climate change is causing a shift in where coastal plant species can survive geographically. Warming temperatures enable the northward expansion of southern species and alter competitive dynamics. These shifts are relevant as **different species will create different dune shapes and levels of protection**.

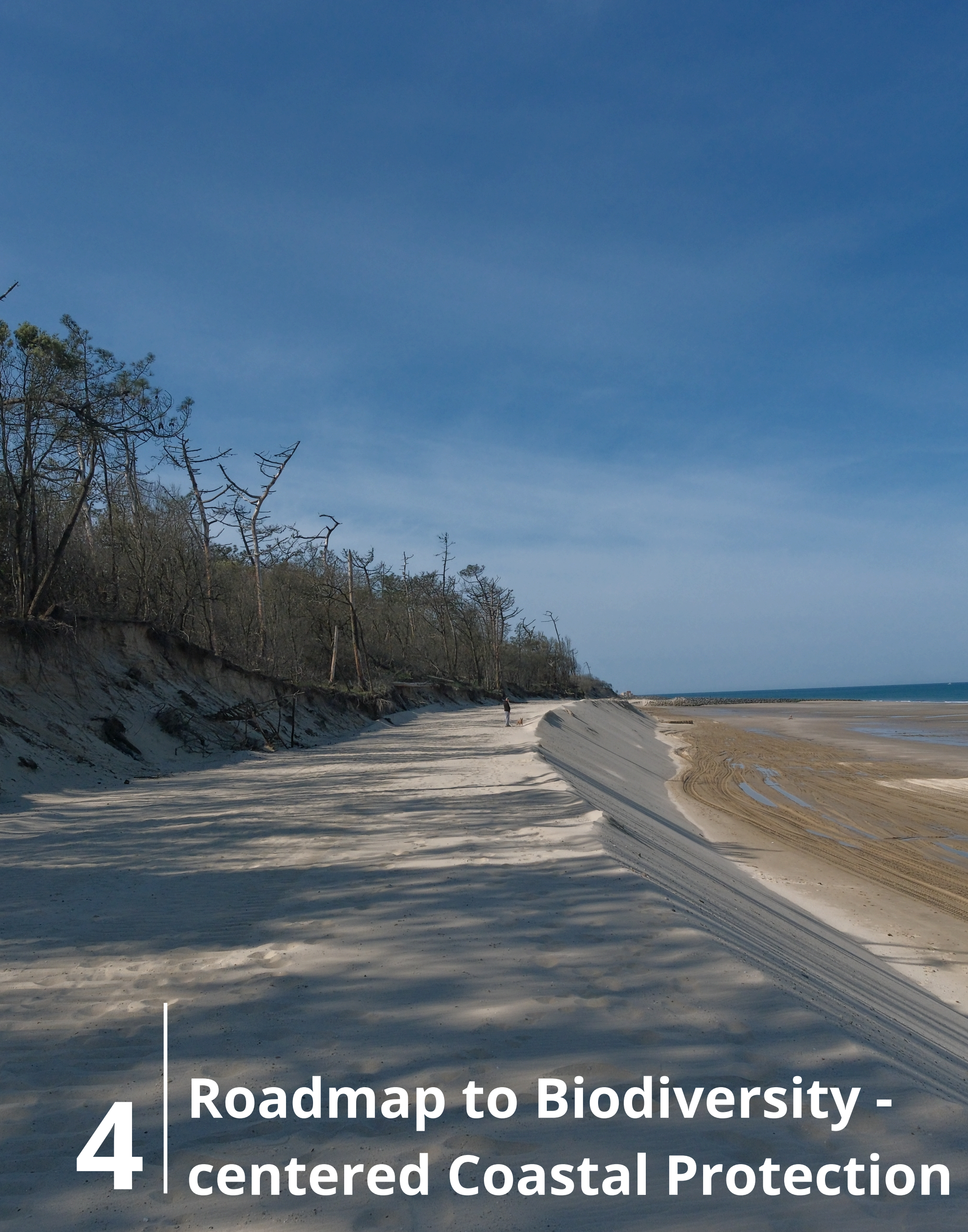
In Europe, results show contrasting suitability for the two major European dune-builders **marram grass** (*Ammophila arenaria*) and **sand couch** (*Elytrigia juncea*) to future climate conditions (Dahirel and Bonte, 2025). Because these species play distinct roles in dune formation, their shifting distributions are expected to fundamentally reshape dune dynamics across European coasts. In North America, models predict that **sea oats** (*Uniola paniculata*) may expand into areas currently dominated by **American beach grass** (*Ammophila breviligulata*). This shift is expected to decrease dune height, impacting the protection dunes provide during storm events (Goldstein et al., 2017).



3.7 Importance of marine habitats as wave-breaking foundations

Marine vegetated habitats such as **seagrasses, salt marshes, macroalgae, and mangroves** occupy only 0.2% of the ocean surface, but can deliver 50% of the carbon burial in marine sediments (Duarte et al., 2013). Their canopies dissipate wave energy and stabilize sediments. Because these habitats trap and bury large amounts of organic material, they can gradually raise the seafloor. For coastal defense, these habitats offer a clear advantage over **artificial structures** as they can **adapt naturally** to changing sea levels and storm conditions, often at very low management or maintenance cost (Duarte et al., 2013). The loss of more than one-third of global cover of these CO₂ sinks results in an estimated carbon emission of 1 Pg CO₂ annually (Pendleton et al., 2012). Restoring these habitats is expected to strengthen coastal defense while supporting climate mitigation in the form of carbon capture and storage.





4

**Roadmap to Biodiversity -
centered Coastal Protection**

Understanding and implementing Nature-based Solutions for coastal management requires addressing critical limitations in current practices. **Decision-makers should hereby prioritise:**

Space for natural dynamics

Mandate setback zones, managed retreat corridors, and zoning to prevent coastal squeeze, ensuring dunes and beaches can migrate and adapt under rising seas.

Functional integration of biodiversity

Move beyond species lists toward functional compliance, embedding bio-geomorphological feedbacks and ecological processes into safety standards and permitting frameworks.

Adaptive governance

Institutionalise continuous monitoring and flexible design standards to accommodate non-linear system behaviors and climate uncertainty.

Finance and incentives

Develop performance-based financing tied to ecological milestones and long-term monitoring, and incentivise multifunctional land use that delivers coastal protection, and biodiversity benefit.

Cross-sector alignment

Harmonise coastal safety, biodiversity conservation, and climate adaptation objectives across local, regional, and national planning frameworks.



To close knowledge gaps and strengthen NbS design, **research should focus on** the following:

**Functional
role of
biodiversity**

Quantify how species traits such as root architecture, sand-trapping efficiency, and growth plasticity affect dune morphology, storm resilience, and adaptive capacity.

**Connectivity
processes**

Investigate land-sea linkages, including wrack-mediated nutrient cycling and faunal decomposition, and their role in dune initiation and resilience. Consider the regional impact of NbS implementation on biodiversity by its importance in connecting existing N2000 areas.

**Regime shifts
and
thresholds**

Identify tipping points where loss of ecological engineers leads to dune collapse and develop strategies to prevent or reverse these shifts.

**Trait-based
restoration
and genetic
diversity**

Advance predictive models for species selection under climate scenarios, incorporating functional traits and genetic variability to ensure long-term resilience.

**Digital Twins
for NbS**

Integrate biodiversity and bio-geomorphological feedbacks into predictive models alongside physical processes, enabling scenario testing for storms, sea-level rise, and (hybrid) NbS performance.

**Long-term
monitoring
and
experiments**

Extend research beyond the typical 4-6-year project cycles to capture successional dynamics, hybrid system evolution, and adaptive responses under real-world conditions.



5 | References

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