ETC-BE Report 2026/2

# Review of Marine Nature-Based Solutions

Authors:
Emanuele Bigagli (BriS) and Samuli Korpinen (SYKE)

European Environment Agency
European Topic Centre
Biodiversity and ecosystems

Cover design: EEA
Cover image © Mats Westerbom
Layout: Oda Ellingsen [NIVA]

**Version:** 1.0

**Publication Date:** 5 May 2026

**EEA activity.** Biodiversity and Ecosystems



**ETC-BE coordinator:** Norwegian Institute for Water Research (NIVA)

**ETC-BE partners:** Federal Agency for Nature Conservation (BfN), Association BIOPOLIS (Biopolis), Brilliant Solutions Engineering & Consulting (BRiS), Danish Centre for Environment and Energy, Aarhus University (DCE-AU), Deltares, Dark Matter Laboratories B.V. (DML), Ecologic Institute (Ecologic), Environment Agency Austria (EAA), Fresh Thoughts Consulting GmbH (Fresh Thoughts), Global Footprint Network (GFN), Hot or Cool Institute gGmbH (HoC), International Council for the Exploration of the Sea (ICES), International Institute for Applied Systems Analysis (IIASA), French national institute for industrial environment and risks (INERIS), Italian Institute for Environmental Protection and Research (ISPRA), LESPROJEKT-SLUŽBY Ltd (LESP), Martin-Luther University Halle-Wittenberg (MLU), Sapienza University Rome (SAP), Seascape Belgium (SSBE), Finnish Environment Institute (SYKE), Thematic Center for Water Research, Studies and Project Development, ltd. (TC Vode), German Environment Agency (UBA-DE), University Duisburg-Essen (UDE), Helmholtz Centre for Environmental Research (UFZ)



**doi**: 10.5281/zenodo.20034157

**How to cite this report:**
Bigagli, E., Korpinen, S. (2026). Review of Marine Nature-Based Solutions. (ETC BE Report 2026/2). European Topic Centre on Biodiversity and Ecosystems.

European Topic Centre on
Biodiversity and Ecosystems
https://www.eionet.europa.eu/etcs/etc-be

## Contents

## Acknowledgements


| | |
|---|---|
| **Lead authors:** | Emanuele Bigagli (BRiS) |
| | Samuli Korpinen (SYKE) |
| **EEA project manager:** | Eirini Glyki |
| **Coordination:** | Claudia Neitzel (NIVA) |
| **English check:** | Shane Hume (LESP) |

The authors would like to thank EEA staff for their guidance and feedback, Rowan Dunn-Capper (MLU) for the constructive comments received, and Claudia Neitzel (NIVA) for the continuous support to this work throughout all phases of development.


## Summary


Nature-based Solutions (NbS) are emerging as a key tool for supporting the conservation of the marine environment, restoring degraded habitats, and creating or enhancing ecosystems to increase the provision of essential ecosystem services and associated benefits to society.

This report presents the results of a review of 21 existing marine NbS, providing detailed information into their spatial and temporal scales of implementation, economic costs and maintenance requirements, as well as their environmental, social, and economic benefits and trade-offs. It also examines strategies for stakeholder engagement and evaluates the potential of these solutions to support the implementation of the MSFD and other major EU and global policy frameworks.

A wide range of marine NbS have already been implemented, demonstrating strong potential to address key challenges to the marine environment, including biodiversity loss, habitat degradation, and climate change, while simultaneously delivering important social-economic benefits to local communities. However, their success depends on a thorough understanding of their applicability, strengths and limitations, as well as their associated benefits and trade-offs, in relation to specific local contexts, challenges and management objectives.

The findings of this report can support Member States in selecting the most appropriate measures for implementing EU policies, including the Nature Restoration Regulation (NRR) and the MSFD, while also contributing to broader global policy goals.

# 1. Introduction

Nature-based Solutions (NbS) are increasingly recognised as an effective approach for conserving the marine environment, restoring degraded habitats, and creating or enhancing ecosystems to support the delivery of essential ecosystem services and associated societal benefits.

Multiple definitions of NbS exist at the global level. The European Commission defines NbS as "solutions that are inspired by and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits, and help build resilience", bringing "more, and more diverse, nature and natural features and processes into cities, landscapes, and seascapes through locally adapted, resource-efficient and systemic interventions" (EC, 2021). In addition, the EU Biodiversity Strategy for 2030 highlights the key role of NbS in reducing greenhouse gas emissions and supporting climate change adaptation (European Commission, 2020a).

On a global scale, the UNEA Resolution on Nature-Based Solutions (March 2022) defines NbS as "actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits".

The aim of this report is to present the results of a review of existing marine NbS, with the objective of supporting EU Member States in selecting effective actions and measures for the implementation of key EU policies, including the Nature Restoration Regulation (NRR) and the Marine Strategy Framework Directive (MSFD).

Section 2 of this report describes the categorisation of NbS and the types of information collected for each NbS. Section 3 presents the scorecards developed for each NbS. Section 4 discusses the main findings, including comparisons of NbS characteristics and implementation, their contribution to addressing anthropogenic pressures listed in Annex II of the MSFD, their role in achieving GES, and their relevance to broader EU and global policy objectives. Finally, Section 5 presents the main conclusions.

## 2. Methodology

In this review, we extended the classification of NbS in 4 categories proposed by Riisager-Simonsen (2022), by adding a fifth category, related to geo-engineering techniques:

1. *Sustainable use and protection of natural marine ecosystems* – measures consisting of no, or minimal intervention in marine ecosystems, with the objective of maintaining or improving the delivery of ecosystem services both inside and outside these preserved ecosystems, while enhancing nature conservation and sustainable use of biodiversity;
2. *Improved multifunctionality of managed marine ecosystems* – the targeted use of 'challenge specific' actions which aim to restore or enhance selected types of naturally occurring biodiversity and ecosystem services in managed areas where they need to coexist with other marine activities;
3. *Novel, restored or deliberately designed artificial marine ecosystems* – the introduction of new habitats in the marine environment to replace destroyed essential habitats, enhance sustainable food provisioning, reduce risk disasters and mitigate climate change;
4. *Nature-inspired designs which reduce environmental pressures* – This category includes technical solutions which adopt a design inspired by nature (Benyus 1997) to exploit marine nature in ways which are relatively more sustainable than its present alternatives, and supports the reduction of environmental pressures;
5. *Geo-engineering techniques* – the main geo-engineering measures proposed internationally to mitigate climate change by manipulating ocean physio-chemical processes and properties.

### 2.1 The structure of the scorecards

A template was developed and used to gather information on each NbS; its structure and description of each category are presented in Table 2.1.

**Table 2.1 The template used to gather information on the marine NbS reviewed.**

| Name/type | Name of the NbS/Title |
|---|---|
| Spatial scale | • Local<br>• National<br>• Sub-national regions<br>• Transnational region |
| Spatial and temporal scope of implementation | Location (region/country) and time when this measure was implemented, including a description of the expected duration and reference to major case-studies, if available |
| Objective of the measure and main actions implemented | Description of the environmental, economic or societal objectives, which triggered the restoration measures, and of the implemented restoration actions |
| Estimated economic cost | Indication of the economic cost of implementation |
| Environmental Benefits | Benefits to the ecosystems (habitats/species, functions, services…)<br>Potential environmental co-benefits and trade-offs to be considered are:<br>• Climate adaptation<br>• Air quality improvement<br>• Water Quality improvement<br>• Soil quality improvement<br>• Increase of landscape amenity |

| Name/type | Name of the NbS/Title |
|---|---|
| Social and economic co-benefits | Description of the benefits to the livelihoods of human communities<br>Potential societal co-benefits and trade-offs to be considered are:<br>• Health and well-being<br>• Availability of food<br>• Availability of water<br>• Job creation<br>• Diversification of livelihood/Income diversification<br><br>Potential economic co-benefits to be considered are:<br>• Strengthening of the local/regional economy (such as preservation of economic activities and creation of new sustainable economic activities)<br>• Other revenues from ecosystem services |
| Maintenance needs | Indication of whether it is a one-off intervention, or if there is the need for long-term maintenance actions |
| Stakeholders' engagement | Description of the stakeholders engaged (what categories are engaged, e.g., public authorities, citizens including all relevant groups, NGOs/ companies, associations, research institutions, economic actors etc.), the form of participation and the participation process |
| Success and/or limiting factors | Description of factors that have been decisive for a successful initiation and implementation and the expected challenges or limiting factors, which may have hindered the process. Example categories of success and limiting factors to consider:<br>• Political factors (e.g. political support/opposition, restoration priorities in the government agendas, capacity of the measure to achieve multiple policy objectives)<br>• Governance factors (e.g. cooperation/opposition across landowners and agencies, collaborative or conflicting environments within institutional settings)<br>• Technical factors (e.g. level of expertise in implementing, managing and maintaining the action, level of knowledge of expected results)<br>• Physical and biological factors (land or space availability/constraints, presence of degraded ecosystems)<br>• Social factors (cultural aspects, attitude to restoration, different perception of risks, resistance to change, social justice consideration)<br>• Economic factors (availability/lack of funding sources, interested investors, possibilities of return on investment) |
| Trade-offs | Indication of trade-offs experienced during implementation |
| Links to MSFD drivers-pressures | Potential contribution of this NbS to address specific MSFD pressures or human activities, and to achieve GES for specific MSFD Descriptors |
| Links to other policy objectives | Indication of the global and EU policies to which this NbS can potentially contribute |
| References | Links to relevant literature (scientific papers, reports, project websites, etc.) |

For the analysis of the links of NbS with policy objectives, we considered global and EU-level policies that explicitly consider NbS, as well as those whose objectives may be achieved by the implementation of one of the NbS analysed. The list of the policies considered is provided in Table 2.2.

**Table 2.2 List of the main global and EU policies considering NbS, or to which marine NbS can contribute.**

| Policy | Objective |
|---|---|
| *Global* | |
| SDG 14.2 | By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans. |
| SDG 14.4 | By 2020, to restore fish stocks in the shortest time feasible, at least to levels that can produce maximum sustainable yield as determined by their biological characteristics. |
| 2021-2030 UN Decade on Ecosystem Restoration | Recover degraded or destroyed ecosystems, and conserve those that are still intact. |
| Convention on Biological Diversity (CBD) | In-situ conservation of biodiversity, including through the establishment of a system of MPAs, and rehabilitate and restore degraded ecosystems and promote the recovery of threatened species. |
| Global Biodiversity Framework | Target 2: Ensure that by 2030 at least 30% of areas of degraded terrestrial, inland water, and marine and coastal ecosystems are under effective restoration, in order to enhance biodiversity and ecosystem functions and services, ecological integrity and connectivity. |
| | Target 4: Ensure urgent management actions to halt human induced extinction of known threatened species and for the recovery and conservation of species, in particular threatened species, to significantly reduce extinction risk, as well as maintain and restore the genetic diversity within and between populations of native, wild and domesticated species to maintain their adaptive potential, including through in situ and ex situ conservation and sustainable management practices, and effectively manage human-wildlife interactions to minimize human-wildlife conflict for coexistence. |
| | Target 5: Ensure that the use, harvesting and trade of wild species is sustainable, safe and legal, preventing overexploitation, minimizing impacts on non-target species and ecosystems, and reducing the risk of pathogen spillover, applying the ecosystem approach, while respecting and protecting customary sustainable use by indigenous peoples and local communities. |
| | Target 10: Ensure that areas under agriculture, aquaculture, fisheries and forestry are managed sustainably, in particular through the sustainable use of biodiversity, including through a substantial increase of the application of biodiversity friendly practices, such as sustainable intensification, agroecological and other innovative approaches, contributing to the resilience and long-term efficiency and productivity of these production systems, and to food security, conserving and restoring biodiversity and maintaining nature's contributions to people, including ecosystem functions and services. |
| BBNJ Agreement | The conservation and sustainable use of marine biodiversity of areas beyond national jurisdiction for the present and in the long term, including reference to ecosystem integrity restoration. |

| Policy | Objective |
|---|---|
| Convention on Migratory Species of Wild Animals (CMS) | Conserve and when feasible and appropriate, fully restore and connect the habitats of migratory species.<br>Goal 2: the habitats and ranges of migratory species are maintained and restored, supporting their connectivity. |
| Convention on Wetlands of International Importance especially as Waterfowl Habitat (Ramsar Convention) | Conservation of wetlands and waterfowl by establishing nature reserves. |
| United Nations Fish Stocks Agreement (UNFSA) | To adopt conservation and management measures for species belonging to the same eco-system or associated with or dependent upon the target stocks (UNFSA, Art 5 (e));<br>iii. to minimise pollution, bycatch and impacts on associated or dependent species (UNFSA, Art. 5(f)); to protect marine biodiversity (UNFSA, Art. 5(g)). |
| UNFCCC, Paris Agreement (2015) | Hold "the increase in the global average temperature to well below 2 °C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5 °C above pre-industrial levels." |
| Sendai Framework for Disaster Risk Reduction 2015-2030 | The substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries, by implementing integrated and inclusive economic, structural, legal, social, health, cultural, educational, environmental, technological, political and institutional measures that prevent and reduce hazard exposure and vulnerability to disaster, increase preparedness for response and recovery, and thus strengthen resilience. |
| MARPOL 73/78, Annex VI (2005) | To prevent air pollution from ships by setting limits on the emission of ozone-depleting substances, Nitrogen Oxides ($NO_x$), Sulphur Oxides ($SO_x$), Particulate Matter (PM). Limits are lower and controls are more stringent in Emission Control Areas (ECAs). |
| *EU* | |
| EU Biodiversity Strategy for 2030 | Halt biodiversity loss and restore degraded ecosystems across EU lands and waters, especially through active restoration efforts.<br>This includes the following commitments:<br>• Legally protecting at least 30% of EU land and sea areas, with the aim of expanding and completing the Nature 2000 Network;<br>• Strictly protecting at least one-third of the protected areas, focusing on highly biodiverse habitats;<br>• Ensuring effective management of all protected areas. |
| Nature Restoration Regulation (NRR) | EU Member States are mandated to restore marine ecosystems by:<br>Implementing restoration measures that:<br>• By 2030 cover at least 30% of the total area of habitat groups 1 to 6 listed in Annex II that are not in good condition;<br>• By 2040 extend to at least 60%, and by 2050, to at least 90% of the area of each of the groups 1 to 6 of the habitat types that are not in good condition;<br>• By 2040, restoration must be implemented on at least two-thirds of the percentage specified in the following point (4) for the area of habitat group 7 listed in Annex II that is not in good condition; |

| Policy | Objective |
|---|---|
| | • By 2050, the restoration must be applied to a percentage of the area of habitat group 7 that is not in good condition.<br>• Implementing restoration measures to re-establish habitat types in areas where these are absent, on at least 30% of the additional area required to reach the favourable reference area by 2030, at least 60% by 2040, and 100% by 2050. |
| Marine Strategy Framework Directive (MSFD) 2008/56/EC | Achieving or maintaining the Good Environmental Status (GES) of European marine waters, and sustainably protect the resource base upon which marine-related economic and social activities depend based on 11 qualitative descriptors:<br>• Descriptor 1: Biodiversity is maintained<br>• Descriptor 2: Non-indigenous species do not adversely alter ecosystems<br>• Descriptor 3: Populations of commercial fish and shellfish species are healthy<br>• Descriptor 4: Food webs ensure long-term abundance and reproduction of species<br>• Descriptor 5: Eutrophication is reduced<br>• Descriptor 6: Sea floor integrity ensures the proper functioning of ecosystems<br>• Descriptor 7: Permanent alteration of hydrographical conditions does not adversely affect ecosystems<br>• Descriptor 8: Concentrations of contaminants give no pollution effects<br>• Descriptor 9: Contaminants in seafood are at safe levels<br>• Descriptor 10: Marine litter does not cause harm<br>• Descriptor 11: Introduction of energy (including underwater noise) does not adversely affect the ecosystem. |
| European Climate Law (Regulation (EU) 2021/1119) | Achieve net-zero GHG emissions for Member States by 2050, in alignment with the long-term objectives of the Paris Agreement, corresponding to a domestic reduction of net GHG emissions by at least 55% compared to 1990 levels by 2030, also through increasing the carbon sink capacity. |
| Common Fisheries Policy (CFP) | Ensure that fishing and aquaculture activities are environmentally sustainable in the long term, are managed in a way consistent with achieving economic, social and employment benefits, and contribute to the availability of food supplies. To ensure sustainable exploitation of fisheries resources, the CFP must apply a precautionary approach to fisheries management. In addition, it must implement an ecosystem-based approach to fisheries management to ensure that negative impacts of fishing activities on the marine ecosystem are minimised, and that aquaculture and fisheries activities avoid degrading the marine environment. |
| Water Framework Directive (WFD) 2000/60/EC | Protect and, where necessary, restore water bodies in order to reach good chemical and ecological status, and to prevent deterioration. In relation to the marine environment, the WFD applies to (Art. 2):<br>transitional waters: “bodies of surface water in the vicinity of river mouths which are partly saline in character as a result of their proximity to coastal waters, but which are substantially influenced by freshwater flows”; and<br>coastal waters: “surface water on the landward side of a line, every point of which is at a distance of one nautical mile on the seaward side from the |

| Policy | Objective |
|---|---|
| | nearest point of the baseline from which the breadth of territorial waters is measured, extending where appropriate up to the outer limit of transitional waters". |
| Zero Pollution Action Plan | Reduce air, water and soil pollution to levels no longer considered harmful to health and natural ecosystems, that respect the boundaries with which our planet can cope, thereby creating a toxic-free environment.<br>Key 2030 targets to reduce pollution at source, related to the marine environment, include improving water quality by reducing waste, plastic litter at sea (by 50%) and microplastics released into the environment (by 30%). |
| The EU Action Plan on the Sendai Framework for Disaster Risk Reduction (2015) | Enhance and promote disaster risk management and its integration in EU policies, including measures based on working with nature, rather than against it, while also providing human, biodiversity and climate benefits. |
| FuelEU Maritime Regulation (EU) 2023/1805 | This Regulation imposes (a) limits on the GHG intensity of energy used on board by a ship arriving at, staying within or departing from ports under the jurisdiction of a Member State; and (b) an obligation to use on-shore power supply (OPS) or zero-emission technology in ports under the jurisdiction of a Member State. |

# 3. Results

## 3.1 Category 1: Sustainable use and protection of natural marine ecosystems

The first category of NbS includes measures "consisting of no, or minimal intervention in marine ecosystems, with the objective of maintaining or improving the delivery of ecosystem services both inside and outside these preserved ecosystems, while enhancing nature conservation and sustainable use of biodiversity" (Riisager-Simonsen et al., 2022).

This category corresponds with the notion of 'passive' or 'indirect' restoration. These are actions that aim to remove the environmental stressors or sources of degradation, relying on the ecosystem's resilience to achieve its natural recovery (IUCN, 2021). They may apply to specific species or groups of species, such as seagrass and seaweeds, as well as to habitats, such as coastal wetlands, or areas, as in the case of MPAs. This category is also linked to the concept of "marine rewilding", defined as "a collaborative, human-initiated, nature-led process involving a range of approaches that work systemically to make degraded marine and coastal environments more ecologically complex while supporting greater social inclusion and enabling sustainable economic and cultural opportunities" (Brooker et al., 2025). In the context of the present review, marine rewilding encompasses both passive (Category 1) and active (Category 2) restoration.

In this review, we considered MPAs, and the passive restoration of seagrass/seaweed habitats and of coastal wetlands, because of their added value in sequestering 'blue carbon'.

### *Marine Protected Areas (MPAs)*

| Name/type | Marine Protected Areas (MPAs) |
|---|---|
| Spatial scale | Local |
| Spatial and temporal scope of implementation | MPAs have existed throughout the 20$^{th}$ century, but the process accelerated in the 1970s with the assignment of exclusive rights to coastal states over water up to 200 nm off their coast through the UNCLOS. The first concrete global targets (10%) have been set with the Rio Summit of 1992, later replaced in the 2010s with the Aichi target 11 and, currently, the CBD Kunming-Montreal Global Biodiversity Framework (Humphreys and Clark, 2020). |
| Objective of the measure and main actions implemented | MPAs are a clearly defined geographical space in estuarine, coastal, or marine areas, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values.<br>MPAs may include different levels of protection, including strict no-take zones or multiple-use areas that allow sustainable activities such as fishing and tourism under certain rules and regulations. Their designation is often combined to an ecologically coherent, connected, network, i.e., a series of protected areas which operate in synergy to provide additional ecological benefits. |
| Estimated economic cost | MPAs have establishment costs (research and planning, outreach, costs for training and infrastructure), maintenance costs (staff and equipment for administration, management, and enforcement) (Davis et al., 2019) and opportunity costs (lost income but also economic benefits) (The Nature Conservancy, 2022). Establishment costs are not necessarily correlated with the size of the MPA but rely heavily on the duration of the creation phase (Binet et al., 2015).<br>McCrea-Strub et al. (2011) report a considerably wide variation in establishment costs of selected MPAs from all over the world, ranging from USD 41-1,117,358 per km$^2$, with higher total costs for larger MPAs and smaller MPAs that are more expensive per unit area. An assessment of the costs of the creation of new MPAs to achieve global 30% coverage targets, estimate establishment costs of USD 0.85-2.8 million (2015 |

| Name/type | Marine Protected Areas (MPAs) |
|---|---|
| | constant values), average annual management costs of USD 0.5-1 million per $km^2$, and opportunity costs that are higher for strongly-protected MPAs and for the fisheries sector, as fish stocks may struggle to recover beyond current levels without additional comprehensive ocean management (The Nature Conservancy, 2022). In the Mediterranean, establishment costs have been estimated at an average of EUR 42,600 (Binet et al., 2015). In the Aegean Sea, operating and management costs have been estimated at an average of USD 13 per hectare (Simons et al., 2023).<br>The expansion of the global network of MPAs may entail global benefits that are 1.4-2.7 times the costs, depending on the scenarios considered, provided MPAs are effectively managed and enforced (Brander et al., 2020). The Nature Conservancy (2022) estimated a total benefit of USD 4.4-6.3 billion per year in 2030, rising to USD 14.7 billion per year in 2060. |
| Environmental Benefits | MPAs can contribute to the delivery of important ecosystem services:<br>• Improved ecological condition of habitats (Brander et al., 2020, The Nature Conservancy, 2022), which includes: improvement in biological parameters, including increase in biomass, density and size of organisms (Hopf et al., 2014) and of species richness (Fenberg et al., 2012) inside boundaries and also outside boundaries, by promoting the dispersal of larvae and adults of target and non-target species (Di Lorenzo et al., 2016; Pendleton et al., 2018).<br>• MPAs may help marine ecosystems adapt to climate change impacts including ocean acidification, sea-level rise, and storm intensification (Davis et al. 2019). The protection of mangroves, seagrasses, kelp and sediments may increase carbon storage and help mitigate climate change (The Nature Conservancy, 2022).<br>• MPAs may contribute to regulate nutrient cycling (The Nature Conservancy, 2022).<br>• Human uses or activities damaging the seabed may be explicitly forbidden inside the MPA area, avoiding physical disturbance to, or loss of, the seabed, or the input of nutrients, pollutants, and other substances (including litter). |
| Social and economic co-benefits | MPAs may increase food security and support sustainable livelihoods, thanks to their market benefits on the fisheries and tourism sectors, as well as having benefits to coastal infrastructure:<br>• Benefits to the fisheries sector: increased profitability through increase in fish stocks, catch volumes, catch per unit effort, fecundity and larval export, spillover of fish biomass from MPAs into fished areas. Some critics argue the lack of no equivocal demonstration of spillover in fisheries adjacent to MPAs, and possible increase in fisheries effort outside MPAs due to fishery displacement (Costello, 2024).<br>• Benefits to the tourism sector: increase in jobs and tourism revenues (Costello, 2024).<br>• Benefits to coastal infrastructure: protection from storms and erosion, sea-level rise, and tsunamis (The Nature Conservancy, 2022).<br>MPAs also have non-market benefits. They have been shown to provide more cultural ecosystem services than adjacent coastal areas (Erskine et al., 2021), supporting the cultural values associated with the conservation of marine biodiversity and mega-fauna (Brander et al., 2020, Davis et al., 2019). |

| Name/type | Marine Protected Areas (MPAs) |
|---|---|
| Maintenance needs | MPAs need sustained funding in the long term, to ensure proper operation and effective protection. A study in the Mediterranean noted that 86% of MPAs have insufficient funding to guarantee effective management, especially in non-EU countries (Binet et al., 2015). |
| Stakeholders' engagement | The involvement of stakeholders is essential for the success of the MPAs. Equity and fairness considerations are key, as the benefits of MPAs may not be evenly distributed across stakeholder groups (Gurney et al., 2014). For example, fishermen may bear the costs of MPA establishment, while not receiving the benefits (Sanchirico et al., 2002). MPAs should be designed to address these concerns and include possible compensation for those stakeholders that face net costs (Brander et al., 2020). Ferreira et al. (2015) report the positive, although difficult, experience of involving stakeholders and the public straight from the outset in a bottom-up process including public participation assemblies to gather input from the fishing community, and visual census and interviews of different users. More recently, the Blue4All project proposed a new approach, placing stakeholders at the centre of the MPA process and ensuring their needs and concerns are addressed from the outset, by designing tools for socially sustainable and acceptable marine conservation and testing them in Living labs in 25 MPAs and MPA networks the Mediterranean, Baltic Sea, and North-East Atlantic. This approach is based on a link of top-down and bottom-up socio-governance processes that help reframe management challenges through a relational perspective (Buitendijk et al., 2026). |
| Success and/or limiting factors | + Strictly protected MPAs (i.e., those that prohibit commercial activity and allow only light fishing) and fully protected MPAs (i.e., those that prohibit fishing; Lester and Halpern, 2008, Edgar et al., 2014; Gill et al., 2017) are more effective than multiple-use MPAs (Rodriguez Rodriguez, 2022).<br><br>+ Newly established MPAs can stop or limit different pressures in those marine and costal ecosystems that need some degree of recovery to reach healthy levels (ICES, 2025).<br><br>+ MPAs can be established in restored areas, as they can actively manage, potentially prevent or minimise cumulative pressures on species and ecosystems, and ensure sustained conservation (ICES, 2025).<br><br>+ Connectivity is fundamental for the success of conservation and restoration; ensuring a coherent and well-connected network of MPAs, based on an ecosystem function approach, and including sites in healthy condition, with positive reproductive rates, fosters the effectiveness of passive restoration (ICES, 2025).<br><br>- MPAs generally entail a slow recovery rate, as the positive effects of MPAs may take years or decades to accumulate (Fenberg et al., 2012). |
| Trade-offs | The establishment of an MPA may restrict certain activities, leading to potential economic losses for some stakeholders in the short term (Simons et al., 2023). Fishing restrictions may increase congestion on non-closed fishing grounds, resulting in increases in fuel usage and higher capital costs, increased conflicts between fishermen such as allocation disputes and gear entanglements, and a possible shift of fishing pressure from one species to another (Sanchirico et al., 2002). A recent study by ICES (2024) showed that the maintenance of a persistently unfished state in 50% of the extent of all MSFD broad habitat types in the EU marine waters of the Baltic Sea and North-East Atlantic is associated with an estimated reduction of 20% of the annual |

| Name/type | Marine Protected Areas (MPAs) |
|---|---|
| | landing value of fishing with mobile bottom-contacting gear; this value increases to 31.6-37.6% for an extension to 70%.<br>Moreover, if left uncontrolled, increased tourism driven by MPA attractiveness could have negative impacts, offsetting the biological and cultural benefits (Sanchirico et al., 2002).<br>At social level, there may be increased prosocial or antisocial behaviour, due to changes in fisheries catch rates and an increase in economic opportunities outside fishing, with varying impacts across stakeholder groups and possible exacerbation of social stratification (Davis et al., 2019). |
| Links to MSFD drivers-pressures | Pressures:<br>• Biological:<br>○ Loss of, or change to, natural biological communities due to the cultivation of animal or plant species;<br>○ Disturbance of species (e.g. where they breed, rest and feed) due to human presence;<br>○ Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities);<br>• Physical:<br>○ Physical disturbance to the seabed (temporary or reversible);<br>○ Physical loss (due to permanent change of seabed substrate or morphology and to extraction of seabed substrate);<br>○ Changes to hydrological conditions;<br>• Substances, litter and energy:<br>○ Input of organic matter – diffuse sources and point sources;<br>○ Input of other substances (e.g. synthetic substances, non-synthetic substances, radionuclides) - diffuse sources, point sources, atmospheric deposition, acute events;<br>○ Input of litter (solid waste matter, including micro-sized litter);<br>○ Input of anthropogenic sound (impulsive, continuous);<br>○ Input of other forms of energy (including electromagnetic fields, light and hear);<br>○ Input of water – point sources (e.g. brine)<br>Contribution to achieve GES: D1, D3, D4, D5, D6, D7, D8, D9, D10, D11. |
| Links to other policy objectives | Global: SDG 14.2, 14.4; 2021-2030 UN Decade on Ecosystem Restoration; CBD and Kunming-Montreal Global Biodiversity Framework; BBNJ Agreement; CMS; UNFSA; Sendai Framework.<br>EU: EU Biodiversity Strategy for 2030; NRR; MSFD; WFD; CFP; EU Action Plan on the Sendai Framework; Zero Pollution Action Plan. |
| References | Binet, T., Diazabakana, A., Hernandez, S. 2015, Sustainable financing of Marine Protected Areas in the Mediterranean: a financial analysis. Vertigo Lab, MedPAN, RAC/SPA, WWF Mediterranean. 114 pp.<br>Buitendijk, T., Adjei, M., Raatikainen, K. J., Cárdenas, E. C. C., Varjopuro, R., and Schuitema, G., 2026, A goal-based typology of sociogovernance processes in the management of marine protected areas. Ocean and Coastal Management, 271, 107948.<br>Costello, M. J., 2024, Evidence of economic benefits from marine protected areas. *Scientia Marina*, *88*, 1. |

| Name/type | Marine Protected Areas (MPAs) |
|---|---|
| | Davis, K. J., Vianna, G. M., Meeuwig, J. J., Meekan, M. G., and Pannell, D. J., 2019, Estimating the economic benefits and costs of highly-protected marine protected areas. *Ecosphere*, *10*(10), e02879.<br><br>Di Lorenzo, M., Claudet, J., and Guidetti, P., 2016, Spillover from marine protected areas to adjacent fisheries has an ecological and a fishery component. Journal for Nature Conservation, 32, 62-66.<br><br>Edgar, G. J., Stuart-Smith, R. D., Willis, T. J., Kininmonth, S., Baker, S. C., Banks, S., ... and Thomson, R. J., 2014, Global conservation outcomes depend on marine protected areas with five key features. Nature, 506(7487), 216-220.<br><br>Erskine, E., Baillie, R., and Lusseau, D., 2021, Marine Protected Areas provide more cultural ecosystem services than other adjacent coastal areas. One Earth, 4(8), 1175-1185.<br><br>Fenberg, P. B., Caselle, J. E., Claudet, J., Clemence, M., Gaines, S. D., García-Charton, J. A., ... and Sørensen, T. K., 2012, The science of European marine reserves: Status, efficacy, and future needs. Marine policy, 36(5), 1012-1021.<br><br>Ferreira, A., Seixas, S., and Marques, J. C., 2015, Bottom-up management approach to coastal marine protected areas in Portugal. Ocean and Coastal Management, 118, 275-281.<br><br>Gill, D. A., Mascia, M. B., Ahmadia, G. N., Glew, L., Lester, S. E., Barnes, M., ... and Fox, H. E., 2017, Capacity shortfalls hinder the performance of marine protected areas globally. Nature, 543(7647), 665-669.<br><br>Humphreys, J., and Clark, R. W., 2020, A critical history of marine protected areas. In Marine protected areas (pp. 1-12). Elsevier.<br><br>ICES, 2024, EU request on spatial trade-off analysis between reducing the extent of mobile bottom-contacting gear (MBCG) disturbance to seabed habitats and potential costs to fisheries. ICES Advice: Special Requests. Report.<br><br>ICES, 2025, Workshop on Nature Restoration and Recovery (WKREST). ICES Scientific Reports. 7:46. 172 pp.<br><br>Lester, S. E., and Halpern, B. S., 2008, Biological responses in marine no-take reserves versus partially protected areas. Marine Ecology Progress Series, 367, 49-56.<br><br>McCrea-Strub, A., Zeller, D., Sumaila, U. R., Nelson, J., Balmford, A., and Pauly, D., 2011, Understanding the cost of establishing marine protected areas. Marine Policy, 35(1), 1-9. Pendleton, L. H., Ahmadia, G. N., Browman, H. I., Thurstan, R. H., Kaplan, D. M., and Bartolino, V., 2018). Debating the effectiveness of marine protected areas. ICES Journal of Marine Science, 75(3), 1156-1159.<br><br>Pendleton L.H., Ahmadia G.N., Browman H.I., et al., 2018, Debating the effectiveness of marine protected areas. ICES J. Mar. Sci. 75: 1156-1159.<br><br>Project Blue4All website.<br><br>Rodríguez-Rodríguez, D., and Martínez-Vega, J., 2022, Ecological effectiveness of marine protected areas across the globe in the scientific literature. In Advances in marine biology (Vol. 92, pp. 129-153). Academic Press.<br><br>Sanchirico, J. N., Cochran, K. A., and Emerson, P. M., 2002, Marine protected areas: economic and social implications.<br><br>Simons, S., Stamatiadou, V., Murillas, A., Delpiazzo, E., Standardi, G., Bosello, F., Key, E., Chen, W., Christiansen, T., Kvisle, K., Liu, J., Merline, A., Bellerby, R., Sulanke, E., Bulleri, F., Visintin, F., Di Cintio, A., Ravaglioli, C., Niccolini, F., Devries, C., Kamermans, |

| Name/type | Marine Protected Areas (MPAs) |
|---|---|
| | P., 2023, Economic costs, benefits and challenges of NBSs. Deliverable 6.2, Project Future MARES. Available at: https://www.futuremares.eu/_files/ugd/753771_cc86fdb9f0d74bc69d3835e290c7c542.pdf (last access: 25 November 2025).<br>The Nature Conservancy, 2022, Sea Change: Costs and Benefits of Marine Protected Areas. Editors: McGowan J., Gammage S., Escovar-Fadul X., Weis S., Hansen A., and Garvey M. Arlington, VA. (pp. 36). |

### *Passive restoration of blue carbon ecosystems*

| Name/type | Passive seagrass and seaweed restoration |
|---|---|
| Spatial scale | Local |
| Spatial and temporal scope of implementation | The earliest recorded kelp restoration projects using passive techniques were implemented in Japan in the 1700s (Wilding et al., 2022). The first scientific studies on seagrass restoration started in the 1930s and focused on *Zostera marina*. In the last few decades, and especially since the 1990s, this measure has been increasingly implemented in different parts of the world, including North America, Europe, Eastern Asia and Oceania (Tan et al., 2020). For kelp, current studies focus mainly on *Macrocystis pyrifera* in California and the genus *Ecklonia* (Wilding et al., 2022). |
| Objective of the measure and main actions implemented | The passive restoration of seagrass and seaweed habitats consists of specific measures to ameliorate the stressors that caused their decline. This includes a wide range of actions, each with its own advantages and disadvantages:<br>• Actions restricting damaging activities such as high-impact fisheries (e.g., banning the use of trawling and other destructive fishing gear, or installing anti-trawling devices);<br>• Regulating small-scale dredging activities or aggregate extraction;<br>• Restricting or regulating the anchoring of boats, or imposing access restrictions;<br>• Improving water quality through the removal of sewage outfalls and agricultural run-off, to tackle eutrophication or sand aggregate extractions (Tan et al., 2020; IUCN, 2021; UNEP, 2020).<br>This measure is often used in combination with active restoration techniques. |
| Estimated economic cost | There is little information in literature reporting specific costs of passive restoration measures as isolated from other types of passive conservation measures (mainly in the context of MPAs), or from active restoration measures. If the measure only restricts activities, costs are lost opportunities, which are difficult to predict.<br>In general, passive restoration is often more cost-effective than active restoration (Puig et al., 2024). A WWF study (Fontcuberta and Piante, 2025) estimated that the establishment of an eco-mooring area for small vessels in the Mediterranean coast of France, consisting in 50 buoys, may incur in the following costs: preliminary studies and design: EUR 160,000-200,000; installation of 50 buoys: EUR 400,000; average annual management and operation costs: EUR 160,000. These costs may be compensated by the establishment of a charge, which in this case was reported as contributing to a revenue of EUR 200,000 per year. |

| Name/type | Passive seagrass and seaweed restoration |
|---|---|
| Environmental Benefits | Successful passive restoration of seagrass meadows allows for the recovery of the key ecosystem services provided by these habitats:<br>• Erosion control (stabilisation and building of sediment);<br>• Carbon sequestration for climate change mitigation;<br>• Increased biodiversity including iconic and highly endangered species (van Katwijk et al., 2016; Thorhaug et al., 2020), and the provision of nursery and foraging area for other marine species (Rogers et al., 2019);<br>• Improvements in nutrient cycling (Unsworth et al., 2025). |
| Social and economic co-benefits | The conservation of seagrass and seaweed habitats may increase fish stock provision (van Katwijk et al., 2016) and related commercial fishing revenues, depending on the species, as well as increase tourism revenues, thanks to improved recreational fishing (Rogers et al., 2019). Moreover, it can increase or restore coastal protection and determine pathogen reduction (Tan et al., 2020). |
| Maintenance needs | Long-term management is necessary, as the complete restoration may take decades or centuries, depending on the stressors and local characteristics; in some cases, corrective actions may be necessary (Bianchelli et al., 2023). |
| Stakeholders' engagement | As for any restoration measure, stakeholders' involvement in all phases of project design and implementation is key to its success, preventing tensions and conflicts, and creating shared visions and objectives for action. |
| Success and/or limiting factors | + Species with significant seed banks and fast-growing species, such as *Zostera* spp. in the Atlantic and Baltic Sea, and *Cymodocea* spp. in the Mediterranean, benefit most from passive restoration strategies (IUCN, 2021).<br><br>+ By predisposing ecosystems for natural recovery, passive restoration measures may be the first step of a multi-tier strategy to abate pressures, paving the way for the implementation of active restoration measures as a second step (Manea et al., 2023).<br><br>+/- The establishment of regulated anchoring areas has low implementation costs and high social acceptability, although it requires hands-on management and regular monitoring (Fontcuberta and Piante, 2025).<br><br>+/- Eco-mooring areas provide no anchoring damage and high safety and service quality, with good user acceptance; however, they entail certain costs of installation and to users, while providing a certain landscape impact (Fontcuberta and Piante, 2025).<br><br>- Species with very small or no seedbank and slow-growing species (e.g., *Posidonia oceanica*) have a relatively low restoration potential. Although they form the most persistent meadows and hold the largest carbon stocks, these species have a low colonisation rate. In these cases, restoration efforts should align with the necessary timeframes (MERCES, 2020). Also, the possibility to combine passive and active restoration techniques should be considered (IUCN, 2021).<br><br>- Previous failures in seagrass restoration have been attributed, *inter alia*, to biotic and abiotic interactions such as predation or physical disturbance; shifts to unsuitable environmental conditions including sediment type or resuspension; or a failure to fully address the original cause of loss (Tan et al., 2020).<br><br>- Seagrass rehabilitation is a slow, site-dependent process (Wilding et al., 2022), and it may take decades or centuries for a successful recolonisation and meadow establishment (Tan et al., 2020). |

| Name/type | Passive seagrass and seaweed restoration |
|---|---|
| | - Success is not guaranteed (Bianchelli et al., 2023), because of changes in environmental conditions (including ocean warming or changes in herbivore abundance), the absence of nearby mature populations to supply propagules, combined with a low dispersal capability of many forest-forming species, and the stabilisation into alternative states, such as urchins or turf algae communities through positive feedback loops (Wilding et al., 2022). In this case, active restoration may be considered to foster ecosystem recovery (Bianchelli et al., 2023).<br>- The establishment of no-anchoring areas is simple and has no implementation costs, while offering strong protection; however, it may encounter poor social acceptability and lack of control (Fontcuberta and Piante, 2025). |
| Trade-offs | Restrictive measures such as fishery no-take zones or no-anchoring zones may conflict with existing uses of the marine environment and have negative impacts on the livelihoods of dependent communities (Herrera et al., 2022).<br>Moreover, there may be trade-offs between long-term, large-scale passive restoration and small-scale, quick-gain active restoration measures, especially in case of limited funds, or of transboundary areas where coordination between different authorities and government levels is necessary. |
| Links to MSFD drivers-pressures | Pressures:<br>• Biological:<br>○ Loss of, or change to, natural biological communities due to cultivation of animal or plant species;<br>○ Disturbance of species (e.g. where they breed, rest and feed) due to human presence;<br>○ Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities)<br>• Physical<br>○ Physical disturbance to the seabed;<br>○ Physical loss (due to permanent changes of seabed substrate or morphology and to extraction of seabed substrate);<br>○ Changes to hydrological conditions;<br>• Substances, litter and energy<br>○ Input of nutrients – diffuse sources, point sources, atmospheric deposition;<br>○ Input of organic matter – diffuse sources and point sources.<br>Contribution to achieve GES: D1, D3, D4, D5, D6, D7. |
| Links to other policy objectives | Global: SGD 14.2, 14.4; 2021-2030 UN Decade on Ecosystem Restoration; CBD and the Kunming-Montreal Framework Global Biodiversity Framework; CMS; UNFSA; Paris Agreement; Sendai Framework.<br>EU: EU Biodiversity Strategy for 2030; NRR; MSFD; WFD; CFP; Climate Law; EU Action Plan on the Sendai Framework. |
| References | Bayraktarov, E., Saunders, M. I., Abdullah, S., Mills, M., Beher, J., Possingham, H. P., ... and Lovelock, C. E., 2016, The cost and feasibility of marine coastal restoration. Ecological applications, 26(4), 1055-1074.<br>Castejón-Silvo, I., and Terrados, J., 2021, Poor success of seagrass Posidonia oceanica transplanting in a meadow disturbed by power line burial. Marine Environmental Research, 170, 105406. |

| Name/type | Passive seagrass and seaweed restoration |
|---|---|
| | Fontcuberta, A. and Piante, C., 2025, Protecting 100% of *Posidonia* seagrass meadows in the Mediterranean by 2030 – toolkit for the establishment of eco-mooring areas for recreational vessels under 24 metres, WWF, Marseille, 50 pages.<br><br>Herrera, M., Tubío, A., Pita, P., Vázquez, E., Olabarria, C., Duarte, C. M., and Villasante, S., 2022, Trade-offs and synergies between seagrass ecosystems and fishing activities: A global literature review. *Frontiers in Marine Science*, *9*, 781713.<br><br>IUCN, 2021, Manual for the creation of Blue Carbon projects in Europe and the Mediterranean. Otero, M. (Ed)., 144 pages.<br><br>Liversage, K., and Chapman, M. G., 2018, Coastal ecological engineering and habitat restoration: incorporating biologically diverse boulder habitat. Marine Ecology Progress Series, 593, 173-185.<br><br>Manea, E., Agardy, T., and Bongiorni, L., 2023, Link marine restoration to marine spatial planning through ecosystem-based management to maximize ocean regeneration. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *33*(11), 1387-1399.<br><br>MERCES, 2020, Marine Ecosystem Restoration in Changing European Seas. Findings from the Field. A Summary for Policy Makers. 23pp.<br><br>Puig, P., Ben Lamine, E., and Cavaliere, F., 2024, Best practices and future directions on ecosystem and species restoration for Mediterranean Marine Protected Areas: A literature review.<br><br>Riisager-Simonsen, C., Fabi, G., van Hoof, L., Holmgren, N., Marino, G., and Lisbjerg, D., 2022, Marine nature-based solutions: Where societal challenges and ecosystem requirements meet the potential of our oceans. *Marine Policy*, *144*, 105198.<br><br>Tan, Y. M., Dalby, O., Kendrick, G. A., Statton, J., Sinclair, E. A., Fraser, M. W., ... and Sherman, C. D., 2020, Seagrass restoration is possible: insights and lessons from Australia and New Zealand. *Frontiers in Marine Science*, *7*, 534963.<br><br>Thorhaug, A., Belaire, C., Verduin, J. J., Schwarz, A., Kiswara, W., Prathep, A., ... and Dorward, S., 2020, Longevity and sustainability of tropical and subtropical restored seagrass beds among Atlantic, Pacific, and Indian Oceans. Marine pollution bulletin, 160, 111544.<br><br>Rogers, A. A., Burton, M. P., Statton, J., Fraser, M. W., Kendrick, G., Sinclair, E., ... and McLeod, I. M., 2019, Benefits and costs of alternate seagrass restoration approaches. *Report to the National Environmental Science Programme, Marine Biodiversity Hub*, *43*.<br><br>Bacci, T., La Porta, B., Maggi, C., Nonnis, O., Paganelli, D., Rende, F. S., and Targusi, M., 2014, Conservazione e gestione della naturalità negli ecosistemi marino-costieri. Il trapianto delle praterie di Posidonia oceanica, 1-97.<br><br>UNEP-Nairobi Convention/WIOMSA, 2020, Guidelines for Seagrass Ecosystem Restoration in the Western Indian Ocean Region. UNEP, Nairobi, 63 pp. Available at: www.nairobiconvention.org/ and www.wiomsa.org<br><br>van Katwijk, M. M., Thorhaug, A., Marbà, N., Orth, R. J., Duarte, C. M., Kendrick, G. A., ... and Verduin, J. J., 2016, Global analysis of seagrass restoration: the importance of large-scale planting. Journal of Applied Ecology, 53(2), 567-578.<br><br>Wilding, C. M., Earp, H. S., Cooper, C. N., Lubelski, A., and Smale, D. A., 2022, British Kelp Forest Restoration: Feasibility Report. Natural England. |

### *Passive coastal wetlands restoration*

| Name/type | Passive coastal wetlands restoration |
|---|---|
| Spatial scale | Local |
| Spatial and temporal scope of implementation | The first efforts in coastal wetlands restoration started in the 1960s (Moore and Kumble, 2024). In the 1990s, interest in wetland restoration has significantly increased globally, thanks to the implementation of conservation actions and policies around the world, such as the US 'no net loss' of wetlands (Zhao et al., 2016). |
| Objective of the measure and main actions implemented | Marine and coastal wetlands comprise ecosystems such as mangroves, lagoons, seagrass beds, saltmarshes, estuaries, tidal flats, kelp forests and coral reefs. The aim of restoration is to return these ecosystems from a disturbed or altered status, caused by anthropogenic activities, to a pristine status. Passive restoration of coastal wetlands focuses on the elimination of the influencing factors that have led to the degradation or destruction of a coastal wetland, by enhancing ecohydrological processes to rebuild the hydrogeomorphology, ensuring the wetland's self-restoration to a healthy state under natural conditions (Zhao et al., 2016).<br><br>Passive restoration includes actions such as the prevention of over-grazing (or using grazing to prevent overgrowth) or reduction of the influx of nutrients from sewage, agricultural run-off and industrial waste, as well as the conversion of cropland to marshes and grass (Zhao et al., 2016); the introduction of appropriate legislation; the protection of ecologically important habitats; and the reduction of intense development along the coast (IUCN, 2021). |
| Estimated economic cost | Wang et al. (2022) provided an estimation of the economic cost of several passive restoration actions for salt marshes (from cheapest to most expensive):<br>• Hydrological restoration: USD 26,500-64,600 per hectare;<br>• Sediment and substrate recovery: USD 26,500-64,600 per hectare;<br>• Invasion control: USD 15,700-72,000 per hectare;<br>• Hard structure restoration methods: USD 56,000-97,000 per hectare;<br>• Removing disturbance: USD 48,000-130,000 per hectare.<br><br>An estimation of the effectiveness of coastal wetland restoration for carbon sequestration indicates a cost of USD 1,800 per tonne of carbon, a value that is significantly lower than that for inland wetlands (USD 4,200-49,200 per tonne; Taillardat et al., 2020). |
| Environmental Benefits | Coastal wetlands restoration has the potential to decrease carbon emissions, increase carbon sequestration rates and build long-term carbon stocks (Fennessy and Lei, 2018), while increasing the provision of a wide range of ecosystem services:<br>• Carbon sequestration – Coastal wetlands have a net long-term carbon sequestration effect, which is only partially offset by limited $CH_4$ emissions (Taillardat et al., 2020). Salt marshes, estuarine forests, and seagrass beds have a high ability to act as net GHG sink, while mangroves have a high ability to hold long-term carbon stock (Fennessy and Lei, 2018).<br>• Water quality improvement (Liu et al., 2021) - The improvement of hydrological connectivity and the recovery of underground hydrology can decrease the concentration of nitrogen, phosphorus, and bacteria, accrete sediment retention and lower soil erosion (Zhao, 2016). Moreover, wetlands increase groundwater retention and maintain atmospheric water cycles.<br>• Biodiversity maintenance (Zhao et al., 2016) - Coastal wetlands provide nursery and shelter places for numerous species, including benthic fauna, fish, and migrating birds (Wang et al., 2022). |

| Name/type | Passive coastal wetlands restoration |
|---|---|
| Social and economic co-benefits | Coastal wetlands improve water quality, ensure groundwater recharge, support commercial fisheries, and increase natural coastal protection, reducing human vulnerability to weather-related events (Fennessy and Lei, 2018; Liu et al., 2021) through storm buffering and protection from windstorm and shore erosion (Zhao et al., 2016). Moreover, coastal wetlands can support tourism and sightseeing, recreation, education and research activities (Wang et al., 2022).<br><br>Restoration projects may also support the local economy and job creation; in the US, coastal wetlands restoration in the Chesapeake Bay, the Great Lakes and Everglades was estimated to generate an economic output of USD 4.3 billion and more than 3,200 jobs (Restore America's Estuaries, 2011). |
| Maintenance needs | Remedial techniques must be maintained regularly to remain effective. Focused monitoring is essential to assess the success of restoration and provide information for future actions (Adnitt et al., 2007), especially because of the slow speed of passive recovery. |
| Stakeholders' engagement | It is fundamental to ensure an equitable participation of local stakeholders (including policy makers or government officials, private-sector businesses, NGOs, and researchers) in the decision-making and management processes of any restoration project, including coastal wetlands, to avoid negative socioeconomic outcomes such as increased lack of trust and conflict between users and officials, and an exacerbation of unsustainable practices (Moore and Kumble, 2024). |
| Success and/or limiting factors | + Restoration techniques for coastal wetlands that include salt marshes and mudflats are more advanced than for other habitat types (IUCN, 2021).<br><br>+ It is important to establish criteria to prioritise the selection of salt marshes restoration sites, considering elements such as ownership, hydrological restrictions, the presence of invasive plant species, history of dredged material or other fill placement, adjacent land use, local communities' concerns, and to evaluate the alternatives that offer the best chance of achieving the greatest outputs (IUCN, 2021).<br><br>+ In tidal marsh restoration, the tidal regime and land elevation are critical parameters as they determine the extent, duration and timing of submergence, and consequently, if a site can adjust to rising sea levels (Fennessy and Lei, 2018).<br><br>+ Restoring and managing water levels, capturing the full range of tidal exchange to promote vegetation reestablishment and sediment trapping, and planning restoration in the context of the surrounding landscape increases site resilience and the recovery of the processes that lead to carbon accumulation (Fennessy and Lei, 2018).<br><br>- Climate change is expected to alter hydrological regimes, and different wetland habitats will have different responses, and the success of restoration will depend on how to adapt the management and techniques adopted to address these effects (Erwin, 2009). |
| Trade-offs | While in Atlantic marshes, low-density grazing can enhance carbon stocks because of vegetation setbacks, in non-Atlantic marshes, passive restoration may not be possible, or the recovery capacity for the ecosystem may be very low, and active restoration would be more appropriate (IUCN, 2021).<br><br>Moreover, because each species has different water quality, salinity and hydrology requirements, the management techniques to increase or enhance habitat for one species may have adverse impacts on others (IUCN, 2021). |

| Name/type | Passive coastal wetlands restoration |
|---|---|
| Links to MSFD drivers-pressures | Pressures:<br>• Biological:<br>  ○ Loss of, or change to, natural biological communities due to cultivation of animal or plant species;<br>  ○ Disturbance of species (e.g. where they breed, rest and feed) due to human presence;<br>  ○ Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities);<br>• Physical:<br>  ○ Physical disturbance to seabed (temporary or reversible);<br>  ○ Physical loss (due to permanent change of seabed substrate or morphology and to extraction of seabed substrate);<br>  ○ Changes to hydrological conditions;<br>• Substances, litter and energy:<br>  ○ Input of nutrients – diffuse sources, point sources, atmospheric deposition;<br>  ○ Input of organic matter – diffuse sources and point sources.<br>Contribution to achieve GES: D1, D3, D4, D5, D6, D7. |
| Links to other policy objectives | Global: SDG 14.2, 14.4; CBD and the Global Biodiversity Framework; Ramsar Convention; CMS; Paris Agreement; Sendai Framework.<br>EU: EU Biodiversity Strategy for 2030; NRR; MSFD; WFD; EU Climate Law; EU Action Plan on the Sendai Framework. |
| References | Adnitt, C., Brew, D., Cottle, R., Hardwick, M., John, S., Leggett, D., McNutty, S., Meakins, N., Staniland, R., 2007, Saltmarsh management manual. Joint Defra / Environment Agency Flood and Coastal Erosion Risk Management R & D Programme. R & D Technical Report SC03.<br>Erwin, K. L., 2009, Wetlands and global climate change: the role of wetland restoration in a changing world. Wetlands Ecology and management, 17(1), 71-84.<br>Fennessy, S.M. and Lei, G., 2018, Wetland restoration for climate change resilience. Ramsar Briefing Note No.10. Gland, Switzerland: Ramsar Convention Secretariat.<br>IUCN, 2021, Manual for the creation of Blue Carbon projects in Europe and the Mediterranean. Otero, M. (Ed)., 144 pages.<br>Liu, Z., Fagherazzi, S., and Cui, B., 2021, Success of coastal wetlands restoration is driven by sediment availability. *Communications Earth and Environment*, *2*(1), 44.<br>Moore, A. C., and Kumble, S., 2024, Community-based conservation and restoration in coastal wetlands: A review. *Wetlands*, *44*(5), 62.<br>Restore America's Estuaries., 2011, Jobs and Dollars: Big Returns from Coastal Habitat Restoration.<br>Taillardat, P., Thompson, B. S., Garneau, M., Trottier, K., and Friess, D. A., 2020, Climate change mitigation potential of wetlands and the cost-effectiveness of their restoration. Interface focus, 10(5), 20190129.<br>Wang, J. J., Li, X. Z., Lin, S. W., and Ma, Y. X., 2022, Economic evaluation and systematic review of salt marsh restoration projects at a global scale. Frontiers in Ecology and Evolution, 10, 865516.<br>Zhao, Q., Bai, J., Huang, L., Gu, B., Lu, Q., and Gao, Z., 2016, A review of methodologies and success indicators for coastal wetland restoration. *Journal 2*, *60*, 442-452. |

## 3.2 Category 2: Improved multifunctionality of managed marine ecosystems

This category includes "the targeted use of 'challenge specific' actions which aim to restore or enhance selected types of naturally occurring biodiversity and ecosystem services in managed areas where they need to coexist with other marine activities" (Riisager-Simonsen et al., 2022).

IUCN (2021) defines these measures as direct interventions to correct a state of degradation in ecosystems that do not have the capacity to recover by themselves after the removal of the environmental stressors. Sometimes these actions are called 'active restoration', though all actions include active interventions.

### *Active seagrass and seaweed restoration*

| Name/type | Active seagrass and seaweed restoration |
|---|---|
| Spatial scale | Local |
| Spatial and temporal scope of implementation | Initial studies on active seagrass restoration started in the 1930s and focused on eelgrass (*Zostera marina*). The first interventions to actively restore these ecosystems started in the 1970s (van Katwijk et al., 2016). In the last few decades, and especially since the 1990s, this measure has been increasingly implemented in different parts of the world, including North America, Europe, Eastern Asia and Oceania (Tan et al., 2020). |
| Objective of the measure and main actions implemented | Several methods have been employed to restore/re-establish/replant seagrass and seaweed: the physical planting of seagrasses; the transplant of shoots, seedlings or rhizome fragments; the distribution or planting of seagrass seeds; sand capping (replenishing sand on seabed) to restore lost substrate for seagrasses; and coastal engineering techniques to modify sediment and/or hydrodynamic regimes to enhance the settlement of seagrass seeds, propagules or fragments (IUCN, 2021, Arnkil et al., 2024).<br>Different species of seagrass and macroalgae have been replanted or transplanted in literature, depending on the marine region:<br>• Atlantic Sea: *Thalassia testudinum, Halodule wrightii, Syringodium filiforme, Halophila englemanii, Ruppia maritima, Zostera marina, Saccharina latissima;*<br>• Baltic Sea: *Zostera marina, Chara tomentosa, Chara vulgaris, Chara globularis, Fucus vesiculosus;*<br>• Indo-Pacific: *Enhalus acoroides, Thalassia hemprichii, Enhalus acoroides, Halodule uninervis, H.pinifolia, Cymodocea serrulata, Cymodocea rotundata, Thalassadendron ciliatum, Halophila decipiens, Posidonia australis, Posidonia coriacea, Amphibolis griffithsii, Amphibolis Antarctica* (Thorhaug et al., 2020).<br>• Mediterranean Sea: *Zostera nolteii, Cymodocea nodosa*, *Posidonia Oceanica* (Bacci et al., 2019; Mancuni et al., 2021; NextGenerationEU Project Marine Ecosystem Restoration); *Cystoseira s.l.* (ROC-POP Life Project; REEForest Life Project). |
| Estimated economic cost | Seagrass restoration projects involve several types of costs, including mapping and ground-truthing, planting (sprigs or sods) or sowing (seeds), monitoring, community participation, contractor involvement, and government oversight (UNEP, 2020). However, only a limited number of studies provide detailed cost estimates, and comprehensive cost–benefit analyses at appropriate spatial scales remain scarce (Wilding et al., 2022).<br>In general, active seagrass restoration is expensive due to the high costs associated with manual planting, while success rates are often relatively low. Some evidence suggests that combining seed-based approaches with the transplantation of shoots, |

| Name/type | Active seagrass and seaweed restoration |
|---|---|
| | seedlings, or rhizome fragments can improve cost-effectiveness (IUCN, 2021). Costs may also be reduced through the effective engagement of local communities, stakeholders, and citizen volunteers (UNEP, 2020).<br><br>However, these cost estimates are likely underestimated for key Mediterranean species such as *Posidonia oceanica* and for *Cystoseira* forests. In the case of *P. oceanica*, seed-based restoration requires long hatchery periods—potentially several years—to produce the large number of shoots needed (typically 20–32 shoots/m² in the Mediterranean). Alternatively, transplantation from donor meadows requires prior ecological characterization and strict limitations on harvesting (no more than ~2 shoots/m²) to avoid damaging source ecosystems. For *Cystoseira s.l.* forests, restoration often requires the establishment of dedicated laboratory facilities for ex situ cultivation. Moreover, for both habitat types, cost assessments should include additional components that are often overlooked, such as high-resolution bathymetric surveys (using ROVs and diver inspections) for site selection and post-restoration evaluation, the development and implementation of coastal morphodynamic models, and provisions for restoration failure and recovery actions. For *P. oceanica*, total costs also vary significantly depending on the specific shoot transplantation technique applied.<br><br>Worldwide, typical costs range from USD 590,000 to 910,000 per hectare (UNEP, 2020). An estimation for Australia points to AUSD 178,000-190,000 per hectare for replanting, and of AUSD 32,000-42,000 per hectare for reseeding, with a cost-benefit ratio of 0.49 for replanting and 2.51 for reseeding. In Sweden, re-planting of shoots was estimated to cost EUR 120,000-600,000 per hectare Kraufvelin et al., 2021). In Finland, this was estimated closer to EUR 120,000 per hectare, as good success was achieved without additional structures (Arnkil et al., 2024). Figures are lower in case activities and are volunteer-based (cost-benefit ratio 1.8 for replanting and 7.57 for reseeding; Rogers et al., 2019). In Europe, a recent estimation for the restoration of kelp forests in Norway reported an estimated costs for restoration from 76 to 634.5 NOK/m². Traps and ROV were identified as the most cost-effective strategies (Simons et al., 2023).<br><br>It has been estimated that existing commitments do not suffice to cover the relative restoration costs in order to reach the GBF goals (i.e. restore 30% of degraded seagrass meadows by 2030) (Duarte et al. 2025). |
| Environmental Benefits | The restoration of seagrass and seaweed ecosystems may increase the provision of related ecosystem services:<br><br>• Erosion control (stabilisation and building of sediment), although with a high variability, spatially and temporally across seasons and years (Liversage and Chapman, 2018);<br>• Carbon sequestration for climate change mitigation – Thorhaug et al. (2020) reported a mean carbon sequestration of seagrass of 38.7Mg Corg per hectare;<br>• Increased biodiversity, including iconic and highly endangered species (van Katwijk et al., 2016; Thorhaug et al., 2020), as well as the provision of nursery and foraging areas for other marine species (Rogers et al., 2019);<br>• Improvements in nutrient cycling (Unsworth et al., 2025). |
| Social and economic co-benefits | The restoration of seagrass and seaweed may increase fish stock provision (van Katwijk et al., 2016) and commercial fishing revenues, although with a high variability depending on the species (Rogers et al., 2019). A Swedish study estimated that 1 hectare of seagrass meadow supports 626 kg of cod and 7,535 individuals of perch |

| Name/type | Active seagrass and seaweed restoration |
|---|---|
| | and binds 98.6t of carbon and 466kg of nitrogen (Cole and Moksnes, 2016), with an annual monetary value of about EUR 950. Moreover, there can be an increase in tourism revenues because of improved recreational fishing benefits (Rogers et al., 2019). |
| Maintenance needs | Fast-growing species have a shortened project duration, while slow-growing species such as *P. oceanica* need long-term sustained efforts (Bacci et al., 2014; IUCN, 2021). The seagrass plants restored generally have a high longevity (6-47 years), provided the planting is well-sited and well-executed, without significant differences across species (Thorhaug et al., 2020). |
| Stakeholders' engagement | Limited attempts have been reported to frame restoration to leverage the benefits of community-supported action in terms of enhancement of social capital, improvement of equality. An early engagement of regulators and government agencies can help reach wider networks and support long-term success. On the contrary, insufficient engagement may lead to unaddressed conflicts and lack of recognition, support or potentially sabotaging operations (Unsworth, 2025). |
| Success and/or limiting factors | + Large-scale planting is beneficial, as it increases trial survival chances and enhances self-sustaining feedback (van Katwijk et al., 2016).<br><br>+ A sheltered location with an adequate light environment is conducive to the success of the restoration project (van Katwijk et al., 2016).<br><br>+ As with any restoration project, the removal of the pressures and stressors is key for the success of the project (van Katwijk et al., 2016, Arnkil et al., 2024). Especially, it is recommended to protect the restored area from illegal trawling activities, marine contamination, and poor water quality (Bayraktarov et al., 2016).<br><br>+ Donor bed proximity is positively correlated with effectiveness, as the environment is already suitable for seagrass growth, locally adapted plants are used (van Katwijk et al., 2016), and handling time is minimised (IUCN, 2021).<br><br>+ The anchoring of rhizome fragments or seedlings and the use of weights enhance survival and success (van Katwijk et al., 2016).<br><br>- Transplantation of seeds often leads to incomplete germination (Bayraktarov et al., 2016).<br><br>- Disturbed, non-consolidated substrata will preclude *P. oceanica* rehabilitation through planting. Preservation of meadow substratum (i.e. dead matter) is a critical element of success (Castejón-Silvo and Terrados, 2021). |
| Trade-offs | "Engineered" solutions are extremely high-cost and have possible side effects, including seagrass disruptions due to loose sediments creating an increase in turbidity, dredge and fill, or changing/increasing sediment transport away from shorelines (Thorhaug et al., 2020).<br><br>Moreover, the focus on maximising only one or a few ecosystem services may increase the risk of project failure, as it can lead to regime shifts with unfavourable and unexpected sudden loss of other services, and lead to conflicts among stakeholders on the perceived benefits/disbenefits (Unsworth et al., 2025). |
| Links to MSFD drivers-pressures | Pressures:<br>• Biological:<br>  ○ Loss of, or change to, natural biological communities due to cultivation of animal or plant species; |

| Name/type | Active seagrass and seaweed restoration |
|---|---|
| | ○ Disturbance of species (e.g. where they breed, rest and feed) due to human presence;<br>○ Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities)<br>• Physical<br>○ Physical disturbance to the seabed;<br>○ Physical loss (due to permanent changes of seabed substrate or morphology and to extraction of seabed substrate);<br>○ Changes to hydrological conditions;<br>• Substances, litter and energy<br>○ Input of nutrients – diffuse sources, point sources, atmospheric deposition;<br>○ Input of organic matter – diffuse sources and point sources.<br>Contribution to achieve GES: D1, D3, D4, D5, D6, D7. |
| Links to other policy objectives | Global: SDG 14.2, 14.4; 2021-2030 UN Decade on Ecosystem Restoration; CBD and the Kunming-Montreal Framework Global Biodiversity Framework; CMS; UNFSA; Paris Agreement; Sendai Framework.<br>EU: EU Biodiversity Strategy for 2030; NRR; MSFD; WFD; CFP; Climate Law; EU Action Plan on the Sendai Framework. |
| References | Arnkil, A., Bäck, A., Haavisto, F., Keskinen, E., Kuningas, S., Laine, A., Nieminen, A., Puttonen, I., Raitanen, H. ja Salovius-Laurén, S. 2024, A Review of Marine Nature Restoration Work and Methods Used in Finland. Nature Protection Publication in Metsähallitus. Series A 252, 139 p., https://julkaisut.metsa.fi/julkaisu/a-review-of-marine-nature-restoration-work-and-methods-used-in-finland/<br>Bacci, T., La Porta, B., Maggi, C., Nonnis, O., Paganelli, D., Rende, F. S.,Targusi, M., 2014, Conservazione e gestione della naturalità negli ecosistemi marino-costieri. *Il trapianto delle praterie di Posidonia oceanica*, 1-97.<br>Bacci, T., Scardi, M., Calvo, S., Tomasello, A., Bulleri, C., Bertasi, F., La Porta, B., 2019, Final report on *Posidonia oceanica* transplanting case studies analysis, Azione A.3, Project S.E.POS.S.O. LIFE16 GIE/IT/000761.<br>Bayraktarov, E., Saunders, M. I., Abdullah, S., Mills, M., Beher, J., Possingham, H. P., ... and Lovelock, C. E., 2016, The cost and feasibility of marine coastal restoration. *Ecological applications*, *26*(4), 1055-1074.<br>Castejón-Silvo, I., and Terrados, J., 2021, Poor success of seagrass Posidonia oceanica transplanting in a meadow disturbed by power line burial. Marine Environmental Research, 170, 105406.<br>Cole, G. S. and Moksnes, P.-O., 2016, Valuing multiple eelgrass ecosystem services in Sweden: fish production and uptake of carbon and nitrogen. – Frontiers in Marine Science 2: 121.<br>IUCN, 2021, Manual for the creation of Blue Carbon projects in Europe and the Mediterranean. Otero, M. (Ed)., 144 pages.<br>Kraufvelin, P., Olsson, J., Bergström, U., Bryhn, A. and Bergström, L., 2021, Restoration measures for coastal habitats in the Baltic Sea: cost-efficiency and areas of highest significance and need. – HELCOM ACTION 2021, https://helcom.fi/helcom-at-work/projects/action/ |

| Name/type | Active seagrass and seaweed restoration |
|---|---|
| | Liversage, K., and Chapman, M. G., 2018, Coastal ecological engineering and habitat restoration: incorporating biologically diverse boulder habitat. Marine Ecology Progress Series, 593, 173-185.<br><br>Mancini, G., Casoli, E., Ventura, D., Lasinio, G. J., Belluscio, A., & Ardizzone, G. D., 2021, An experimental investigation aimed at validating a seagrass restoration protocol based on transplantation. *Biological Conservation*, *264*, 109397.<br><br>Moksnes, P.-O., Gipperth, L., Eriander, L., Laas, K., Cole, S. G. and Infantes, E., 2016, Handbook for eelgrass restoration in Sweden – national guideline. Swedish Agency for Marine and Water Management, Gothenburg, Sweden.<br><br>Simons, S., Stamatiadou, V., Murillas, A., Delpiazzo, E., Standardi, G., Bosello, F., Key, E., Chen, W., Christiansen, T., Kvisle, K., Liu, J., Merline, A., Bellerby, R., Sulanke, E., Bulleri, F., Visintin, F., Di Cintio, A., Ravaglioli, C., Niccolini, F., Devries, C., Kamermans, P., 2023, Economic costs, benefits and challenges of NBSs. Deliverable 6.2, Project Future MARES.<br><br>Tan, Y. M., Dalby, O., Kendrick, G. A., Statton, J., Sinclair, E. A., Fraser, M. W., ... and Sherman, C. D., 2020, Seagrass restoration is possible: insights and lessons from Australia and New Zealand. *Frontiers in Marine Science*, *7*, 534963.<br><br>Thorhaug, A., Belaire, C., Verduin, J. J., Schwarz, A., Kiswara, W., Prathep, A., ... and Dorward, S., 2020, Longevity and sustainability of tropical and subtropical restored seagrass beds among Atlantic, Pacific, and Indian Oceans. *Marine pollution bulletin*, *160*, 111544.<br><br>UNEP-Nairobi Convention/WIOMSA, 2020, Guidelines for Seagrass Ecosystem Restoration in the Western Indian Ocean Region. UNEP, Nairobi, 63 pp. Available at: www.nairobiconvention.org/; www.wiomsa.org.<br><br>Unsworth, R. K., Jones, B. L., Bertelli, C. M., Coals, L., Cullen-Unsworth, L. C., Mendzil, A. F., ... and Evans, A. J., 2025, Ten golden rules for restoration to secure resilient and just seagrass social-ecological systems. Plants, People, Planet, 7(1), 33-48.<br><br>van Katwijk, M. M., Thorhaug, A., Marbà, N., Orth, R. J., Duarte, C. M., Kendrick, G. A., ... and Verduin, J. J., 2016, Global analysis of seagrass restoration: the importance of large-scale planting. Journal of Applied Ecology, 53(2), 567-578.<br><br>Wilding, C. M., Earp, H. S., Cooper, C. N., Lubelski, A., and Smale, D. A., 2022, British Kelp Forest Restoration: Feasibility Report. Natural England. |

### *Restoration of sub-tidal boulder structures*

| Name/type | Restoration of sub-tidal boulder structures |
|---|---|
| Spatial scale | Local |
| Spatial and temporal scope of implementation | The first temperate reef restoration in European waters occurred at Laesø Trindel in Kattegat, Denmark (Støttrup et al., 2014). Since then, more than 40 projects have been completed in Danish waters (Dahl et al., 2024), and several others all over the world. |
| Objective of the measure and main actions implemented | Marine reefs are important habitats, as they provide refuge for fish and a hard substrate for benthic fauna and macroalgal forests. In previous decades, subtidal boulder structures have been extracted from coastal reefs for the construction of harbours and coastal protection (Støttrup et al., 2014), or have been impacted by pollution, sedimentation, and bait collection (Liversage and Chapman, 2018). Restoration aims at the recovery of essential threatened habitats and the associated |

| Name/type | Restoration of sub-tidal boulder structures |
|---|---|
| | spatial heterogeneity and biodiversity (Riisager-Simonsen et al., 2022). The restoration of boulder reefs may have distinct objectives:<br>• Protection or restoration of a specific habitat type, such as seaweed forests;<br>• Preservation or increase of biodiversity and well-functioning food chains;<br>• Production of food for fish;<br>• Restoration of the stability of a reef;<br>• Strengthening of blue corridors;<br>• Improvement of water quality; and<br>• Restoration of fish populations (Dahl et al., 2024).<br>Examples of restoration projects include the creation of boulder habitats for sea ranching of abalone fisheries, using either artificial materials (such as concrete and plastic) or natural rocks (quarried boulders, rock pavers or blocks; Liversage and Chapman, 2018). In the case of Kattegat, Denmark, the intervention aimed at increasing complexity by restoring larger boulders, creating more relief and providing a physically stable substrate for the development of macroalgae (Støttrup et al., 2014).<br>The boulder habitat may be introduced to the base of seawalls either by leaving building rubble after construction, or by replacing the armouring with a "living shoreline" including sand dunes, beach, saltmarsh or mangrove, and the restoration of natural boulder fields using boulders of different shapes and dimensions (Liversage and Chapman, 2018). |
| Estimated economic cost | The restoration is relatively low cost and has a high chance of success (Liversage and Chapman, 2018). Examples from Danish implemented projects indicate costs ranging from DKK 3.9 million for the restoration of an area of 4,300 $m^2$, to DKK 27.7 million for the placement of 100,000 tonnes of boulders (Dahl et al., 2024). |
| Environmental Benefits | The restoration of sub-tidal boulder structures may generate the following environmental benefits:<br>• Greater abundance of species, including species of commercial interest – The experience in Kattegat, Denmark, showed a recolonisation with macroalgae, which normally dominate the physical structure of temperate reefs. This drove the dynamics of fish recruitment and led to an increase in fish populations and diversity, including the residency time of cod and other commercially viable species (Støttrup et al., 2014; Kristensen et al., 2017).<br>• Contribution to mitigate the negative impacts of climate change on marine biodiversity, by contrasting the reduction of intertidal habitats induced by sea level rise and the increase in extreme weather events (Liversage and Chapman, 2018).<br>• Improvements in carbon sequestration (Riisager-Simonsen et al., 2022), by fostering carbon-sequestrating species.<br>• Shoreline stabilisation (Liversage and Chapman, 2018).<br>• Boulders can be placed to create local upwelling and increase oxygen transport to the bottom water (Dahl et al., 2024). |
| Social and economic co-benefits | The restoration of sub-tidal boulder structures supports the maintenance and development of local coastal communities, thanks to the re-establishment of commercial fish species population (Riisager-Simonsen et al., 2022). Moreover, it can attract divers and stimulate local tourism activities. |

| Name/type | Restoration of sub-tidal boulder structures |
|---|---|
| Maintenance needs | Although this is a one-off intervention, it is fundamental to monitor the development of the restored area to assess the effectiveness of restoration. After the successful restoration, the competent authorities should decide on the future management of the area, considering whether the habitat should be further protected (e.g., by including it in a protected area), or if specific measures should be imposed (e.g., ban on fishing; Dahl et al., 2024). |
| Stakeholders' engagement | Public and stakeholders' involvement are important to secure ownership of challenges and problems. A plan should be prepared for how to involve the public in all phases of the project, and ensure a transparent decision-making process, open to contribution from all actors before taking decisions.<br>Also, stakeholders should be identified; typically, they include local authorities and citizens, commercial navigation, the fishing industry, anglers, divers, local nature and recreation associations, and local tourist associations. Moreover, their contribution in terms of knowledge and experience should be given appropriate space (Dahl et al., 2016). |
| Success and/or limiting factors | + Fish survivorship is greater when multiple layers of material are created (Liversage and Chapman, 2018).<br>+ Initial seeding may be useful, as the presence of conspecifics in a newly deployed habitat can support subsequent recruitment (Liversage and Chapman, 2018).<br>+ It is fundamental to consider the exposure to water motion, which can cause disturbance of substrata and large reductions in habitat value (Liversage and Chapman, 2018).<br>+ Boulder size should be calibrated according to the physical environment and budgeted costs (Dahl et al., 2024). The size and stability of boulders affect the assemblages not only of sessile species, but also of mobile species such as abalone (Liversage and Chapman, 2018).<br>+ It is important to assess the capacity of the seabed to support the weight of the restored reef before implementing this measure, to avoid the partial or complete sinking of the reef through the sediment (Støttrup et al., 2017).<br>+ Natural boulders should be used for restoration, as they ensure a surface structure for which algae and benthic animals have optimised their attachment structures. The best types of boulders are those sourced from disused piers in connection with harbour expansion; also, boulders collected from farmers fields or from infrastructure projects may be employed, as well as quarry stones (Dahl et al., 2024).<br>- Boulders should be placed far from shipping lanes and other trafficked areas, especially in shallow areas (Dahl et al., 2024).<br>- Created habitats rarely mimic natural habitats, and it may take decades to fully develop ecological functions (Liversage and Chapman, 2018). For example, in the Blue Reef project implemented in Denmark, succession and biomass build-up took around 10 years (Dahl et al., 2024).<br>- The use of gabion baskets for coastal defence provides useful habitats, but it is not considered a suitable option in the open-coast with increased wave energy (Liversage and Chapman, 2018). |

| Name/type | Restoration of sub-tidal boulder structures |
|---|---|
| Trade-offs | Depending on the geometrical properties of the reef and local hydrodynamic conditions, reefs located close to coastal areas may impact coastal erosion and deposition rates (Støttrup et al., 2017). Also, the type of material employed for boulders may play a role, affecting the development of associated assemblages (Green et al., 2012). |
| Links to MSFD drivers-pressures | Pressures:<br>• Biological:<br>  ○ Disturbance of species (e.g. where they breed, rest and feed) due to human presence;<br>  ○ Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities);<br>• Physical:<br>  ○ Physical disturbance to the seabed (temporary or reversible);<br>  ○ Physical loss (due to permanent change of seabed substrate or morphology and to extraction of seabed substrate);<br>  ○ Changes to hydrological conditions;<br>Contribution to achieve GES: D1, D3, D4, D7. |
| Links to other policy objectives | Global: SDG 14.2, 14.4; 2021 UN Decade on Ecosystem Restoration; CBD and the Global Biodiversity Framework; CMS; UNFSA; Paris Agreement.<br>EU: EU Biodiversity Strategy for 2030; NRR; MSFD; WFD; CFP; EU Climate Law. |
| References | Dahl, K., Stæhr, P. A., Göke, C., Svendsen, J. C., Steinfurth, R. C. H., and Bramming Jørgensen, T., 2024, Best practice for boulder reef restoration. Center for Marin Naturgenopretning.<br>Green, D. S., Chapman, M. G., and Blockley, D. J., 2012, Ecological consequences of the type of rock used in the construction of artificial boulder-fields. Ecological Engineering, 46, 1-10.<br>Kristensen, L. D., Støttrup, J. G., Svendsen, J. C., Stenberg, C., Højbjerg Hansen, O. K., and Grønkjær, P., 2017, Behavioural changes of Atlantic cod (*Gadus morhua*) after marine boulder reef restoration: Implications for coastal habitat management and Natura 2000 areas. Fisheries Management and Ecology, 24(5), 353-360.<br>Liversage, K., and Chapman, M. G., 2018, Coastal ecological engineering and habitat restoration: incorporating biologically diverse boulder habitat. Marine Ecology Progress Series, 593, 173-185.<br>Riisager-Simonsen, C., Fabi, G., van Hoof, L., Holmgren, N., Marino, G., and Lisbjerg, D., 2022, Marine nature-based solutions: Where societal challenges and ecosystem requirements meet the potential of our oceans. *Marine Policy*, *144*, 105198.<br>Støttrup, J. G., Dahl, K., Niemann, S., Stenberg, C., Reker, J., Stamphøj, E. M., ... and Svendsen, J. C., 2017, Restoration of a boulder reef in temperate waters: Strategy, methodology and lessons learnt. Ecological Engineering, 102, 468-482.<br>Støttrup, J., Stenberg, C., Dahl, K., Kristensen, L. D., and Richardson, K., 2014). Restoration of a temperate reef: effects on the fish community. Open Journal of Ecology, 4(16), 1045-1059. |

### *Lagoon restoration*

Coastal lagoons are specific habitats which have a limited connection to the sea because of sand bars, underwater sills, narrow inlets or other physical features. As a consequence, the lagoon environment has higher temperature, lower water currents, clearly different chemical conditions (e.g. salinity, nutrients, turbidity) and specific species assemblages. Lagoon ecosystems are typically degraded by deepening or widening the inlet to allow boating into the sea.

| Name/type | Lagoon restoration |
|---|---|
| Spatial scale | Local |
| Spatial and temporal scope of implementation | Denmark: Kristensen et al. (2024) analysed how Danish coastal lagoons could be restored.<br>Finland: Restoration took place in the period 2016-2019 in the Kvarken flada project, Finland (reviewed in Arnkil et al., 2024).<br>Ireland: Lady's Island Lake in County Wexford (O'Connor et al. 2018).<br>Italy: Restoration actions in LIFE Lagoon Refresh project of the Venice lagoon (Brusá et al. 2022).<br>Baltic Sea: an overview of eight marine/coastal active and passive restoration measures from the Baltic Sea and the Skagerrak region (Kraufvelin et al. 2025).<br>Mediterranean and Black Sea: De Wit and Boutin (2023) reviewed 18 restoration projects. |
| Objective of the measure and main actions implemented | Dredged coastal lagoons have more open connection to the sea, which has caused hydrological changes (higher water flows and lower temperature), altering the species community (Arnkil et al., 2024). The main restoration measure is to restore the underwater sill at the lagoon entrance. This may also include different designs which still allow boating through the entrance, if needed. As boating disturbs shallow lagoons, the placement of the marina outside the lagoon may be a successful solution.<br>Depending on lagoon size, the restoration measures may vary from boats (Kraufvelin et al. 2025) to ships (Brusá et al. 2022).<br>Nutrient enrichment threatens many lagoons and therefore catchment area management may be an important restoration action (O'Connor et al. 2018, Kristensen et al. 2024). |
| Estimated economic cost | Swedish projects (Halsskärsgraven, Ytteravan) had cost ranges between EUR 11,000-25,000, while Finnish projects (Ormskataglo, Kobbfladan, Långviken) had cost ranges between EUR 4,500-17,000 (Arnkil et al., 2024). |
| Environmental Benefits | Lagoons are significant spawning and nursery areas for fish and breeding, resting and foraging areas for birds.<br>The lagoon species communities significantly differ from the ones at sea, outside the lagoon. |
| Social and economic co-benefits | Social and economic benefits of the restoration are mainly aesthetic or for improved fish stocks and bird densities. |
| Maintenance needs | Restoration is a one-off effort. |
| Stakeholders' engagement | Lagoons are sheltered areas and hence preferred boat harbours. They may also be important recreational fishing or hunting areas. Therefore, stakeholders' engagement is critical for the success. |

| Name/type | Lagoon restoration |
|---|---|
| Success and/or limiting factors | + Improved fish reproduction.<br>- Material choices for sill reconstruction (Arnkil et al., 2024). |
| Trade-offs | Restoring the lagoon sill negatively impacts boating activities to the lagoon. Therefore, it potentially creates conflicts with local people. These can be solved by finding new marina sites or specific designs to allow minor boating into the lagoon. |
| Links to MSFD drivers-pressures | Pressures:<br>• Biological:<br>  ○ Disturbance of species (e.g. where they breed, rest and feed) due to human presence;<br>• Physical:<br>  ○ Physical disturbance to the seabed (temporary or reversible);<br>  ○ Physical loss (due to permanent change of seabed substrate or morphology and to extraction of seabed substrate);<br>  ○ Changes to hydrological conditions;<br>Contribution to achieve GES: D1, D4, D6, D7. |
| Links to other policy objectives | Global: SDG 14.2; SDG 14.4; 2021-2030 UN Decade for Ecosystem Restoration; CBD and the Global Biodiversity Framework; Ramsar Convention; CMS.<br>EU: EU Biodiversity Strategy for 2030; NRR; MSFD; WFD. |
| References | Arnkil, A., Bäck, A., Haavisto, F., Keskinen, E., Kuningas, S., Laine, A., Nieminen, A., Puttonen, I., Raitanen, H. ja Salovius-Laurén, S., 2024, A Review of Marine Nature Restoration Work and Methods Used in Finland. Nature Protection Publication in Metsähallitus. Series A 252, 139 p., https://julkaisut.metsa.fi/julkaisu/a-review-of-marine-nature-restoration-work-and-methods-used-in-finland/ (last access: 2 December 2025).<br>Brusá, R.B., Feola, A., Cacciatore, F., Ponis, E., Sfriso, A., Franzoi, P., Lizier, M., Peretti, P., et al., 2022, Conservation actions for restoring the coastal lagoon habitats: Strategy and multidisciplinary approach of LIFE Lagoon Refresh. Front. Ecol. Evol. 10, https://doi.org/10.3389/fevo.2022.979415.<br>De Wit, R., & Boutin, N., 2023), European LIFE Projects Dedicated to Ecological Restoration in Mediterranean and Black Sea Coastal Lagoons. Environments, 10(6), 101. https://doi.org/10.3390/environments10060101.<br>Kraufvelin, P., Olsson, J., Bergström, L., Bergström, U. & Bryhn, A.C., 2025, Ecological restoration measures for shallow coastal habitats of the Baltic Sea and the Skagerrak – effectiveness, costs and knowledge gaps. Estuarine, Coastal and Shelf Science 321, 109353.<br>Kristensen, E., Banta, G., Canal-Vergés, P., Jørgensen, T.B, Markager, S. & Quintana, C.O., 2024, Guideline for Marine Nature Restoration through Managed Realignment of Reclaimed Coastal Areas. Center for Marine Restoration, available at: https://danishmarinerestoration.com/media/72920/guideline-for-marine-nature-restoration-through-managed-realignment-of-reclaimed-coastal-areas-1.pdf (last accessed 12 December 2025).<br>O'Connor, B., Oliver, G., Cawley, T., Roden, C., Perrin, P., de Witt, R., McCaffrey, K. & O'Connor, A., 2018, Coastal Lagoons: Ecology and Restoration (CLEAR). EPA Research Report No. 473. Available: https://www.epa.ie/publications/research/water/Research-Report_473.pdf (last access 12 December 2025). |

### *Shellfish reefs/beds restoration*

| Name/type | Shellfish reefs/beds restoration |
|---|---|
| Spatial scale | Local (intertidal, low intertidal and fully subtidal zones) |
| Spatial and temporal scope of implementation | In the 1990s, the first restoration efforts focused on the eastern oyster (C*rassostrea virginica)* in the USA and on rebuilding oyster production for harvest. After the mid-1990s, emphasis shifted to recovering ecosystem services (Smith and Pruett, 2025). Since 2000, and especially after 2010 (zu Ermgassen et al., 2020), efforts have increased all over the world (USA; New Zealand, Australia, China/Hong Kong, Germany, the Netherlands, the United Kingdom and Italy), targeting temperate oyster species (Smith and Pruett, 2025). |
| Objective of the measure and main actions implemented | This measure aims to restore bivalve reefs, mainly mussel and oyster beds.<br>Around 600 projects have been implemented for different shellfish species (34 bivalves and 15 gastropods), especially belonging to the genus *Crassostrea*, *Ostrea*, and *Mytilus* genera (Fitzsimons et al., 2020), using different strategies: habitat restoration providing hard substrata for settlement (including substrates with bio engineered coatings), supplementation or redistribution of natural recruitment, adults and/or hatchery seed or individuals for population or species recovery (Riisager-Simonsen et al., 2022).<br>Habitat restoration may utilize a variety of materials to add elevation and durability to existing, degraded reef, for example, by deploying fossilized shell material bagged into individual mesh bags; creating oyster reefs from fresh oyster shell on a relict oyster reef site; or constructing and placing oyster domes and/or bars (Carranza and zu Ermgassen, 2020). For oysters, this may involve the deployment of settlement substrate (as a surface for oyster settlement from existing larval oyster populations) or live oysters (to increase larval supply) to enhance degraded reefs or create new habitats (Smith and Pruett, 2025). |
| Estimated economic cost | Project costs depends on project setting and may include: planning and project development costs; the cost of eyed oyster larvae and remote setting equipment; bottom cultch and placement material; sourcing of natural biological material; other equipment and maintenance; transportation and vehicle costs; a baseline survey; the cost of a monitoring program; data analysis and interpretation; enforcement; infrastructure; labour; and project implementation (Northern Economics, 2009). These may vary considerably depending on the location, species, and techniques employed.<br>In general, project costs are high, especially the surveying and up-front permitting requirements, and vary depending on the purpose and size of the project. Brumbaugh et al. (2007) indicate a cost of more than USD 100,000 per acre for the restoration of oyster reefs. Monitoring costs may be from USD 100,000 to, 200,000 per year (Northern Economics, 2009). Also, the potential costs of shellfish consumption-related illnesses should be taken into account (Northern Economics, 2009); Hoagland et al. (2002) estimated a cost of USD 1,400 per reported illness and of USD 1 million per mortality. |
| Environmental Benefits | The main environmental benefits of this measure include:<br>• Biodiversity – Increase in species richness and diversity, abundance of associates species, which showed to be higher than in nearby unstructured habitats, including seagrass (zu Ermgassen et al., 2020). Increased shellfish recruitment and potential larval output (Riisager-Simonsen et al., 2022). Increased shell mining, i.e., returning shells to the seafloor to replenish the underlying habitat (zu Ermgassen et al., 2020). |

| Name/type | Shellfish reefs/beds restoration |
|---|---|
| | • Under certain conditions, hard structures may reduce coastal erosion and increase water clarity (zu Ermgassen et al., 2020).<br>• Increase the rate of sedimentation and drawdown of material, including carbon and nitrogen, to the benthos, which can increase microbial activity in the sediments, including denitrifying bacteria (Smith and Pruett, 2025).<br>• The use of shells of bivalve molluscs in the northern Adriatic as biomaterials showed to reduce heavy metals contamination and improve the quality of marine waters and sediments (Pasti and Cavazzini, 2020; Riisager-Simonsen et al., 2022).<br><br>All these benefits are highly spatially variable, as they depend on the local hydrodynamic conditions and the species restored, and depth of intervention. |
| Social and economic co-benefits | While these habitats clearly provide ecosystem services, these are largely unquantified to date, or even undescribed for most species, apart from US projects, especially those targeting *Crassostrea virginica* (zu Ermgassen et al., 2020).<br><br>Zu Ermgassen et al. (2020) identify the following ecosystem services provided by shellfish reef restoration projects globally, with a warning that these may vary across locations and targeted species, although current knowledge is still insufficient to quantify these variations:<br><br>• Provisioning services: support commercial and recreational fisheries, by increasing bivalve harvest and enhancing other fisheries species (e.g., blue crab, shrimp, flounder, sea bass); enhancement of natural recruitment, that in turn may support the collection of juveniles and their use in farming activities.<br>• Cultural services: protection of harvesting traditions (e.g., *Perna canaliculus* in New Zealand) and of species of cultural value (e.g., oystercatcher *Haematopus ostralegus* in the Wadden Sea).<br><br>The establishment of the North Carolina Oyster Sanctuary Network was estimated to support 143 jobs, generate USD 34 million in revenue for local businesses, and provided USD 8.7 million (in 2023 USD) in employee wages and benefits (Cowell et al., 2024). In the US, oyster restoration is estimated to produce almost double the amount spent in economic and environmental benefits (1.70 USD for every 1 USD spent; Cowell et al., 2024). |
| Maintenance needs | Despite their high initial investment costs, artificial oyster reefs are more cost-effective over a longer time scale than man-made reefs, as they can provide denitrification benefits at almost zero cost once established (Simons et al., 2023). |
| Stakeholders' engagement | Community engagement should be prioritized, as several stakeholders contribute to, benefit from, and are affected by oyster restoration (academics, governments, indigenous groups, NGOs, industry, resource-dependent communities, the public; Smith and Pruett, 2025). A good communication strategy is essential, as it can provide clarity (Fitzsimons et al., 2020). |
| Success and/or limiting factors | + Success depends on the capacity to meet both the biological needs of the target species and the interests of the local human community (Westby et al., 2019).<br><br>+ Adequate financing is necessary. Often, projects rely on multiple sources of funding; therefore, it is useful to identify sources of funding (or in-kind resources) early in the planning process and identify how different sources of funding can be leveraged to support the various elements of a project (Fitzsimons et al., 2020). |

| Name/type | Shellfish reefs/beds restoration |
|---|---|
| | + Oyster aquaculture may support restoration through the production of a hatchery, which can relieve fishing pressure on wild populations or may enhance stocks. The latter measure is especially effective in areas with recruitment limitation or low numbers of adults and high juvenile survival and growth post-settlement. Considerations on oysters' health and genetics are needed when deploying farmed individuals. Also, knowledge exchange on the conditions for the optimization of oyster recruitment, growth and survival can be exchanged (Smith and Pruett, 2025).<br><br>- Active restoration may not be more successful than passively protecting areas with good natural recruitment, as in the case of *Mytilus edulis* in the Dutch Wadden Sea (zu Ermgassen et al., 2020).<br><br>- Taxonomic ambiguities may pose a challenge in areas with more diverse oyster communities, as species misidentification may result in the selection of wrong restoration targets or unsuitable restoration conditions. Also, interspecific interactions should be considered, as well as differences in species abiotic tolerances or physical preferences (Smith and Pruett, 2025).<br><br>- Climate change alters the environmental factors that define oysters' niche (temperature, salinity, dissolved oxygen, pH, and inundation), either in short-term events or with long-term changes in mean conditions. These may add to other co-occurring stressors of anthropogenic origin (e.g., nutrient runoff, coastal development). Temperature changes may determine a higher mortality or local extinctions, alterations in growth, immunity, and reproduction, and may favour oyster predators such as blue crabs, or pathogens, as well as species range shifts that alter oyster distribution. Heatwaves may also affect oysters' populations. Sea level rise may impact intertidal oyster species, reducing aerial exposure, while coastal development may limit the vertical space available for growth, and subtidal oysters may be affected through saltwater intrusion that increases salinity. Acidification can dissolve oysters' shells, interfere with their formation, or impair metabolic activities and immune response. Decreases in oxygen solubility may worsen oxygen depletion and increase the frequency of hypoxia, which can reduce oyster growth, increase disease susceptibility, and cause mass mortalities. To address these challenges, site selection should incorporate knowledge of climate change drivers and impacts. Site diversification for restoration can increase overall system stability, resilience, and resistance. In addition, it is recommended to adjust the choice of species and genotypes used for out-planting and optimize the substrate material to increase resilience to climate change drivers (Smith and Pruett, 2025). |
| Trade-offs | Restricted access to oyster bottoms can cause conflict among user groups. This emphasises the need for transparent, inclusive communication among the commercial wild oyster fishery, the aquaculture industry, and restoration practitioners during site selection (Smith and Pruett, 2025).<br><br>Moreover, reintroduced non-native shellfish species may compete with native species, either directly or indirectly through habitat modification, and may negatively affect food webs and bring with them new diseases (Northern Economics, 2009).<br><br>Finally, shellfish may ingest and concentrate undesirable pathogens and other toxic pollutants, with potential negative impacts on human health (Northern Economics, 2009). |

| Name/type | Shellfish reefs/beds restoration |
|---|---|
| Links to MSFD drivers-pressures | Pressures:<br>• Biological:<br>○ Loss of, or change to, natural biological communities due to cultivation of animal or plant species;<br>○ Disturbance of species (e.g. where they breed, rest and feed) due to human presence;<br>○ Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities);<br>• Physical:<br>○ Physical disturbance to the seabed (temporary or reversible);<br>○ Physical loss (due to permanent change of seabed substrate or morphology and to extraction of seabed substrate)<br>○ Changes to hydrological conditions;<br>• Substances, litter and energy<br>○ Inputs of nutrients – diffuse sources, point sources, atmospheric deposition;<br>○ Input of organic matter – diffuse sources and point sources;<br>○ Input of other substances (e.g. synthetic substances, non-synthetic substances, radionuclides) - diffuse sources, point sources, atmospheric deposition, acute events<br>Contribution to achieve GES: D1, D3, D4, D5, D6, D7, D8, D9. |
| Links to other policy objectives | Global: SDG 14.2, 14.4; 2021-2030 UN Decade on Ecosystem Restoration; CBD and the Global Biodiversity Framework; UNFSA; Paris Agreement.<br>EU: EU Biodiversity Strategy for 2030; NRR; MSFD; CFP; EU Climate Law. |
| References | Brumbaugh, R.D., M. W. Beck, L. D. Coen, L. Craig, and P. Hicks., 2006, A Practitioner's Guide to the Design and Monitoring of Shellfish Restoration Projects: An Ecosystem Services Approach. Arlington, VA: The Nature Conservancy.<br>Carranza, A., and Zu Ermgassen, P. S., 2020, A global overview of restorative shellfish mariculture. *Frontiers in Marine Science*, *7*, 722.<br>Cowell, C., Walsh, A., Vazquez Caballero, S., Nienow, S., 2024, North Carolina Oyster Sanctuaries Growing Coastal Communities 2013–2023. Report prepared by RTI International for the North Carolina Coastal Federation, September 2024.<br>Fitzsimons, J. A., Branigan, S., Gillies, C. L., Brumbaugh, R. D., Cheng, J., DeAngelis, B. M., ... and Zu Ermgassen, P. S., 2020, Restoring shellfish reefs: Global guidelines for practitioners and scientists. *Conservation Science and Practice*, *2*(6), e198.<br>Northern Economics, Inc. Valuation of Ecosystem Services from Shellfish Restoration, Enhancement and Management: A Review of the Literature. Prepared for Pacific Shellfish Institute. September 2009.<br>Pasti, L., Cavazzini, A., 2020, Shellfish ecodesign. Rapporto tecnico MIPAAF-FLAG, Emila Romagna.<br>Riisager-Simonsen, C., Fabi, G., van Hoof, L., Holmgren, N., Marino, G., and Lisbjerg, D., 2022, Marine nature-based solutions: Where societal challenges and ecosystem requirements meet the potential of our oceans. *Marine Policy*, *144*, 105198.<br>Simons, S., Stamatiadou, V., Murillas, A., Delpiazzo, E., Standardi, G., Bosello, F., Key, E., Chen, W., Christiansen, T., Kvisle, K., Liu, J., Merline, A., Bellerby, R., Sulanke, E., |

| Name/type | Shellfish reefs/beds restoration |
|---|---|
| | Bulleri, F., Visintin, F., Di Cintio, A., Ravaglioli, C., Niccolini, F., Devries, C., Kamermans, P., 2023, Economic costs, benefits and challenges of NBSs. Deliverable 6.2, Project Future MARES.<br><br>Smith, R. S., and Pruett, J. L., 2024, Oyster restoration to recover ecosystem services. Annual Review of Marine Science, 17.<br><br>Westby, S., Geselbracht, L., and Pogoda, B., 2019, Shellfish reef restoration in practice. In *Restoration guidelines for shellfish reefs* (pp. 36-48). The Nature Conservancy.<br><br>Zu Ermgassen, P. S., Thurstan, R. H., Corrales, J., Alleway, H., Carranza, A., Dankers, N., … and Sanderson, W. G., 2020, The benefits of bivalve reef restoration: A global synthesis of underrepresented species. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *30*(11), 2050-2065. |

### *Active coastal wetlands restoration*

| Name/type | Active coastal wetlands restoration |
|---|---|
| Spatial scale | Local |
| Spatial and temporal scope of im-plementation | Coastal wetlands restoration efforts have a long history, with the first examples starting in the 1960s (Moore and Kumble, 2024). In the 1990s, global interest in wetland restoration increased significantly, thanks to the implementation of key conservation actions and policies, such as the US 'no net loss' of wetlands (Zhao et al., 2016). |
| Objective of the measure and main actions implemented | Marine and coastal wetlands comprise ecosystems such as mangroves, lagoons, seagrass beds, saltmarshes, estuaries, tidal flats, kelp forests and coral reefs. The aim of restoration is to return a wetland from a disturbed or altered status, caused by anthropogenic activities, to a pristine status, characterised by a self-organising, self-maintaining and functioning natural ecosystem that is resilient to perturbation and does not need further assistance (Zhao et al., 2016). The active restoration of coastal wetlands consists in actions to restore the natural hydrology and tidal morphology (elevation, slope, substrate), so as to recreate or improve the community structure and ecosystem processes. These vary depending on the wetland type, and may include:<br>• The removal of manmade barriers (e.g., dykes, dams, tide gates), or the development of new tidal channels. In areas with sufficient tidal flooding, or where the removal of water control structures is not feasible, it is recommended to replant native vegetation to accelerate natural recovery (Zhao et al., 2016).<br>• The restoration of salinity conditions, which includes the restoration of disconnected saline tidal flows, removing the dykes or tide gates that block or restrict tidal flows and allow freshwater to be retained.<br>• Chemical restoration, which refers to the removal of in-flowing pollutants or the control of their sources (Zhao et al., 2016). This includes improvements in wastewater and stormwater management, through the reduction of the volume and frequency of stormwater runoff and increase the quality of stormwater before discharge downstream to coastal wetlands.<br>• The removal of dredged material from salt marshes and restoration of soils. This includes the increase in sediment supply, by removing dams or raising soil surface using dredged material. |

| Name/type | Active coastal wetlands restoration |
|---|---|
| | • Planting of propagules and plants, such as mangroves (Zhao et al., 2016), to facilitate the recovery of local vegetal communities after restoring hydrology and soil conditions (IUCN, 2021).<br>• Rewetting coastal flood plains for fish spawning (e.g. pike, Arnkil et al., 2024). |
| Estimated economic cost | Wang et al. (2022) provided an estimation of the economic cost of several restoration actions for salt marshes (from cheapest to most expensive):<br>• Hydrological restoration: USD 26,500-64,600 per hectare;<br>• Sediment and substrate recovery: USD 26,500-64,600 per hectare;<br>• Invasion control: USD 15,700-72,000 per hectare;<br>• Hard structure restoration methods: USD 56,000-97,000 per hectare;<br>• Removing disturbance: USD 48,000-130,000 per hectare;<br>• Vegetation restoration: USD 90,000–180,000 per hectare.<br>Liu et al. (2021) confirm that planting is 10-20 times more expensive than hydrological restoration.<br>Restoration costs depend also on the type of ecosystem:<br>• Saltmarshes – they are generally expensive to restore. Bayraktarov et al. (2016) reported an average of USD 151,129 per hectare of total restoration costs in developed economies, while Taillardat et al. (2020) indicate total annual project costs of about USD 90,000 per hectare;<br>• Mangroves – they are generally less expensive to restore. Bayraktarov et al. (2016) indicate total restoration costs of USD 52,006 per hectare in developed economies, while Taillardat et al. (2020) indicate total annual project costs of USD 4,368 per hectare.<br>Rewetting of coastal flood plains have typically cost up to EUR 20,000, as these mainly require the partial damming of brooks, some machine digging and removal of overgrown reed belts (Arnkil et al., 2024).<br>Moreover, the effectiveness of coastal wetland restoration for carbon sequestration also varies depending on the ecosystem. It may be highly effective for mangroves (USD 1,800 per tonne of carbon), a value that is significantly lower than that for inland wetlands (USD 4,374-26,174 per tonne of carbon). In contrast, saltmarsh restoration is less cost-effective for carbon sequestration, with a cost of USD 40,820 per tonne of carbon. |
| Environmental Benefits | Active wetlands restoration may increase the capacity of a wetland to sequester carbon in the long-term, while having limited $CH_4$ emissions, thus providing net carbon sequestration benefits (Taillardat et al., 2020). Moreover, restored coastal wetlands may help stabilise shorelines, mitigate damage to natural marshes and mudflats, revegetate destroyed salt marshes, and have a positive impact on biodiversity (IUCN, 2021). Restored wetlands have a higher vegetation density than natural wetlands, which can reduce tidal currents speed, prevent erosion, trap more sediment, and promote belowground root production (Liu et al., 2021).<br>In particular:<br>• Biodiversity – The restoration of the natural hydrology and tidal morphology will support the diversity of native salt marsh plants and animals, allow the natural flushing of nutrients across the marshland and increase carbon sequestration. Furthermore, planting and revegetation allow to recover biodiversity and increase ecosystem services such as hydrological dynamics, |

| Name/type | Active coastal wetlands restoration |
|---|---|
| | soil fertility and decrease of erosion, and the provision of terrestrial habitat (IUCN, 2021).<br>• Climate change – The restoration of salinity conditions can considerably reduce methane and $CO_2$ emissions. Moreover, the removal of dredged material enhances carbon sequestration.<br>• Water quality – Improving wastewater and stormwater management can reduce the entry of nutrients into salt marshes through the sewer systems or from rainwater runoff and improve water quality for salt marshes and seagrass meadows. |
| Social and economic co-benefits | Coastal wetlands improve water quality, ensure groundwater recharge, support commercial fisheries, and increase natural coastal protection, reducing human vulnerability to weather-related events (Fennessy and Lei, 2018; Liu et al., 2021) through storm buffering and protection from windstorm and shore erosion (Zhao et al., 2016). Moreover, coastal wetlands can support tourism and sightseeing, recreation, education and research activities (Wang et al., 2022). Wetlands are spawning sites for several coastal fish species. Increased fish reproductive success has been documented (Nilsson et al., 2014).<br>Restoration projects may also support the local economy and job creation; in the US, coastal wetlands restoration in the Chesapeake Bay, the Great Lakes and Everglades have been estimated to generate an economic output of USD 4.3 billion and more than 3,200 jobs (Restore America's Estuaries, 2011). |
| Maintenance needs | Active coastal wetlands restoration requires a certain level of maintenance over the years. Experience from mangrove restoration in Southeast Asia showed that these needs are lower if the local community performs earthworks, instead of using mechanical means (Taillardat et al., 2020). |
| Stakeholders' engagement | It is fundamental to ensure an equitable participation of local stakeholders (including policy makers or government officials, private-sector businesses, NGOs, and researchers) in the decision-making and management processes of any restoration project, including coastal wetlands, to avoid negative socioeconomic outcomes such as increased lack of trust and conflict between users and officials, and an exacerbation of unsustainable practices (Moore and Kumble, 2024). |
| Success and/or limiting factors | + Restoration techniques for coastal wetlands that include salt marshes and mudflats are more advanced than for other habitat types (IUCN, 2021).<br>+ It is important to establish criteria to prioritise the selection of salt marsh restoration sites, considering elements such as ownership, hydrological restrictions, the presence of invasive plant species, history of dredged material or other fill placement, adjacent land use, local communities' concerns, and to evaluate the alternatives that offer the best chance of achieving the greatest outputs (IUCN, 2021).<br>+ Erosion control, nutrient addition, the establishment of fast-growing species as 'foundation species' or 'ecosystem engineers', and the removal of any invasive species are necessary factors to ensure successful wetland revegetation (IUCN, 2021).<br>+ In tidal marsh restoration, the tidal regime and land elevation are critical parameters as they determine the extent, duration and timing of submergence, and consequently, if a site can adjust to rising sea levels (Fennessy and Lei, 2018). |

| Name/type | Active coastal wetlands restoration |
|---|---|
| | + Restoring and managing water levels, capturing the full range of tidal exchange to promote vegetation reestablishment and sediment trapping, and planning restoration in the context of the surrounding landscape increase site resilience and the recovery of the processes that lead to carbon accumulation (Fennessy and Lei, 2018).<br><br>- The low success of some restoration projects has been attributed to the limited understanding of wetland functions, poorly defined success criteria, lagged monitoring, inappropriate selection of sites for restoration, and limited time (Zhao et al., 2016).<br><br>- Restored coastal wetlands may be lower in the tidal frame than natural ones because of erosion or soil compaction due to previous land reclamation, and experience higher hydroperiods and more time for sediment deposition; over time, if there is enough sediment supply, the difference with natural marshes will disappear (Liu et al., 2021).<br><br>- The effectiveness of the use of mangroves and saltmarsh plants for shore stabilization and protection from wave action and strong currents is highly variable both spatially and temporally, i.e., across seasons and years, due to changes in their biomass (Liversage and Chapman, 2018).<br><br>- Restoring the tidal influence in areas that suffered subsidence effects may result in higher flooding time and can transform high marsh areas into mid or low marsh areas, or even to unvegetated tidal flats. Hence, it is recommended to perform an evaluation of whether there is the need to perform substrate elevation or installation of water-level controls (IUCN, 2021). |
| Trade-offs | Because each species has different water quality, salinity and hydrology requirements, the management techniques to increase or enhance habitat for one species may have adverse impacts on others (IUCN, 2021). |
| Links to MSFD drivers-pressures | Pressures:<br>• Biological:<br>  ○ Loss of, or change to, natural biological communities due to cultivation of animal or plant species;<br>  ○ Disturbance of species (e.g. where they breed, rest and feed) due to human presence;<br>  ○ Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities);<br>• Physical:<br>  ○ Physical disturbance to the seabed (temporary or reversible);<br>  ○ Physical loss (due to permanent change of seabed substrate or morphology and to extraction of seabed substrate)<br>  ○ Changes to hydrological conditions;<br>• Substances, litter and energy<br>  ○ Inputs of nutrients – diffuse sources, point sources, atmospheric deposition;<br>  ○ Input of organic matter – diffuse sources and point sources;<br><br>Contribution to achieve GES: D1, D3, D4, D5, D6, D7. |

| Name/type | Active coastal wetlands restoration |
|---|---|
| Links to other policy objectives | Global: SDG 14.2, 14.4; 2021-2030 UN Decade for Ecosystem Restoration; CBD and the Global Biodiversity Framework; Ramsar Convention; CMS; Paris Agreement.<br>EU: EU Biodiversity Strategy for 2030; NRR; MSFD; WFD; EU Climate Law. |
| References | Arnkil, A., Bäck, A., Haavisto, F., Keskinen, E., Kuningas, S., Laine, A., Nieminen, A., Puttonen, I., Raitanen, H. ja Salovius-Laurén, S., 2024, A Review of Marine Nature Restoration Work and Methods Used in Finland. Nature Protection Publication in Metsähallitus. Series A 252, 139 p., https://julkaisut.metsa.fi/julkaisu/a-review-of-marine-nature-restoration-work-and-methods-used-in-finland/<br>Fennessy, S.M. and Lei, G., 2018, Wetland restoration for climate change resilience. Ramsar Briefing Note No.10. Gland, Switzerland: Ramsar Convention Secretariat.<br>IUCN, 2021, Manual for the creation of Blue Carbon projects in Europe and the Mediterranean. Otero, M. (Ed)., 144 pages.<br>Liu, Z., Fagherazzi, S., and Cui, B., 2021, Success of coastal wetlands restoration is driven by sediment availability. Communications Earth and Environment, 2(1), 44.<br>Liversage, K., and Chapman, M. G., 2018, Coastal ecological engineering and habitat restoration: incorporating biologically diverse boulder habitat. Marine Ecology Progress Series, 593, 173-185.<br>Moore, A. C., and Kumble, S., 2024, Community-based conservation and restoration in coastal wetlands: A review. Wetlands, 44(5), 62.<br>Nilsson, J., Engstedt, O. and Larsson, P., 2014, Wetlands for northern pike (Esox lucius L.) recruitment in the Baltic Sea. – Hydrobiologia 721: 145–154.<br>Restore America's Estuaries., 2011, Jobs and Dollars: Big Returns from Coastal Habitat Restoration.<br>Taillardat, P., Thompson, B. S., Garneau, M., Trottier, K., and Friess, D. A., 2020, Climate change mitigation potential of wetlands and the cost-effectiveness of their restoration. Interface focus, 10(5), 20190129.<br>Wang, J. J., Li, X. Z., Lin, S. W., and Ma, Y. X., 2022, Economic evaluation and systematic review of salt marsh restoration projects at a global scale. Frontiers in Ecology and Evolution, 10, 865516.<br>Zhao, Q., Bai, J., Huang, L., Gu, B., Lu, Q., and Gao, Z., 2016, A review of methodologies and success indicators for coastal wetland restoration. *Ecological Indicators 60*, 442-452. |

### *Restoration of polluted/hypoxic seabed*

| Name/type | Restoration of polluted/hypoxic seabed |
|---|---|
| Spatial scale | Local |
| Spatial and temporal scope of implementation | Several projects have been implemented in the last decades to address the issue of seabed contamination and hypoxia. In Europe, one of the most notable efforts is the project SEABASED, which tested methods to remediate polluted and hypoxic sea floor in Finland and Sweden (2018-2021). |
| Objective of the measure and main | Contaminants have been released into the environment for decades, and sediments in water bodies have served as sinks, particularly for hydrophobic organic compounds (such as polycyclic aromatic hydrocarbons-PAHs, polychlorinated biphenyls-PCBs, and dichloro-diphenyl-trichloroethane-DDT) and heavy metals. |

| Name/type | Restoration of polluted/hypoxic seabed |
|---|---|
| actions implemented | While many sources have been limited or eliminated, the sediments became sources of contamination and environmental risk (Reible and Lampert, 2014).<br>Also, hypoxia events induced by eutrophication change the sediment chemistry and cause a high release of nutrients into the water column, further increasing eutrophication, while impacting the benthos and depressing standing stocks in local areas through mass mortality events and effects on the food web (Maar et al., 2021).<br>There are several methods to restore a soft-sediment sea floor from hypoxia/anoxia, organic pollution or hazardous substances:<br>• *Ex situ* activities, such as dredging of surface sediments to remove excessive nutrients, organic matter or hazardous substances. Dredging may be necessary in case there is the need to maintain a constant level of seabed, e.g., in harbour areas or to allow navigation.<br>• Oxygenating bottom waters.<br>• Adding thermally treated limestone to bind phosphorus.<br>• Capping with even inert materials, such as sand.<br>• *In situ* physico-chemical (i.e., active mixing and thin capping, solidification/stabilization, chemical oxidation, dechlorination, electrokinetic separation, and sediment flushing) and bio-assisted treatments, including hybrid solutions (i.e., nanocomposite reactive capping, bioreactive capping, microbial electrochemical technologies; Lofrano et al., 2016).<br>• Monitored Natural Remediation (MNR), which consists in leaving the contaminated sediments in place and relying upon effective source control and natural processes that are already ongoing at a certain site (biodegradation, biotransformation, bioturbation, diffusion, dilution, adsorption, volatilisation, chemical reaction or destruction, resuspension, and burial by clean sediment) to reduce the environmental risks (Magar et al., 2009).<br>• In Denmark, the transplantation of hypoxia-resistant blue mussels (*Mytilus edulis*) in estuaries was trialled to mitigate seasonal hypoxia (Maar et al., 2021). |
| Estimated economic cost | In general, in situ treatments are less expensive than ex situ techniques, typically an order of magnitude lower (Lofrano et al., 2017). MNR may have high costs for site investigations, and low capital costs because there are no construction-related costs (Magar et al., 2009).<br>In Finland, the removal of surface sediments in Finland had a cost of EUR 482,000-1,774,000 (EUR 1,606–5,913/kg P; Mäki et al., 2021), while the oxygenation: investment was of EUR 41,500 and annual maintenance costs were EUR 3,000., and adding the thermally treated limestone costed EUR 30/kg P (Mäki et al., 2021). |
| Environmental Benefits | The reduction of contamination benefits local habitats and species. In an Estonian lake, macrophytes, invertebrates and fish recovered quickly after the restoration with suction dredging (Tammeorg et al., 2024). The transplantation of blue mussels in Denmark showed positive effects on water quality elements (oxygen, chlorophyll α, nutrients level, and Secchi depth; Maar et al., 2021). |
| Social and economic co-benefits | • Safer seafood (removal of hazardous substances)<br>• More fish (restoration of hypoxic areas) |

| Name/type | Restoration of polluted/hypoxic seabed |
|---|---|
| Maintenance needs | Removal of surface sediment is a one-off effort, while oxygenation is continuous. In situ and MNR require long-term monitoring to assess risk reduction and ecological recovery. |
| Stakeholders' engagement | Important in bays and areas close to shore. |
| Success and/or limiting factors | + Sediment removal has been successful in lakes (Härkönen et al., 2025). In coastal waters, it decreased the chemical oxygen demand (Mäki et al., 2021).<br><br>+ Capping with even inert materials can be effective for sites contaminated with metal and hydrophobic organic compounds, in case groundwater upwelling is not a significant factor (Reible and Lampert, 2014).<br><br>+/- There are still significant knowledge gaps on the application of *in situ* contaminated sediment remediation techniques, especially in relation to their ecotoxicological implications, with only activated carbon-based technologies that are well-developed and currently applied (Lofrano et al., 2016).<br><br>+/- In situ measures allow to avoid the negative impacts of dredging; however, they are characterised by a longer implementation time, uncertainty about treatment uniformity, and difficulties in assessing the overall efficiency of the process (Lofrano et al., 2016).<br><br>+/- The suitability of monitored natural remediation has been established by several cases of successful implementation in the USA, with low implementation risks and high effectiveness, provided that the source has been controlled and the natural recovery processes are in place. However, there are concerns regarding exposure to contaminants at the site and uncertainty regarding the time required for recovery (Magar et al., 2009).<br><br>- Sediment removal will not help, if external substance frows (nutrients, organic matter, hazardous substances) have not been ceased.<br><br>- Oxygenation requires continuous activity which is not cost-effective. Experience has shown that the system returns to degraded state after the pumping has ceased.<br><br>- Adding thermally treated limestone did not provide long-lasting phosphorus binding.<br><br>- Dredging may be necessary in case of the need to reach a certain bathymetric level; however, it can heavily remobilise sediment and associated pollution via washing out events (Lofrano et al., 2016). |
| Trade-offs | While physico-chemical techniques are quicker than in situ techniques, they have a potential environmental impact from the generation of post-treatment by-products (Lofrano et al., 2016). Sediment removal may be harmful for species in near-by areas. The risk for spreading of hazardous substances must be assessed. |
| Links to MSFD drivers-pressures | <u>Pressures</u>:<br>• Physical:<br>  ○ Physical disturbance to the seabed (temporary or reversible);<br>  ○ Physical loss (due to permanent change of seabed substrate or morphology and to extraction of seabed substrate);<br>  ○ Changes to hydrological conditions;<br>• Substances, litter and energy |

| Name/type | Restoration of polluted/hypoxic seabed |
|---|---|
| | ○ Inputs of nutrients – diffuse sources, point sources, atmospheric deposition;<br>○ Input of organic matter – diffuse sources and point sources;<br>○ Input of other substances (e.g. synthetic substances, non-synthetic substances, radionuclides) - diffuse sources, point sources, atmospheric deposition, acute events<br><br>Contribution to achieve GES: D1, D3, D4, D5, D6, D8, D9. |
| Links to other policy objectives | Global: SDG 14.2, 14.4; 2021-2030 UN Decade for Ecosystem Restoration; CBD and the Global Biodiversity Framework; CMS.<br><br>EU: EU Biodiversity Strategy for 2030; NRR; MSFD; WFD. |
| References | Arnkil, A., Bäck, A., Haavisto, F., Keskinen, E., Kuningas, S., Laine, A., Nieminen, A., Puttonen, I., Raitanen, H. ja Salovius-Laurén, S., 2024, A Review of Marine Nature Restoration Work and Methods Used in Finland. Nature Protection Publication in Metsähallitus. Series A 252, 139 p., https://julkaisut.metsa.fi/julkaisu/a-review-of-marine-nature-restoration-work-and-methods-used-in-finland/<br><br>Härkönen, L. H., Taskinen, A., Tammeorg, O. and Granlund-Blomfelt, A.-L., 2025, Long-term water quality responses to sediment removal in a small, shallow, urban lake. Ecological Engineering 219, 107715. ISSN 0925-8574. https://doi.org/10.1016/j.ecoleng.2025.107715<br><br>Lofrano, G., Libralato, G., Minetto, D., De Gisi, S., Todaro, F., Conte, B., ... & Notarnicola, M., 2017, In situ remediation of contaminated marine sediment: an overview. Environmental Science and Pollution Research, 24(6), 5189-5206.<br><br>Maar, M., Larsen, J., Saurel, C., Mohn, C., Murawski, J., & Petersen, J. K. (2021). Mussel transplantation as a tool to mitigate hypoxia in eutrophic areas. *Hydrobiologia*, *848*(7), 1553-1573.<br><br>Magar, V. S., Chadwick, D. B., Bridges, T. S., Fuchsman, P. C., Conder, J. M., Dekker, T. J., ... & Mills, M. A., 2009, Monitored natural recovery at contaminated sediment sites.<br><br>Mäki, M., Porvari, M. and Tähtikarhu, E., 2021, Practical Guidelines for sea-based measures. John Nurmisen säätiö. https://johnnurmisensaatio.fi/en/our-work/projects/seabased-project/<br><br>Reible, D. D., & Lampert, D. J., 2013, Capping for remediation of contaminated sediments. In *Processes, assessment and remediation of contaminated sediments* (pp. 325-363). New York, NY: Springer New York.<br><br>Tammeorg O, Kiani M, Nõges P, et al., 2024, Management im-plications following the reconstruction of the small and shallow Lake Mustijärv (Estonia). J Limnol; 83:2188. |

## 3.3 Category 3: Novel, restored or deliberately designed artificial marine ecosystems

This category encompasses the introduction of new habitats in the marine environment in order to replace destroyed essential habitats, enhance sustainable food provisioning, reduce risk disasters and mitigate climate change (Riisager-Simonsen et al., 2022). This type of solution typically addresses multiple issues and provides a range of ecological and societal services.

### *Creation of artificial reefs*

| Name/type | Creation of artificial reefs (i) as new habitats for reef-dwelling or fish species, (ii) for ecological restoration, or (iii) for coastal protection |
|---|---|
| Spatial scale | Local |
| Spatial and temporal scope of implementation | The study and support of artificial fishing reef technology in Japan have been ongoing since 1976 (Nakamura, 1985), and its use has been intensified since the 1990s (Vivier et al., 2021). In parallel, the use artificial reefs for coral reef ecological research, conservation, and socio-cultural purpose has been ongoing since the 1980s (Higgins et al., 2021). |
| Objective of the measure and main actions implemented | This measure consists of the intentional placing of man-made underwater constructions below the sea surface and on the seabed, to mimic natural reef functions and protect, regenerate, concentrate and enhance populations of marine organisms. This can be done either for the purpose of restoring and increasing the population of recreational and/or commercially important fish or shellfish, or to restore degraded marine ecosystems that lost habitat heterogeneity, biomass, diversity, richness, and abundance or marine organisms due to various impacts such as mining, oil and gas extraction, trawling, overfishing and pressure from tourism. Other less frequent uses include anti-drag tools, coastal erosion protection, or mitigation of tourism pressure on corals (Bracho-Villavicencio et al., 2023).<br><br>A wide range of artificial reefs has been installed all over the world, with different shapes and materials (Vivier et al., 2021). Materials employed include steel, reinforced or pre-stressed concrete, fibre glass, and other composite materials such as wrecked cars, aeroplanes, military tanks, used truck or car tyres, junked appliances, docks, old boats, ballistic missiles, decommissioned ships and obsolete oil rigs (Lakesha et al., 2013). Some representative examples include the installation of concrete cages to develop wild mussel populations (central and northern Adriatic Sea), the deployment of suitable artificial habitats for colonisation by macroalgae and the seeding with juvenile abalone from onshore hatcheries (Flinders Bay, Western Australia), and the building of an induction reef at the entrance of a bay to attract adults of snapper, a spawning reef and a nursery reef (Iki Islands, Japan; Riisager-Simonsen et al., 2022).<br><br>Artificial reefs (e.g., breakwaters and dykes) may represent an alternative approach to conventional armoured structures for the purpose of ensuring coastal protection. Examples include the restoration of the seawall along Seattle's waterfront, in the USA, through a pocket beach and habitat bench, and the construction of intertidal reefs using artificial modules and oyster shell bags in the Gulf of Mexico (Riisager-Simonsen et al., 2022). In Europe, Dinu (2025) performed simulations for different setups of artificial reefs with different heights, and for extreme storms with various return periods, confirming their effectiveness in reducing wave height and energy in the Danube Delta Coast.<br><br>These strategies may be effectively combined. Multipurpose Artificial Surfing Reefs are increasingly being used for the simultaneous purposes of coastal protection, habitat provision, and socioeconomic purposes (Lokesha et al., 2013). |
| Estimated economic cost | Artificial reefs have a relatively high cost of construction and maintenance, reaching even an order of magnitude greater if compared to other restoration measures (Bracho-Villavicencio et al., 2023; Dinu et al., 2025; Higgins et al., 2022). Especially, fish aggregation devices have been highlighted as costly (Rogers et al., 2015). Gibson-Banks et al. (2021) report a cost of deployment of 674 reef structures for the Red Snapper at around USD 1.5 million. In Japan, based on a reef productivity index value of 5-50kg of fish per $m^3$ of reef volume, artificial reefs are considered as having a |

| Name/type | Creation of artificial reefs (i) as new habitats for reef-dwelling or fish species, (ii) for ecological restoration, or (iii) for coastal protection |
|---|---|
| | justifiable cost/benefit ratio over a 30-year service life (Nakamura, 1985). In Sweden, a stone reef was constructed costing EUR 1.2 M (Kraufvelin et al., 2021).<br>On the other hand, a small-scale reef-like structure may cost nothing. In Helsinki, Finland, citizens were encouraged to take their Christmas trees to the sea to help perch spawning. Increased spawning success was monitored (Arnkil et al., 2024). |
| Environmental Benefits | Artificial reefs for fisheries enhancement provide greater food availability, shelter from predators, and new recruitment areas for juveniles of benthic invertebrates or fish, thus increasing species richness and the diversification of trophic contributions (Vivier et al., 2021).<br>In parallel, artificial reefs for coral conservation have reported an increase in fish abundance, enhancement of habitat quantity or coral cover, and general success in the conservation of target species. Other reported benefits include stressor mitigation, as well as the provision of coral nursery habitat or source populations (Higgins et al., 2021). Finally, the construction of artificial reefs for coastal protection may effectively reduce coastal erosion and increase flood control (Dinu, 2025). |
| Social and economic co-benefits | Artificial reefs for habitat creation have three main socioeconomic benefits: enhancement of fishery catches, creation of nursery grounds, and protection of overharvested fish stocks (Nakamura, 1985). These benefits allow to increase food production and sustain the local communities (Riisager-Simonsen et al., 2022). Moreover, artificial reefs for coral conservation may have a socio-cultural value, increasing the attractiveness of an area to divers or tourists (Higgins et al., 2021). Finally, artificial reefs may ensure effective coastal protection against the negative impacts of climate change on the coasts, including sea level rise and increasing frequency of storm surges events. |
| Maintenance needs | Long-term monitoring is important to prevent undesirable consequences, such as overfishing. Optimal monitoring should be seasonal and continue for at least 5 years; moreover, it should include the assessment of different trophic groups to correctly evaluate the effect of the artificial reef on the associated ecosystem (Vivier et al., 2021).<br>Artificial reefs for coastal protection require long-term management plans including environmental monitoring. Long-term changes in the wave climate and sea level rise require periodical re-design, to ensure that their function of protection is maintained in the future (Dinu, 2025). |
| Stakeholders' engagement | The inclusion of fisheries stakeholders and the interest of the fishing industry play an essential role in the success and economic value of artificial reefs. Moreover, trusted communication between local fishermen and project managers allows to maximise the efficiency and longevity of the monitoring and of the structures (Vivier et al., 2021). The success of artificial reefs for coastal protection depends also on stakeholder involvement and integration of the project with existing fisheries and tourism policies (Dinu, 2025). |
| Success and/or limiting factors | + Reefs must be designed based on the characteristic behaviour patterns of the targeted fish species and their stage of maturation. For example, while some species tend to hover over the reef, others prefer to occupy holes and narrow openings (Nakamura, 1985).<br>+ Before establishing a reef, it is fundamental to have a comprehensive knowledge of existing fish life and the performance of existing reefs in the vicinity, as well as to |

| Name/type | Creation of artificial reefs (i) as new habitats for reef-dwelling or fish species, (ii) for ecological restoration, or (iii) for coastal protection |
|---|---|
| | ensure that the new reef is complementary and/or remedial to existing conditions (Nakamura 1985).<br><br>+ Although very heavy and requiring substantial construction and logistics prior to deployment, concrete structures are cost-effective, durable, stable and often designed specifically for the purpose of reefing (Gibson Banks et al., 2021). They are characterised by high roughness, and are significantly correlated with higher effectiveness, as they proved to ensure a high fixation rate of marine organisms and a high level of colonisation (Vivier et al., 2021). Higgins et al. (2022) reported that concrete may leach metals and has a high alkalinity that may inhibit colonization; to address this issue, new materials are being developed using aggregate concrete with different chemistries.<br><br>+ Vivier et al. (2021) argue that the most effective shape of an artificial reef is cylindrical. Moreover, facility volumes higher than 1,000 $m^3$ are significantly correlated with high effectiveness, as they could create upwelling currents and promote primary production and, consequently, fish abundance.<br><br>+ Surface heterogeneity also plays an important role: a higher surface complexity promotes biodiversity and facilitates colonisation, while the addition of large holes could enhance the capacity to hold fish at reproductive ages (Vivier et al., 2021)<br><br>+ Artificial reefs for coral conservation had higher success rates for the provision of nursery habitat and increase coral cover, while the conservation of target species was the least successful (Higgins et al., 2021).<br><br>+ Well-defined ecological criteria are necessary to comprehensively evaluate the effectiveness of artificial reefs. This means not only to assess effectiveness based on changes in abundance, biomass, diversity, and species richness, but also to include changes in species composition, community structure and the introduction of invasive species (Bracho-Villavicencio et al., 2023).<br><br>- The scale of the artificial reefs deployed to date (tens of $m^2$) is too small to effectively address regional losses in coral cover; despite this limitation, they have potential to support reef conservation and restoration, by providing nursery habitat for target species, or recruitment substrate for corals and other organisms (Higgins et al., 2021).<br><br>- PVC or other plastics are sometimes used as building material for artificial reefs; however, they are toxic and generate microplastic particles. To avoid this, biogenic materials are being developed, partially composed of shells (e.g., oyster or queen scallop), to limit the environmental impact (Vivier et al., 2021).<br><br>- Although artificial reefs generally harbour fewer species than their natural counterparts, they achieve restoration success in a shorter time (Bracho-Villavicencio et al., 2023). |
| Trade-offs | Attracting local fish biomass without increasing productivity could lead to overfishing and/or an increase in accidental captures (Vivier et al., 2021), with negative socioeconomic consequences. Other possible trade-offs include pollution and toxicity, changes in local hydrodynamics (Bracho-Villavicencio et al., 2023), and the introduction and spread of invasive species (Higgins et al., 2022). |

| Name/type | Creation of artificial reefs (i) as new habitats for reef-dwelling or fish species, (ii) for ecological restoration, or (iii) for coastal protection |
|---|---|
| Links to MSFD drivers-pressures | Pressures:<br>• Biological:<br>  ○ Loss of, or change to, natural biological communities due to cultivation of animal or plant species;<br>  ○ Disturbance of species (e.g. where they breed, rest and feed) due to human presence;<br>  ○ Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities);<br>• Physical:<br>  ○ Physical disturbance to seabed (temporary or reversible); Physical loss (due to permanent change of seabed substrate or morphology and to extraction of seabed substrate);<br>Contribution to achieve GES: D1, D3, D4, D6 |
| Links to other policy objectives | Global: SDG 14.2, 14.4; 2021-2030 UN Decade on Ecosystem Restoration; CBD and the Global Biodiversity Framework; CMS; UNFSA; BBNJ Agreement; Sendai Framework.<br>EU: EU Biodiversity Strategy for 2030; NRR; MSFD; CFP; EU Action Plan on the Sendai Framework |
| References | Arnkil, A., Bäck, A., Haavisto, F., Keskinen, E., Kuningas, S., Laine, A., Nieminen, A., Puttonen, I., Raitanen, H. ja Salovius-Laurén, S., 2024, A Review of Marine Nature Restoration Work and Methods Used in Finland. Nature Protection Publication in Metsähallitus. Series A 252, 139 p., https://julkaisut.metsa.fi/julkaisu/a-review-of-marine-nature-restoration-work-and-methods-used-in-finland/<br>Bracho-Villavicencio, C., Matthews-Cascon, H., and Rossi, S., 2023, Artificial reefs around the world: A review of the state of the art and a meta-analysis of its effectiveness for the restoration of marine ecosystems. Environments, 10(7), 121.<br>Dinu, I., Gràcia, V., García-León, M., Lin-Ye, J., Stănică, A., and Sánchez-Arcilla, A., 2025, Feasibility of artificial reefs as coastal protection measures at the Danube Delta coast, Romania. Frontiers in Environmental Science, 13, 1568364.<br>Gibson Banks, K., Curtis, J. M., Williams, J. A., Wetz, J. J., and Stunz, G. W., 2021, Designing cost-effective artificial reefs: fine-scale movement and habitat use of Red Snapper around a nearshore artificial reef complex. North American Journal of Fisheries Management, 41(6), 1850-1862.<br>Higgins, E., Metaxas, A., and Scheibling, R. E., 2022, A systematic review of artificial reefs as platforms for coral reef research and conservation. PLoS One, 17(1), e0261964.<br>Lokesha, Sundar, V., and Sannasiraj, S. A., 2013, Artificial reefs: a review. *The International Journal of Ocean and Climate Systems*, *4*(2), 117-124.<br>Nakamura, M., 1985, Evolution of artificial fishing reef concepts in Japan. Bulletin of marine science, 37(1), 271-278.<br>Riisager-Simonsen, C., Fabi, G., van Hoof, L., Holmgren, N., Marino, G., and Lisbjerg, D., 2022, Marine nature-based solutions: Where societal challenges and ecosystem requirements meet the potential of our oceans. *Marine Policy*, *144*, 105198.<br>Rogers, A., Harborne, A. R., Brown, C. J., Bozec, Y. M., Castro, C., Chollett, I., ... and Mumby, P. J., 2015, Anticipative management for coral reef ecosystem services in the 21st century. *Global Change Biology*, *21*(2), 504-514. |

| Name/type | Creation of artificial reefs (i) as new habitats for reef-dwelling or fish species, (ii) for ecological restoration, or (iii) for coastal protection |
|---|---|
| | Vivier, B., Dauvin, J. C., Navon, M., Rusig, A. M., Mussio, I., Orvain, F., ... and Claquin, P., 2021, Marine artificial reefs, a meta-analysis of their design, objectives and effectiveness. Global Ecology and Conservation, 27, e01538. |

### *Greening of grey/hard infrastructures*

| Name/type | Greening of grey/hard infrastructure |
|---|---|
| Spatial scale | Local |
| Spatial and temporal scope of implementation | Artificial habitat design first appeared in the 1970s in Japan; nowadays, the application of integrated greening of grey hard infrastructure to artificial shorelines is being embraced globally (Firth et al., 2020). |
| Objective of the measure and main actions implemented | Usually, the damage to the environment from construction projects (toxicity of materials, problems with using smooth surfaces, landscape disruption, and indirect impacts of $CO_2$ emissions during concrete production; Pioch et al., 2018) has been offset through *ex-post* compensatory mitigation, often at high expense and without a thorough assessment of the effectiveness of the results, resulting in the failure to achieve the intended goals. An example is the fact that artificial reefs were normally built using any kind of material (e.g., used tyres, construction rubble).<br>To counteract this failure, "eco-design" or "integrated Greening of Grey Infrastructure" has been proposed, consisting in the introduction of ecological considerations in the design and implementation of artificial structures that are ecosystem-friendly and also sustain the ecosystem services impacted by the construction (Pioch et al., 2011), with the aim to improve the ecological value of hard infrastructure (Firth et al., 2020). In practice, this approach consists in the shaping of concrete or steel pillars and walls in harbours, breakwaters, pipelines, port complexes and offshore renewable energy installations, to favour better attachment of organisms and offer shelter from predation to juvenile fish (Riisager Simonsen et al., 2022).<br>Examples of previously implemented green infrastructure straight from design include the engineering of scour protection in wind farms to provide complex habitats for Atlantic cod, and the construction of a pipeline in Mayotte (2008) through a shallow coral lagoon using two types of modules, the first designed to mimic shallow biotopes and create effective habitat for juvenile fish, and the other to mimic deeper biotopes and function as a habitat for adult fish (Pioch et al., 2011; Riisager Simonsen et al., 2022). |
| Estimated economic cost | Green construction practices can often be integrated at the outset with little or no extra construction costs. This allows to minimise the capital and operational costs of the mitigation of the impacts of construction, by minimising the loss of ecosystem services (Pioch et al., 2011).<br>A review of experience in the UK (Naylor et al., 2017) indicates that all the green measures considered implied a small increase in overall construction costs and provided value for money thanks to a wide range of environmental and socioeconomic benefits. |

| Name/type | Greening of grey/hard infrastructure |
|---|---|
| Environmental Benefits | Green eco-design helps avoid or offset the negative impacts of traditional construction practices. More in detail, it may increase the capacity of the artificial structure to provide refuge, breeding sites and increased feeding opportunities to several species, including habitat-forming species such as macroalgae and corals. Also, artificial reefs can protect important habitats from trawling (Firth et al., 2024). |
| Social and economic co-benefits | Green artificial reefs can provide social benefits such as aesthetic landscape appreciation of the increase in naturalness and water quality, and an increase in the production of commercially important fish and bivalves (Firth et al., 2024), with positive impacts on the local economy and society. |
| Maintenance needs | Eco-designed habitat elements typically do not require special maintenance to maintain their effects on colonisation enhancement (Pioch et al., 2018). Some of the implemented solutions have been reported as self-maintaining, while others need repair and maintenance to counteract the natural weathering and erosion over time, depending on the material employed (Naylor et al., 2017). |
| Stakeholders' engagement | Stakeholders may have different perceptions in the benefits of this measure; moreover, there are potential social and ecological conflicts arising from the different positions and interests of stakeholders. These aspects require thorough consideration during all phases of implementation and further scientific investigation (Firth et al., 2024). |
| Success and/or limiting factors | + The creation of artificial structures should be calibrated along the behavioural preference of the specific species intended to protect/restore; for example, holes with an appropriate size reduce the predation of invertebrates such as lobsters, while the creation of blind-ended tunnels may encourage the presence of some blennioid fishes (Pioch et al., 2011).<br><br>+ While caging has been used to protect species from predators, its effects on the environment are not clear, as the caging material may not be appropriate for long-term use and create problems of fouling (Pioch et al., 2011).<br><br>+ The interaction of the artificial structure with the local hydrological regime should be assessed. In fact, structures may create currents that may enhance food availability and feeding opportunities while simultaneously providing shelter from currents (Pioch et al., 2011).<br><br>+ Habitat size should be regulated around resource availability or density dependent predator-prey interactions (Pioch et al., 2011).<br><br>+ The profile and the height of the structure relative to the height of the water column may attract species that prefer vertically oriented surfaces (Pioch et al., 2011), while the shading provided by the construction may favour shade-preferring species (Pioch et al., 2011).<br><br>+ The material, texture and colour of the substrate may play a role, with some species preferring limestone and others preferring concrete aggregate, corals preferring rugose substrate, and the majority of fishes, invertebrate, and algae preferring dark-coloured substrate (Pioch et al., 2011).<br><br>- The effectiveness of green-grey interventions is strongly context-dependent, and the results cannot be generalised over different latitudes, tidal heights, size of local species pool and locally dominant stressors (Firth et al., 2024).<br><br>- Green-grey interventions may be subject to sedimentation, which limits their capacity to host hard-substrate biota. While retained sediment may be a potential |

| Name/type | Greening of grey/hard infrastructure |
|---|---|
| | habitat, undesirable sedimentation may be avoided thanks to a greater understanding of the local sediment supply and the depositional environment prior to the installation (Firth et al., 2024)<br><br>- The majority of Integrated Green-Gray Infrastructure projects have been conducted in few locations and over short time scales; hence, caution should be exercised over the claimed environmental benefits of this measure. To this respect, it is fundamental to revisit, repeat and expand research to improve the evidence base for policy development. Especially, the measurement of effectiveness should be based not on simple biodiversity measures but should include functional responses and other biologically meaningful responses, comparing pre-existing sedimentary and new hard artificial habitats, and reporting shortcomings and limitations (Firth et al., 2020). |
| Trade-offs | Green-grey infrastructure may inadvertently facilitate the spread of invasive species, or act as an ecological trap or environmental filter, depending on the geographical location, tidal height, type of intervention and functional groups or species involved. An experiment consisting of adding physical and biological complexity to seawalls, demonstrated a trade-off between species richness and functional outcomes. Moreover, the promotion of novel communities with high filtration capacity has led to impacts on marine food webs beyond the footprint of the structure (Firth et al., 2024).<br><br>Furthermore, there is the risk that greening practices are misused or used for 'greenwashing'. Therefore, caution should be adopted in piloting this type of intervention, focusing on failures or unintended outcomes and testing responses over broader spatio-temporal scales to improve the evidence base (Firth et al., 2020). Firth et al. (2024) report that the strategical incorporation of green-grey infrastructure into marine infrastructure on existing reclaimed land may sway public opinion to support proposals for further land reclamation, thereby causing additional environmental harm.<br><br>An example of failure, reported by Firth et al. (2024), is the creation of artificial reefs in Qatar as transplantation sites for coral destroyed by a new oil pipeline, where the survivorship of transplanted coral was low (about 20%). Worst, the creation of artificial reefs may hide simple ocean dumping (either inadvertent or deliberate), such as in the case of the Osborne Reef in Florida. |
| Links to MSFD drivers-pressures | Pressures:<br>• Biological:<br>○ Loss of, or change to, natural biological communities due to cultivation of animal or plant species;<br>○ Disturbance of species (e.g. where they breed, rest and feed) due to human presence;<br>○ Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities);<br>• Physical:<br>○ Physical disturbance to seabed (temporary or reversible);<br>○ Physical loss (due to permanent change of seabed substrate or morphology and to extraction of seabed substrate);<br><br>Contribution to achieve GES: D1, D3, D4, D6. |

| Name/type | Greening of grey/hard infrastructure |
|---|---|
| Links to other policy objectives | Global: SDG 14.2, 14.4; 2021-2030 UN Decade on Ecosystem Restoration; CBD and the Global Biodiversity Framework; CMS; UNFSA; BBNJ Agreement.<br>EU: EU Biodiversity Strategy for 2030; NRR; MSFD; CFP. |
| References | Firth, L. B., Airoldi, L., Bulleri, F., Challinor, S., Chee, S. Y., Evans, A. J., ... and Hawkins, S. J., 2020, Greening of grey infrastructure should not be used as a Trojan horse to facilitate coastal development. Journal of Applied Ecology, 57(9), 1762-1768.<br>Firth, L. B., Bone, J., Bartholomew, A., Bishop, M. J., Bugnot, A., Bulleri, F., ... and Knights, A. M., 2024, Coastal greening of grey infrastructure: an update on the state of the art. In *Proceedings of the Institution of Civil Engineers-Maritime Engineering* (Vol. 177, No. 2, pp. 35-67). Emerald Publishing Limited.<br>Naylor, L. A., Kippen, H., Coombes, M. A., Horton, B., MacArthur, M., and Jackson, N., 2017, Greening the Grey: a framework for integrated green grey infrastructure (IGGI). University of Glasgow report. URL: http://eprints.gla.ac.uk/150672/<br>Pioch, S., Kilfoyle, K., Levrel, H., and Spieler, R., 2011, Green marine construction. Journal of Coastal Research, (61), 257-268.<br>Riisager-Simonsen, C., Fabi, G., van Hoof, L., Holmgren, N., Marino, G., and Lisbjerg, D., 2022, Marine nature-based solutions: Where societal challenges and ecosystem requirements meet the potential of our oceans. Marine Policy, 144, 105198. |

### *Low-trophic aquaculture*

| Name/type | Low-trophic aquaculture |
|---|---|
| Spatial scale | Local |
| Spatial and temporal scope of implementation | Seaweed aquaculture production has been increasing in the last two decades, from 10.6 million tonnes in 2000 to around 32 million tonnes in 2018 (Chopin and Tacon, 2021). While most installations are concentrated in Asia (Chopin and Tacon, 2021), in recent years, their increase has concentrated in the Americas and in Europe, mainly driven by Integrated Multi-Trophic Aquaculture (IMTA; see below). |
| Objective of the measure and main actions implemented | The reduction of the dependence of the aquaculture sector on wild-caught fish for feeding is considered as an important strategy to ensure aquaculture sustainability. Low-trophic aquaculture has been proposed to address these issues, as it has the potential to support large-scale increases in production volumes while avoiding environmental impacts (if properly managed; Slater and James, 2023). Another purpose is in capturing nutrients from an eutrophied sea area by seaweed or mussel farming.<br>This measure consists in the cultivation of low-trophic species, i.e., species whose natural diets do not include fish (Cottrell et al., 2021), namely primary producers (seaweed) and primary consumers (bivalves such as clams, mussels, and oysters). Considerable interest has been given recently on the cultivation of finfish species that are naturally non-carnivorous, such as carps and tilapia (Cottrell et al., 2021).<br>Seaweed aquaculture currently focuses on 8 genera (*Saccharina japonica*, the carrageenophytes *Euchema*, *Kappaphycus*, and *Sargassum*, the agarophytes *Gracilaria*, *Porphyra*, and *Pyropia*, and *Undaria pinnatifida*). The main species farmed are *Saccharina japonica* and *Eucheuma* spp., which make up about 50% of total global production, which is about 35 million tonnes per year (Slater and James, 2023). In parallel, bivalves are the third most important production sector globally, with 18 million tonnes produced per year (Slater and James, 2023). |

| Name/type | Low-trophic aquaculture |
|---|---|
| Estimated economic cost | <u>Seaweed</u><br>A review of case-studies by Moscicki et al. (2025) indicate a total cost of production of seaweeds of USD 30-2,618 per tonne.<br>For the North Sea, van den Burg et al. (2016) determined the following costs for seaweed farming: total investment of USD 138,000 per hectare (with costs doubled in offshore areas compared to estuaries); total costs for harvesting and transport of USD 2,860 per hectare; maintenance costs of USD 690 per hectare; insurance costs of USD 700 per hectare. Considering the potential revenues, these authors argue that offshore seaweed production in the North Sea is not currently economically feasible, given the high costs and the heavy competition from Chinese production, and that the combination of different applications through advanced biorefinery might be the key to develop a feasible seaweed value chain. In contrast, a study in Scotland showed the existence of several viable scenarios to achieve a payback in investments within 3-5 years for farms with an extension of 8-32 hectares (Menzies et al., 2021). The establishment of seaweed farming in combination with offshore wind energy installations can reduce costs of both activities (van den Burg et al., 2016).<br>The following factors have been identified as drivers for cost reduction in kelp large-scale farming: (1) use of purpose-built, correctly sized vessels, (2) heavily mechanized operations, (3) at-sea processing of harvested kelp into a slurry (4) biomass storage in vessel holds, (5) structural design that minimizes loads, maximizes operational efficiency and spatial productivity, and (6) cultivation at maximal depths for site specific light penetration (Moscicki et al., 2025).<br><u>Bivalves</u><br>In the Baltic, Kotta et al. (2023) report for blue mussel (*Mytilus edulis/trossolus*) aquaculture a cost of EUR 0.52-8.52 per kg of biomass harvested (depending on the location), and of EUR 76-1.638 per kg of nitrogen removed. Another study (Holdt and Edwards, 2013) based on experiences in Ireland and Denmark, indicate that bivalves are a more cost-effective biofilter than seaweed, with a cost of EUR 11.4-19.2/kg of nitrogen removed, against a cost of EUR 209-672/kg for *Laminaria digitata* and of EUR 1,013/kg for *Alaria esculenta*. |
| Environmental Benefits | Bivalve shellfish and seaweed aquaculture can have numerous environmental benefits:<br>• Nutrients cycling – Bivalves filter large quantities of organic matter from the water column, incorporating part of the nutrients within their body and depositing the rest onto the surface of the sediment as faeces or pseudo faeces. Oysters are particularly effective, filtering 26-34 litres of water per hour. This filtration removes chlorophyll α, nitrogen, and phosphorus, thereby helping mitigate the impacts of inland nutrient pollution (van der Schatte Olivier et al., 2020) and standing as a cost-effective strategy to mitigate eutrophication (Kotta et al., 2023). Similarly, seaweeds take up nitrogen and phosphorus, with a potential total nitrogen removal by the five major aquaculture groups of 65,000 tonnes per year (Kim et al., 2017).<br>• Capture $CO_2$ in coastal waters – Seaweeds accumulate $CO_2$, used (together with nitrogen and phosphorus) for growth and production of energy storage products, with a potential total carbon removal by the five major aquaculture groups of 760,000 tonnes per year (Kim et al., 2017). The long-term effect of bivalves in the carbon cycle is still unclear, as while they sequester carbon in their shell in the form of calcium carbonate, (acting as a |

| Name/type | Low-trophic aquaculture |
|---|---|
| | long-term carbon sink), they also release $CO_2$ into the atmosphere during this process (van der Schatte Olivier et al., 2020).<br>• Improving water transparency – Mussel farming has been demonstrated to promote the growth of macrophytes, whose presence is an indicator of water quality (Schröder et al.2014).<br>• Biodiversity – Richer ecological communities, supporting numerous trophic levels – Mussels and oysters may naturally form reefs, which provide refuge and a hard substrate for other species of invertebrates and algae to settle. Artificial structures (racks, cages, nets, ropes) can provide further substrate for colonisation. Intertidal mussels' beds are also important foraging grounds for many avian species. Moreover, the accumulation of 'mussel mud' may support soft-bottom species (Riisager-Simonsen et al., 2022; van der Schatte Olivier et al., 2020). In general, bivalve and seaweed aquaculture was found to be associated with higher abundance and species richness of wild, mobile macrofauna, especially suspended or elevated mussel and oyster culture, mainly through the provision of structured habitat, food resources, and enhanced reproduction and recruitment (Theuerkauf et al., 2022).<br>• Coastal defence – Bivalve reefs and beds provide protective structures against erosion; moreover, they are able to protect the ecological integrity of other important habitats such as marshes.<br>• The use of seaweeds as feed additive for livestock can reduce soy imports, contributing to combating deforestation in soy-producing countries (van den Burg et al., 2016). |
| Social and economic co-benefits | Low-trophic aquaculture may provide a wide range of socioeconomic benefits:<br>• Fisheries – The structured habitats provided by bivalves can lead to increases in the production of finfish and invertebrates important for commercial and recreational fisheries (van der Schatte Olivier et al., 2020).<br>• Aquaculture sector – Seaweed aquaculture allows the local diversification and a more balanced aquaculture industry (Chopin and Tacon, 2021).<br>• Cultural heritage and recreational purposes – Van der Schatte Olivier et al. (2020) highlight the cultural role of seafood globally, as well as the importance of bivalve reefs and beds for birdwatching, and as an element of cultural heritage among indigenous peoples and historically.<br>• Human health – Through filtering, bivalves may accumulate microbes that may be harmful to human health, within their tissues.<br>• Other uses and sectors – Bivalve shells may be grinded and used as integrator for poultry or as agricultural lime to provide nitrogen, phosphate and potash to agriculture. Oyster shells may be used as construction material in sea defences, thanks to their lighter weight than traditional shoreline protection materials, and for buildings in their burnt form as lime (or quicklime). Seaweeds are also used to produce animal feed, paper, chemicals, fertiliser, biofuel and other renewable, derivative products (Kim et al., 2017). They are currently considered as an alternative source of biofuels (van den Burg et al., 2016). |
| Maintenance needs | Once established, bivalve reefs do not require additional upkeep (van der Schatte Olivier et al., 2020). Similarly, seaweed farming needs few repairs to the production system (van den Burg et al., 2016). |

| Name/type | Low-trophic aquaculture |
|---|---|
| Stakeholders' engagement | Stakeholder awareness and consultation to minimise conflicts is an important practice (Tett et al., 2025); especially, maritime planning to avoid spatial conflicts of use with other coastal and offshore activities such as fisheries, tourism, and renewable energy generation. |
| Success and/or limiting factors | + The expansion of low-trophic aquaculture is favoured by its high scalability (Slater and James, 2023).<br><br>+ To be effective for habitat protection, oyster reef barriers require circulation currents suitable for larval recruitment and adequate water quality (van der Schatte Olivier et al., 2020.<br><br>+ For the blue mussel (*Mytilus edulis*), it is important to prioritise high-salinity sites to enhance the yield (Kotta et al., 2023).<br><br>+ The cost-effectiveness of mussel farming for eutrophication mitigation depends more on farm type than on mussel nutrient content (Kotta et al., 2023).<br><br>+ Tett et al. (2025) identified some conditions for the success of low-trophic aquaculture, targeting government, market organisations and civil society organisations:<br>• The government should provide stable policy and legal frameworks within which developers can operate with commercial confidence; ensure public trust in low-trophic aquaculture products; support low-trophic aquaculture start-ups; and ensure availability of researchers and public officials with low-trophic aquaculture relevant skills and knowledge.<br>• Market organisations should allow low-trophic aquaculture to better access financial capital and insurance, develop consultancy services, and inform the public about it.<br>• Civil Society organisations, including universities, producer organisations and NGOs, should lead the development of low-trophic aquaculture with arrangements for local control, and help certify appropriate low-trophic aquaculture as sustainable, healthy and socially equitable.<br><br>- In the aquaculture of non-carnivorous fish, the sustainability of the dietary profile of these species must be considered and weighed up against the efficiency with which they convert feed into biomass. In fact, species farmed at higher trophic levels may still have a lower forage fish demand than non-carnivorous species, if the former's feeding efficiency is higher (Cottrell et al., 2021). |
| Trade-offs | The destruction of shells for e.g., poultry grit (to increase calcium for eggshells) or agricultural lime (thanks to the nutrients inside the shell), hinders their capacity to act as carbon storage (van der Schatte Olivier et al., 2020).<br><br>Bivalves are able to accumulate environmental elements and sewage-related microbes within their tissues, causing potential trade-offs with human consumption. To this respect, van der Schatte Olivier et al. (2020) suggest that bivalves could be 'sacrificed' to regulate and safeguard shellfish/finfish production locations, coastal waters and bathing beaches by accumulating pathogens before reaching humans.<br><br>Mussel farming may generate local nutrient enrichment in the immediate vicinity of the farm and in very sheltered areas, with possible local eutrophication phenomena (Kotta et al., 2023).<br><br>Some studies suggested that mussel farms can promote lower oxygen concentrations, associated with a reduction in bioturbation or excessive |

| Name/type | Low-trophic aquaculture |
|---|---|
| | accumulation of organic matter, while other studies reached opposite conclusions (Kotta et al., 2023).<br>In the Atlantic coast of the USA, there is an increasing conflict of uses between low-trophic aquaculture and ocean energy production. To this respect, Calhoun et al. (2025) proposed to co-locate low-trophic aquaculture within offshore wind energy areas, showing that it could be a viable approach for high-value species such as easter oyster and soft-shell clam, and for high-yield species such as sugar and winged kelp, with profits ranging from 4% to 31%. |
| Links to MSFD drivers-pressures | Pressures:<br>• Biological:<br>○ Input of microbial pathogens;<br>○ Loss of, or change to, natural biological communities due to cultivation of animal or plant species;<br>○ Disturbance of species (e.g. where they breed, rest and feed) due to human presence;<br>○ Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities);<br>• Physical:<br>○ Physical disturbance to seabed (temporary or reversible);<br>Physical loss (due to permanent change of seabed substrate or morphology and to extraction of seabed substrate);<br>• Substances, litter and energy:<br>○ Input of nutrients – diffuse sources, point sources, atmospheric deposition;<br>○ Input of organic matter – diffuse sources and point sources;<br>○ Input of other substances (e.g. synthetic substances, non-synthetic substances, radionuclides) – diffuse sources, point sources, atmospheric deposition, acute events<br>Contribution to achieve GES: D1, D3, D4, D5, D6, D7, D8, D9. |
| Links to other policy objectives | Global: SDG 14.2, 14.4; 2021-2030 UN Decade on Ecosystem Restoration; CBD and the Global Biodiversity Framework; CMS; UNFSA; BBNJ Agreement; Paris Agreement; Sendai Framework.<br>EU: EU Biodiversity Strategy for 2030; NRR; MSFD; WFD; CFP; EU Climate Law; EU Action Plan on the Sendai Framework. |
| References | Calhoun, W. R., Scheld, A. M., Taylor, D., and Walton, W. C., 2025, Economic feasibility of low-trophic aquaculture within U.S. Offshore wind energy areas. Aquaculture Economics and Management, 29(3), 524–554.<br>Chopin, T., and Tacon, A. G., 2021, Importance of seaweeds and extractive species in global aquaculture production. Reviews in Fisheries Science and Aquaculture, 29(2), 139-148.<br>Cottrell, R. S., Metian, M., Froehlich, H. E., Blanchard, J. L., Sand Jacobsen, N., McIntyre, P. B., ... and Halpern, B. S., 2021, Time to rethink trophic levels in aquaculture policy. *Reviews in Aquaculture*, *13*(3), 1583-1593.<br>Holdt, S. L., and Edwards, M. D., 2014, Cost-effective IMTA: a comparison of the production efficiencies of mussels and seaweed. *Journal of applied phycology*, *26*(2), 933-945. |

| Name/type | Low-trophic aquaculture |
|---|---|
| | Kim, J. K., Yarish, C., Hwang, E. K., Park, M., and Kim, Y., 2017, Seaweed aquaculture: cultivation technologies, challenges and its ecosystem services. *Algae*, *32*(1), 1.<br><br>Kotta, J., Futter, M., Kaasik, A., Liversage, K., Rätsep, M., Barboza, F. R., ... and Virtanen, E., 2020, Cleaning up seas using blue growth initiatives: Mussel farming for eutrophication control in the Baltic Sea. Science of the Total Environment, 709, 136144.<br><br>Menzies, B., Brook, T., and Parker, A., 2021, CROWN ESTATE SCOTLAND. Economic Feasibility Study on Seaweed (Cultivation and Supply Scenario).<br><br>Moscicki, Z., Gelais, A. T. S., Coleman, S., Kinley, A., Dewhurst, T., Lindell, S., ... and Brady, D. C., 2025, Comprehensive quantification of production costs for large-scale kelp aquaculture and cost reduction opportunities. Algal Research, 104383.<br><br>Riisager-Simonsen, C., Fabi, G., van Hoof, L., Holmgren, N., Marino, G., and Lisbjerg, D., 2022, Marine nature-based solutions: Where societal challenges and ecosystem requirements meet the potential of our oceans. Marine Policy, 144, 105198.<br><br>Schröder, T., Stank, J., Schernewski, G., and Krost, P., 2014, The impact of a mussel farm on water transparency in the Kiel Fjord. *Ocean and coastal management*, *101*, 42-52.<br><br>Slater, M., and James, P., 2023, Low trophic species in aquaculture—growth and research challenges. *Journal of the World Aquaculture Society*, *54*(1).<br><br>Tett, P., Charalambides, G., Franco, S. C., Hughes, A. D., Mikkelsen, E., Nielsen, K. N., ... and James, P., 2025, Leaving the niche: Recommendations for mainstreaming Low Trophic Aquaculture in countries around the Atlantic basin. *Marine Policy*, *171*, 106475.<br><br>Theuerkauf, S. J., Barrett, L. T., Alleway, H. K., Costa-Pierce, B. A., St. Gelais, A., and Jones, R. C., 2022, Habitat value of bivalve shellfish and seaweed aquaculture for fish and invertebrates: Pathways, synthesis and next steps. Reviews in Aquaculture, 14(1), 54-72.<br><br>van den Burg, S. W., van Duijn, A. P., Bartelings, H., van Krimpen, M. M., and Poelman, M., 2016, The economic feasibility of seaweed production in the North Sea. *Aquaculture Economics and Management*, *20*(3), 235-252.<br><br>van der Schatte Olivier, A., Jones, L., Vay, L. L., Christie, M., Wilson, J., and Malham, S. K., 2020, A global review of the ecosystem services provided by bivalve aquaculture. *Reviews in Aquaculture*, *12*(1), 3-25. |

### *Integrated multi-trophic aquaculture*

| Name/type | Integrated multi-trophic aquaculture |
|---|---|
| Spatial scale | Local |
| Spatial and temporal scope of im-plementation | While integrated farming of rice and fish was established in Asia for millennia, the first research on integrated methods for treating the waste from fish farming started in the 1970s and was renewed in the 1900s (Barrington et al., 2009). Today, integrated multi-trophic aquaculture has been increasingly implemented all around the globe, mainly in marine temperate waters in both hemispheres (from 23° to 65° latitude), including China and Canada (Riisager-Simonsen et al. 2022). |
| Objective of the measure and main | The objective of Integrated Multi-Trophic Aquaculture is to mitigate the excess nutrients and organic matter generated by intensive aquaculture activities, by combining the farming of species of different trophic positions or nutritional levels |

| Name/type | Integrated multi-trophic aquaculture |
|---|---|
| actions implemented | into a same system (Barrington et al., 2009). In practice, this includes the farming of marine species (e.g., finfish or shrimps) with organic extractive aquaculture species, i.e., seaweeds and bivalve shellfish species[1]. In this way, the wastes from the culture of finfish become endogenous feed for seaweed and bivalves, which are also of commercial value.<br>While Integrated Multi-Trophic Aquaculture is usually implemented in coastal areas, promising potential was also shown from its establishment in offshore areas (Buck et al., 2019). |
| Estimated economic cost | <u>Seaweed</u><br>A review of some case-studies by Moscicki et al. (2025) indicate a total cost of production of seaweeds of USD 30-2,618 per tonne.<br>For the North Sea, van den Burg et al. (2016) determined the following costs for seaweed farming: total investment of USD 138,000 per hectare (with costs doubled in offshore areas compared to estuaries); total costs for harvesting and transport of USD 2,860 per hectare; maintenance costs of USD 690 per hectare; insurance costs of USD 700 per hectare. Considering the potential revenues, these authors argue that offshore seaweed production in the North Sea is not currently economically feasible, given the high costs and the heavy competition from Chinese production, and that the combination of different applications through advanced biorefinery might be the key to develop a feasible seaweed value chain. In contrast, a study in Scotland showed the existence of several viable scenarios to achieve a payback in investments within 3-5 years for farms with an extension of 8-32 hectares (Menzies et al., 2021). The establishment of seaweed farming in combination with offshore wind energy installations can reduce costs of both activities (van den Burg et al., 2016).<br>The following factors have been identified as drivers for cost reduction in kelp large-scale farming: (1) use of purpose-built, correctly sized vessels, (2) heavily mechanized operations, (3) at-sea processing of harvested kelp into a slurry (4) biomass storage in vessel holds, (5) structural design that minimizes loads, maximizes operational efficiency and spatial productivity, and (6) cultivation at maximal depths for site specific light penetration (Moscicki et al., 2025).<br><u>Bivalves</u><br>In the Baltic and for blue mussel (*Mytilus edulis/trossolus*) aquaculture, Kotta et al. (2023) report a cost of EUR 0.52-8.52 per kg of biomass harvested (depending on the location), and of EUR 76-1.638 per kg of nitrogen removed. Another study (Holdt and Edwards, 2013) based on experiences in Ireland and Denmark, indicate that bivalves are a more cost-effective biofilter than seaweed, with a cost of EUR 11.4-19.2/kg of nitrogen removed, against a cost of EUR 209-672/kg for *Laminaria digitata* and of EUR 1,013/kg for *Alaria esculenta*. |

[1] Barrington et al. (2009) identify the following genera and species with a high potential for development in Integrated Multi-Trophic Aquaculture systems in temperate waters: Seaweeds (*Laminaria*, *Saccharina*, *Sacchoriza*, *Undaria*, *Alaria*, *Ecklonia*, *Lessonia*, *Durvillaea*, *Macrocystis*, *Gigartina*, *Sarcothalia*, *Chondracanthus*, *Callophyllis*, *Gracilaria*, *Gracilariopsis*, *Porphyra*, *Chondrus*, *Palmaria*, *Asparagopsis* and *Ulva*); Molluscs (*Haliotis*, *Crassostrea*, *Pecten*, *Argopecten*, *Placopecten*, *Mytilus*, *Choromytilus* and *Tapes*); Echinoderms (*Strongylocentrotus*, *Paracentrotus*, *Psammechinus*, *Loxechinus*, *Cucumaria*, *Holothuria*, *Stichopus*, *Parastichopus*, *Apostichopus* and *Athyonidium*); Polychaetes (*Nereis*, *Arenicola*, *Glycera* and *Sabella*); Crustaceans (*Penaeus* and *Homarus*); and *Fish (Salmo*, *Oncorhynchus*, *Scophthalmus*, *Dicentrarchus*, *Gadus*, *Anoplopoma*, *Hippoglossus*, *Melanogrammus*, *Paralichthys*, *Pseudopleuronectes* and *Mugil*).

| Name/type | Integrated multi-trophic aquaculture |
|---|---|
| | Chopin et al. (2001) report that Integrated Multi-Trophic Aquaculture has considerably lower annual environmental costs of gross fish production per 250 tonnes (USD 64,000), compared to those for intensive aquaculture (about USD 200,000.<br>Nobre et al. (2010) estimated an increase in profits for abalone farming by 1.4-5% compared to monoculture. |
| Environmental Benefits | Integrated Multi-Trophic Aquaculture can reduce the impact of aquaculture on organic matter and nutrient loading in marine and coastal areas. Moreover, it can help capture $CO_2$ through bivalves farming, improve water transparency, and reduce the negative impacts of feeding through land-cultivated products. Alexander et al. (2016) highlight also the increase in oxygen levels in the bottom sediments, and the use of mussels as a pollution indicator. |
| Social and economic co-benefits | Integrated Multi-Trophic Aquaculture allows to reduce the costs for feed, which is one of the core operational costs of finfish aquaculture, ensuring that all components have an economic value (Barrington et al., 2009). It also allows to reduce the cost of the manual removal of excess nutrients and organic matter from wastewaters and estuaries (Kim et al., 2017; van der Schatte Olivier et al., 2020).<br>Moreover, the integration of different commercially viable species into an aquaculture system allows to reduce economic risks, thanks to the increased diversification of the product portfolio (Barrington et al., 2009), leading to a potential increase in income (Alexander et al., 2016).<br>At the social level, Integrated Multi-Trophic Aquaculture may support food security, by stabilising seafood supply thanks to greater production diversity and reduced markets risks associated with price volatility. Moreover, it can increase job diversity (Knowler et al., 2020). Also, the reduction of environmental impacts may improve the social perceptions of aquaculture (Knowler et al., 2020). |
| Maintenance needs | Once established, bivalve reefs generally do not require additional upkeep (van der Schatte Olivier et al., 2020). Similarly, seaweed farming needs few repairs to the production system (van den Burg et al., 2016). |
| Stakeholders' engagement | All relevant stakeholders (the government, industry, academia, the public and NGOs) must be included in the development of Integrated Multi-Trophic Aquaculture, as their understanding of the environmental and socioeconomic benefits is key for their support and promotion of Integrated Multi-Trophic Aquaculture. Given the existence of potential conflicts in the use of marine space, the role of Integrated Multi-Trophic Aquaculture in the integrated coastal zone management plans must be clearly defined (Barrington et al., 2009). |
| Success and/or limiting factors | + To ensure the expansion of Integrated Multi-Trophic Aquaculture in temperate regions, some success factors have been identified: (i) establishing economic and environmental values of Integrated Multi-Trophic Aquaculture systems and their co-products; this entails choosing the species that make the system profitable, (ii) carefully selecting the right species, which should be appropriate to the habitats, the available technologies, and the oceanographic conditions; these species should be complementary in their ecosystem functions, and be capable of growing to a significant biomass in order to capture many of the excess nutrients and remove them efficiently at harvesting time, (iii) promote effective legislation and incentives to facilitate the development of Integrated Multi-Trophic Aquaculture and the commercialisation of the products, (iv) educate stakeholders about this practice, and |

| Name/type | Integrated multi-trophic aquaculture |
|---|---|
| | (v) establish a continuum among research, development and commercialisation (R&D&C; Barrington et al., 2009).<br><br>+ Positive public attitudes towards Integrated Multi-Trophic Aquaculture, expressed by a higher willingness to pay, can increase its profitability (Knowler et al., 2020). |
| Trade-offs | Bivalves are able to accumulate environmental elements and sewage-related microbes within their tissues, causing potential trade-offs with human consumption. To this respect, van der Schatte Olivier et al. (2020) suggest that bivalves could be 'sacrificed' to regulate and safeguard shellfish/finfish production locations, coastal waters and bathing beaches by accumulating pathogens before reaching humans.<br><br>Mussel farming may generate local nutrient enrichment in the immediate vicinity of the farm and in very sheltered areas, with possible local eutrophication phenomena (Kotta et al., 2023).<br><br>Some studies suggested that mussel farms can promote lower oxygen concentrations, associated with a reduction in bioturbation or excessive accumulation of organic matter, while other studies reached opposite conclusions (Kotta et al., 2023).<br><br>Conflicts of use may arise between aquaculture stakeholders and those of other sectors, which may be reduced by moving Integrated Multi-Trophic Aquaculture further offshore. However, as in offshore areas the marine uses are quite different from coastal ones (e.g., energy extraction and production, security and defence), stakeholders that operate offshore are more powerful and there may be conflicts between local and regional/international entrepreneurs. This requires a different governance and management approach compared to coastal Integrated Multi-Trophic Aquaculture (Buck et al., 2019). |
| Links to MSFD drivers-pressures | Pressures:<br>• Biological:<br>  ○ Input of microbial pathogens;<br>  ○ Loss of, or change to, natural biological communities due to cultivation of animal or plant species;<br>  ○ Disturbance of species (e.g. where they breed, rest and feed) due to human presence;<br>  ○ Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities);<br>• Physical:<br>  ○ Physical disturbance to seabed (temporary or reversible);<br>  Physical loss (due to permanent change of seabed substrate or morphology and to extraction of seabed substrate);<br>• Substances, litter and energy:<br>  ○ Input of nutrients – diffuse sources, point sources, atmospheric deposition;<br>  ○ Input of organic matter – diffuse sources and point sources;<br>  ○ Input of other substances (e.g. synthetic substances, non-synthetic substances, radionuclides) – diffuse sources, point sources, atmospheric deposition, acute events<br><br>Contribution to achieve GES: D1, D3, D4, D5, D6, D8, D9. |

| Name/type | Integrated multi-trophic aquaculture |
|---|---|
| Links to other policy objectives | Global: SDG 14.2, 14.4; 2021-2030 UN Decade on Ecosystem Restoration; CBD and the Global Biodiversity Framework; CMS; UNFSA; BBNJ Agreement; Paris Agreement.<br>EU: EU Biodiversity Strategy for 2030; NRR; MSFD; WFD; CFP; EU Climate Law. |
| References | Alexander, K. A., Angel, D., Freeman, S., Israel, D., Johansen, J., Kletou, D., ... and Potts, T., 2016, Improving sustainability of aquaculture in Europe: stakeholder dialogues on integrated multi-trophic aquaculture (IMTA). *Environmental Science and Policy*, *55*, 96-106.<br>Barrington, K., Chopin, T., and Robinson, S., 2009, Integrated multi-trophic aquaculture (IMTA) in marine temperate waters. Integrated mariculture: a global review. FAO Fisheries and Aquaculture Technical Paper, 529, 7-46.<br>Buck, B. H., Troell, M. F., Krause, G., Angel, D. L., Grote, B., and Chopin, T., 2018, State of the art and challenges for offshore integrated multi-trophic aquaculture (IMTA). Frontiers in Marine Science, 5, 165.<br>Chopin, T., Buschmann, A., Halling, C., Troell, M., Kautsky, N., Neori, A., et al., 2001, Integrating seaweeds into aquaculture systems: a key towards sustainability. J. Phycol. 37, 975–986. doi: 10.1046/j.1529-8817.2001.01137.x<br>Holdt, S. L., and Edwards, M. D., 2014, Cost-effective IMTA: a comparison of the production efficiencies of mussels and seaweed. *Journal of applied phycology*, *26*(2), 933-945.<br>Kim, J. K., Yarish, C., Hwang, E. K., Park, M., and Kim, Y., 2017, Seaweed aquaculture: cultivation technologies, challenges and its ecosystem services. *Algae*, *32*(1), 1.<br>Knowler, D., Chopin, T., Martínez-Espiñeira, R., Neori, A., Nobre, A., Noce, A., and Reid, G., 2020, The economics of Integrated Multi-Trophic Aquaculture: where are we now and where do we need to go? Reviews in Aquaculture, 12(3), 1579-1594.<br>Kotta, J., Futter, M., Kaasik, A., Liversage, K., Rätsep, M., Barboza, F. R., ... and Virtanen, E., 2020, Cleaning up seas using blue growth initiatives: Mussel farming for eutrophication control in the Baltic Sea. Science of the Total Environment, 709, 136144.<br>Nobre, A. M., Robertson-Andersson, D., Neori, A., and Sankar, K., 2010, Ecological–economic assessment of aquaculture options: comparison between abalone monoculture and integrated multi- trophic aquaculture of abalone and seaweeds. Aquaculture 306, 116–126. doi: 10.1016/j.aquaculture.2010.<br>06.002 van den Burg, S. W., van Duijn, A. P., Bartelings, H., van Krimpen, M. M., and Poelman, M., 2016, The economic feasibility of seaweed production in the North Sea. *Aquaculture Economics and Management*, *20*(3), 235-252.<br>van der Schatte Olivier, A., Jones, L., Vay, L. L., Christie, M., Wilson, J., and Malham, S. K., 2020, A global review of the ecosystem services provided by bivalve aquaculture. *Reviews in Aquaculture*, *12*(1), 3-25. |

### 3.4 Category 4: Nature-inspired designs which reduce environmental pressures

This category includes technical solutions which adopt a design inspired by nature (*sensu* Benyus 1997) to exploit marine nature in ways which are relatively more sustainable than its present alternatives, and support the reduction of environmental pressures (Riisager-Simonsen et al., 2022). These solutions are likely easily transferable across environmental contexts or global in impact, and thus not necessarily place-based to the same degree as the other NbS types.

*Decarbonise transport: use of wind to provide propulsion for cargo ships*

| Name/type | Use of wind to provide propulsion for cargo ships |
|---|---|
| Spatial scale | N/A |
| Spatial and temporal scope of implementation | The first studies emerged in the 2000s, and after 2015 these technologies started to enter the global market. Currently, there is a trend of high growth and increased diversity (Chou et al., 2021). |
| Objective of the measure and main actions implemented | The idea behind this measure is to harness wind power for cargo ships propulsion using innovative technologies such as wingsails or kite sails, Flettner rotor sails (Riisager-Simonsen et al., 2022; Seddiek and Ammar, 2021), and the DynaRig sails (Lu and Ringsberg, 2020). |
| Estimated economic cost | High capital costs required for the initial investment (Chou et al., 2021) |
| Environmental Benefits | Exploiting wind to support cargo ship propulsion allows to reduce GHG emissions from the maritime transportation sector. Flettner rotors are estimated to potentially reduce annual ship $NO_x$ emissions by 270.4 tonnes and $CO_2$ emissions by 9,272 tonnes (Seddiek and Ammar, 2021).<br>Moreover, these solutions could contribute to the reduction of anthropogenic underwater noise and related pressure on marine life (Duarte et al., 2021). |
| Social and economic co-benefits | The reduction in the use of fossil fuels would allow savings in annual ships' fuel consumption, estimated at up to 15% per year at a speed of 15 knots for some ship types (Clauss et al., 2007). For Flettner rotors, this saving has been estimated from as low as 8.9% (Lu and Ringsberg, 2020) up to 22.28% of the annual fuel consumption, with a payback period of 6 years (Seddiek and Ammar, 2021), and of 13 years for the other wind-powered technologies (Tadros et al., 2023). |
| Maintenance needs | These technologies generally require low levels of regular maintenance by trained crew (IWSA, 2023). |
| Stakeholders' engagement | Early stakeholder engagement is key to remove barriers and ensure the success of any innovation process, including the development of innovative solutions to decarbonise maritime transport (Stalmokaité et al., 2023). Moreover, the engagement of all stakeholders is an important tool to mitigate the impact of the upgrade of IMO/EU regulations on the maritime transport sector (IWSA, 2023). |
| Success and/or limiting factors | **+/-** Kites can catch stronger winds that are at higher altitude and create smaller roll heeling movements, but their power output is more volatile that the Flettner rotors. Also, kites are more effective under tailwind and take up less deck space, while Flettner rotors are more effective under sideway winds and require fundamental deck construction (Chou et al., 2021).<br>**-** There are no single solutions that can be applied to all ships (Tadros et al., 2023); these technologies must be applied and operated depending on the ship type, speed, voyage routes, and weather conditions to achieve the maximum possible fuel savings (Lu and Ringsberg, 2020).<br>**-** There is still scientific uncertainty over the precise reduction in fuel consumption form the use wind-assisted ship propulsion, and more studies are needed. |
| Trade-offs | The actual amount of fuel savings and, consequently, the adoption of these technologies depend on factors such as fossil fuel prices, retrofit complexity, financing, and average wind conditions (Reche-Villanova et al., 2025) |

| Name/type | Use of wind to provide propulsion for cargo ships |
|---|---|
| Links to MSFD drivers-pressures | Pressures:<br>• Substances, litter and energy:<br>  ○ Input of anthropogenic sound (impulsive, continuous)<br>Contribution to achieve GES: D11. |
| Links to other policy objectives | Global: MARPOL Annex VI; Paris Agreement.<br>EU: FuelEU Maritime Regulation; EU Climate Law. |
| References | Chou, T., Kosmas, V., Acciaro, M., and Renken, K., 2021, A comeback of wind power in shipping: An economic and operational review on the wind-assisted ship propulsion technology. *Sustainability*, *13*(4), 1880.<br>Clauss GF, Siekmann H, Tampier BG., 2007, Simulation of the operation of wind-assisted cargo ships. Hauptversammlung der Schiffbautechnischen Gesellschaft, 21–23 November 2007, Berlin, Germany. p. 1–12.<br>Duarte, C. M., Chapuis, L., Collin, S. P., Costa, D. P., Devassy, R. P., Eguiluz, V. M., ... and Juanes, F., 2021, The soundscape of the Anthropocene ocean. Science, 371(6529), eaba4658.<br>IWSA, Gavin Allwright, 2023, Best Practice Manual. Deliverable D2.4c of the project WASP (Wind Assisted Ship Propulsion). Available at: https://vb.northsearegion.eu/public/files/repository/20230720134933_WASP-BPM-version5-FINAL27June2023.pdf (last access: 2 December 2025).<br>Lu, R., and Ringsberg, J. W., 2020, Ship energy performance study of three wind-assisted ship propulsion technologies including a parametric study of the Flettner rotor technology. *Ships and offshore structures*, *15*(3), 249-258.<br>Reche-Vilanova, M., Bingham, H. B., Fluck, M., Morris, D., and Psaraftis, H. N., 2025, Cost–benefit analysis and design optimization of wind propulsion systems for a Tanker retrofit case. Maritime Transport Research, 8, 100132.<br>Stalmokaitė, I., Larsson Segerlind, T., and Yliskylä-Peuralahti, J., 2023, Revival of wind-powered shipping: Comparing the early-stage innovation process of an incumbent and a newcomer firm. Business Strategy and the Environment, 32(2), 958-975.<br>Seddiek, I. S., and Ammar, N. R., 2021, Harnessing wind energy on merchant ships: case study Flettner rotors onboard bulk carriers. *Environmental Science and Pollution Research*, *28*(25), 32695-32707.<br>Tadros, M., Ventura, M., and Soares, C. G., 2023, Review of current regulations, available technologies, and future trends in the green shipping industry. *Ocean Engineering*, *280*, 114670. |

### *Constructed wetland designs to filter waste waters and industrial effluents*

| Name/type | Constructed wetland designs to filter waste waters and industrial effluents |
|---|---|
| Spatial scale | Local |
| Spatial and temporal scope of implementation | Designs were first tried in the 1960s in Europe and North America (Shutes, 2001). Currently, this measure is implemented in temperate and tropical areas in most continents (Shutes, 2001; Santos et al., 2024). |

| Name/type | Constructed wetland designs to filter waste waters and industrial effluents |
|---|---|
| Objective of the measure and main actions implemented | Reduced water flow, sedimentation pools and use of vegetation to trap substances are used in different designs, mimicking the natural processes. |
| Estimated economic cost | Low construction and operating costs. |
| Environmental Benefits | Capturing of hazardous substances, nutrients, organic matter, pharmaceuticals, litter and microplastics, as well as pathogens. |
| Social and economic co-benefits | Easy to operate, economical, less-energy consuming, and suitable for both small communities and areas that are not connected to the sewerage system. |
| Maintenance needs | Low |
| Stakeholders' engagement | The application is typically used in small communities where local involvement is critical. |
| Success and/or limiting factors | + Balancing removal efficiency with outflow quality while accounting for site-specific condition.<br>- In some areas, support is needed from other management measures to influence the inflow waters, e.g. buffer zones (Gaballah and Lammers, 2025). |
| Trade-offs | NA |
| Links to MSFD drivers-pressures | Pressures:<br>• Biological:<br>  ○ Input of microbial pathogens;<br>• Physical:<br>  ○ Physical disturbance to seabed (temporary or reversible);<br>• Substances, litter and energy:<br>  ○ Input of nutrients – diffuse sources, point sources, atmospheric deposition;<br>  ○ Input of organic matter – diffuse sources and point sources;<br>  ○ Input of other substances (e.g. synthetic substances, non-synthetic substances, radionuclides) – diffuse sources, point sources, atmospheric deposition, acute events<br>  ○ Inputs of litter (solid waste matter, including micro-sized litter)<br>Contribution to achieve GES: D5, D8, D9, D10. |
| Links to other policy objectives | Global: SDG 14.2, 14.4; Ramsar Convention.<br>EU: NRR; MSFD; WFD; Zero Pollution Action Plan. |
| References | Gaballah, M.S. and Lammers, R.W., 2025, Assessing the factors influencing constructed wetland performance for mitigating agricultural nutrient runoff in the U.S. Journal of Water Process Engineering 71, 107293<br>Santos, J., Rodrigues, S., Magalhães, M., Rodrigues, K., Pereira, L. and Marinho, G., 2024, A state-of-the-art review (2019–2023) on constructed wetlands for greywater treatment and reuse. Environmental Challenges 16, 100973<br>Shutes, R.B.E, 2001, Artificial wetlands and water quality improvement. Environment International 26: 441-447. |

### *Bio-anti-fouling agents*

| Name/type | Bio anti-fouling agents |
|---|---|
| Spatial scale | Local |
| Spatial and temporal scope of implementation | The search for natural antifouling substances has gained momentum in recent years to address the urging issues of environmental pollution associated with the use of toxic chemicals (Satheesh et al., 2016). |
| Objective of the measure and main actions implemented | Antifouling agents have been proved to have significant negative environmental impacts. For example, tributyltin (TBT), widely used in anti-fouling paints and now banned in 27 countries (Almeida and Vasconcelos, 2015), has been proved to trigger imposex (i.e., the imposing of male genitalia on females) in shoreline whelks and other neogastropod molluscs in Southeast Asia (Ellis and Agan Pattisina 1990).<br>To address this issue, new types of anti-fouling agents have been developed, based on naturally occurring marine compounds or even on microorganisms associated with sponges, corals, ascidians, seaweeds and seagrasses (Almeida and Vasconcelos, 2015, Satheesh et al., 2016), which have a limited environmental impact on marine biodiversity and increase the efficiency of propulsion (Riisager-Simonsen et al., 2022). |
| Estimated economic cost | It is not possible to estimate the economic costs of this measure, as these substances are still in the development phase and have not been commercialised yet |
| Environmental Benefits | • Reduction in the negative impact of chemicals on marine biodiversity;<br>• The increase in propulsion efficiency may contribute to lower $CO_2$ emissions from ships (Riisager-Simonsen et al., 2022). |
| Social and economic co-benefits | The use of bio-antifouling substances may reduce the costs for the control and cleaning processes, as well as the ship's fuel consumption |
| Maintenance needs | Each substance has its own duration and needs for replacement and recoating. |
| Stakeholders' engagement | No particular needs for stakeholders' engagement, as the development process is still at the research stage and, once successfully terminated, bio antifouling products will be launched onto the market. |
| Success and/or limiting factors | - There are still research gaps on the mode of action, specific targets, and presumable environmental fate of the numerous bio anti-fouling substances that have been characterised as effective and non-toxic (Almeida and Vasconcelos, 2015).<br>- Most studies have been conducted under laboratory conditions and there is the need to test the compounds proposed in natural water for commercial applications. (Satheesh et al., 2016).<br>- These substances are still far from commercialisation, but there are promising prospects for their future implementation |
| Trade-offs | The toxicity of proposed compounds may be toxic for non-target organisms, and further assessments are needed (Satheesh et al., 2016). |
| Links to MSFD drivers-pressures | Pressures:<br>• Biological:<br>  ○ Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities);<br>• Substances, litter and energy: |

| Name/type | Bio anti-fouling agents |
|---|---|
| | ○ Input of other substances (e.g. synthetic substances, non-synthetic substances, radionuclides) - diffuse sources, point sources, atmospheric deposition, acute events;<br><br>Contribution to achieve GES: D1, D3, D4, D8, D9. |
| Links to other policy objectives | Global: CBD and the Global Biodiversity Framework; Paris Agreement<br><br>EU: WFD; MSFD; EU Climate Law. |
| References | Ellis, D. V., and Pattisina, L. A., 1990, Widespread neogastropod imposex: a biological indicator of global TBT contamination? *Marine pollution bulletin*, *21*(5), 248-253.<br><br>Satheesh, S., Ba-Akdah, M. A., and Al-Sofyani, A. A., 2016, Natural antifouling compound production by microbes associated with marine macroorganisms—A review. *Electronic Journal of Biotechnology*, *21*, 26-35.<br><br>Yan, H., Wu, Q., Yu, C., Zhao, T., and Liu, M., 2020, Recent progress of biomimetic antifouling surfaces in marine. *Advanced materials interfaces*, *7*(20), 2000966. |

## 3.5 Category 5: Geo-engineering techniques

This category includes the main techniques to deliberately manipulate the planetary environment at large scale, which have been proposed internationally to mitigate climate change exploiting ocean physico-chemical processes and properties. The Royal Society classifies these techniques into two categories (GESAMP, 2019):

1. Carbon Dioxide Removal (CDR) methods, which aim to reduce the levels of $CO_2$ in the atmosphere, allowing outgoing long-wave thermal infra-red radiation to escape more easily – In this review, the following CDR techniques were included: ocean iron/macro-nutrients fertilisation; artificial structures for upwelling; ocean alkalinity enhancement; and ocean thermal energy conversion.
2. Solar Radiation Management (SRM) methods, which aim to reduce the net incoming short-wave, ultra-violet and visible solar radiation received, either by deflecting sunlight or by increasing the reflectivity (albedo) of the atmosphere, clouds or the Earth's surface (Royal Society, 2009). In this review, increasing ocean albedo was included as an SRM measure.

### *CDR – Ocean iron/macro-nutrients fertilisation*

| Name/type | Ocean iron/macro-nutrients fertilisation |
|---|---|
| Spatial scale | Local, National, Transnational |
| Spatial and temporal scope of implementation | There is a long history of scientific field experiments, since 1993 (GESAMP, 2025). Previous studies identified oceanic high-nitrate and low-chlorophyll areas, i.e., Eastern Equatorial Pacific, subarctic North Pacific, and Southern Ocean (GESAMP, 2025), as the most suitable areas for the implementation of this measure. Especially, the latter area is the most promising for net carbon sequestration (GESAMP, 2019). |
| Objective of the measure and main actions implemented | This measure consists of the introduction of iron or macronutrients (phosphorus, nitrogen, or silicate) into surface waters, directly or indirectly, via external sources or via enhanced ocean mixing, to stimulate the growth of microscopic marine plants and the uptake of atmospheric $CO_2$ by the ocean, with the aim to mitigate climate change.<br><br>In recent years, several variations have been explored (but not yet tested in the field), involving iron-rich biogenic dust, or adding mineral dust to blooms to |

| Name/type | Ocean iron/macro-nutrients fertilisation |
|---|---|
| | accelerate settling driven by particle scavenging, combining it with artificial upwelling or with ocean alkalinity enhancement approaches (GESAMP, 2025). |
| Estimated economic cost | In general, iron fertilisation is economically and logistically more attractive than macronutrient fertilization, as it has the potential to stimulate a significantly large removal of $CO_2$ (GESAMP, 2025).<br>Ward et al. (2025) estimated a levelized cost of carbon for iron fertilization of approximately USD 200 per tonne of $CO_2$, with a perspective future cost as low as USD 180 per tonne of $CO_2$. They also highlight that costs depend more on oceanographic parameters, such as the export efficiency of carbon biomass to the deep ocean, than on engineering parameters such as the cost of equipment or materials. |
| Environmental Benefits | This measure enhances the ocean's biological pump, increasing primary productivity and stimulating the removal of $CO_2$ from the atmosphere, part of which will be ultimately stored in seabed sediments (Rackley, 2023). However, the quantification of the amount of carbon sequestration is uncertain, due to the long (months to > 1 year) equilibration times to balance the difference in $CO_2$ concentrations between the atmosphere and the ocean (GESAMP, 2025). |
| Social and economic co-benefits | This measure has the potential to decrease global warming and mitigate climate change, with global-scale and wide-range socioeconomic benefits for all humanity. However, these benefits have not been proved to date, because of the lack of large-scale experiments. |
| Maintenance needs | The deployment of iron must last multiple years or even decades to be effective (GESAMP, 2019). The durability of carbon removal is difficult to estimate, depending on the depths to which carbon sinks; this is the main limitation of this approach (GESAMP, 2025). |
| Stakeholders' engagement | As for other geo-engineering measures, it is key to ensure adequate public engagement on ocean fertilisation projects, to help improve trust between scientists and the public, ensure that the decisions consider a broad set of societal interests, values and framing, and address the general concerns of the inherently undemocratic nature of such measures (Williamson and Bodle, 2016). |
| Success and/or limiting factors | - It is still unclear how wide-ranging bloom characteristics lead to different carbon sequestration patterns (GESAMP, 2019).<br>- Modelling projections indicate that having only iron-mediated increases in particle export is insufficient to drawdown more carbon, and that other factors play a key role in influencing the efficacy of this measure, namely ocean circulation, stoichiometric ratios (carbon and nutrients) and gas exchange (GESAMP, 2019). |
| Trade-offs | Given the insufficient understanding of the potential impacts on marine ecosystems, due to the lack of sound and objectively verifiable scientific data, both the UNESCO-IOC (2008) and the London Convention/London Protocol (Resolution LC-LC.1 of 31 October 2008) required not to implement such projects before adequate scientific knowledge is produced. Currently, there is scientific uncertainty on the rate and scale of $CO_2$ removal, due to long equilibration times to balance the difference in $CO_2$ concentrations between the atmosphere and the ocean (GESAMP, 2025).<br>Possible unintended consequences of this measure include the production of more climate-relevant gases, such as nitrous oxide and methane, during the subsurface decomposition of the sinking particles from iron-stimulated blooms (GESAMP, 2019), which may reinforce or offset the benefits of $CO_2$ sequestration; negative effects on productivity, because of impacts on photosynthesis due to the depletion of nitrogen |

| Name/type | Ocean iron/macro-nutrients fertilisation |
|---|---|
| | or phosphorus nutrients; mid-water oxygen decrease; changes in the spatial patterns of ocean acidification (higher acidification in deep ocean waters); and negative impacts on the seafloor ecosystem from enhanced POC sinking flux (Williamson et al., 2012; GESAMP, 2025). Also, the emergence of stocks of potential toxic species of diatoms was observed in several mesoscale experiments (GESAMP, 2019).<br>Overall, benefits are modest in relation to anthropogenic climate forcing and are difficult to quantify in the long term; therefore, currently, ocean fertilization would not provide a particularly effective approach to counteract increasing atmospheric concentrations of $CO_2$ (Williamson et al., 2012). |
| Links to MSFD drivers-pressures | Pressures: N/A<br>Benefits to GES: N/A |
| Links to other policy objectives | Global: Paris Agreement.<br>EU: EU Climate Law. |
| References | GESAMP, 2019, "High level review of a wide range of proposed marine geoengineering techniques". (Boyd, P.W. and Vivian, C.M.G., eds.). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 98, 144 p.<br>GESAMP, 2025, The State of the Science for Marine $CO_2$ Removal (mCDR) – A Scientific Summary for Policy-Makers. https://doi.org/10.5281/zenodo.15490407<br>Rackley, S., 2023, "Chapter 2—overview of negative emissions technologies," in Negative emissions Technologies for Climate Change Mitigation, eds. S. Rackley, G. Andrews, D. Clery, RichterR. De, G. Dowson and P. Knopset al. (Amsterdam, Netherlands; Oxford, United Kingdom; Cambridge, United States: Elsevier), 19–39. doi: 10.1016/B978-0-12-819663-2.00001-0.<br>UNESCO-Intergovernmental Oceanographic Commission. Statement of the IOC ad-hoc Consultative Group on Ocean Fertilization. Paris, 14 June 2008. Available at: https://web.whoi.edu/ocb-fert/wp-content/uploads/sites/100/2017/07/IOC_Group_Submission_June14_56384.pdf (last access: 26 November 2025).<br>Ward, C., Lee Pereira, R. J., Foteinis, S., and Renforth, P., 2025, Techno-economic analysis of ocean iron fertilization. *Frontiers in Climate*, *7*, 1509367.<br>Williamson, P., and Bodle, R., 2016, Update on Climate Geoengineering in Relation to the Convention on Biological Diversity: Potential Impacts and Regulatory Framework. Convention on Biological Diversity Technical Series No. 66, 1-152. Retrieved from https://www.cbd.int/doc/publications/cbd-ts-84-en.pdf (last access: 26 November 2025).<br>Williamson, P., Wallace, D.W.R., Law, C.S., Boyd, P.W., Collos, Y., Croot, P., Denman, K., Riebesell, U., Takeda, S. and Vivian, C., 2012, Ocean fertilization for geoengineering: A review of effectiveness, environmental impacts and emerging. Process Safety and Environmental Protection, Vol. 90, No. 6, pp. 475–88. https://doi.org/10.1016/j.psep.2012.10.007 |

### *CDR – Artificial structures to increase primary production through upwelling*

| Name/type | Construction of artificial structures to increase primary production through upwelling |
|---|---|
| Spatial scale | Local, National, Transnational |
| Spatial and temporal scope of implementation | In Japan, the first studies were conducted since 1989, while evaluations of the effects of artificial seamounts were conducted from 1995 to 2001 (Suzuki and Hashimoto, 2011).<br>The most suitable areas are mid- and low-latitude ocean areas, where nutrients are depleted in surface waters and biological production is limited (GESAMP, 2019). This measure is considered to be ineffective in iron-limited regions, such as the equatorial Pacific and Southern Ocean, and promising in areas such as the subarctic Pacific (National Academies of Sciences, Engineering, and Medicine, 2022).<br>Nowadays, several experiments have been performed, mainly in the UK, Japan, Norway, Taiwan, EU (Ocean ArtUp project) and China (Pan et al., 2016; Riisager-Simonsen et al., 2022), usually on a small scale and with deployments of less than a week (National Academies of Sciences, Engineering, and Medicine, 2022).<br>To date, there are no concrete applications in proof-of-concept sea trials. |
| Objective of the measure and main actions implemented | This measure consists in the construction of eco-engineering solutions to foster the artificial upwelling of nutrient-rich deep water in areas with low primary production due to nutrient scarcity, to stimulate phytoplankton growth and the export of organic carbon to deep areas (GESAMP, 2019). Some experiments have been conducted through purposely designed artificial reefs, also called “sea mountains”, and by using wave-powered pumps. Pan et al. (2016) report that the following methods have been experimented: wave-pump; electrical pump; perpetual salt fountain; brackish water uplift pump; air-bubble pump; and air-lift pump.<br>Artificial downwelling, i.e., the engineered downward generation of vertical currents, has also been suggested to be coupled with artificial upwelling to pump recalcitrant dissolved organic carbon to depth or to prevent outgassing, so as to enhance the sequestration of dissolved and particulate organic carbon; however, to date it has not been tested in the field to this purpose (National Academies of Sciences, Engineering, and Medicine, 2022). |
| Estimated economic cost | Artificial upwelling/downwelling is considered as one of the most expensive Carbon Dioxide Removal (CDR) geo-engineering techniques (Webb et al., 2022). It has been estimated that the planning and implementation of demonstration-scale in situ experimentation (>1 year, >1,000 km) in region-sited-based input from modelling and preliminary experiments would cost USD 25 million per year, for 10 years (National Academies of Sciences, Engineering, and Medicine, 2022), corresponding to USD 100-150 per tonne of $CO_2$ sequestered (Webb et al., 2022). Another estimate from Ocean-Based Climate Solutions, Inc. Indicates a cost of USD 60,000 per 500-meter tube capable of sequestering 250 $tCO_2$/year (corresponding to USD 240/tonne). If scaled up, this would correspond to a cost of tens of millions (National Academies of Sciences, Engineering, and Medicine, 2022). In previous years, a significant increase has been observed in research investments in artificial upwelling to support medium-scale deployments (National Academies of Sciences, Engineering, and Medicine, 2022). |
| Environmental Benefits | Artificial upwelling can increase the presence of phytoplankton and its rate of photosynthesis through the uplift of cold and hypoxic ocean water to the euphotic layer (Pan et al., 2016); this may enhance productivity and create foraging areas for pelagic organisms. Moreover, it may enhance the export of organic carbon to the |

| Name/type | Construction of artificial structures to increase primary production through upwelling |
|---|---|
| | deep ocean via the biological pump (Pan et al., 2016; Riisager-Simonsen et al., 2022), contributing to cooling of the ocean's surface and overlying air at local/regional scales (GESAMP, 2019), thereby mitigating global warming. Artificial upwelling could even enhance terrestrial carbon storage (National Academies of Sciences, Engineering, and Medicine, 2022).<br>While upwelled nutrients are accompanied by a stochiometric equivalent of respired carbon, which does not lead to a drawdown of $CO_2$, a net uptake can be achieved in regions where upwelled waters have a particularly low content of $CO_2$ (GESAMP, 2019). An estimate to 2100 points to an oceanic carbon uptake of this measure of less than 20 Gt of carbon, equivalent to a 10-ppm atmospheric drawdown, with an indirect enhancement of terrestrial carbon sequestration of up to 100 Gt of carbon, thanks to reduced soil respiration at lower atmospheric temperatures that follow colder sea surface temperatures (Oschlies et al., 2010, GESAMP, 2019).<br>In a series of simulated experiments off Bermuda, Sawall et al. (2020) indicated that controlled upwelling could abate coral bleaching during heat stress events. |
| Social and economic co-benefits | Artificial upwelling may be employed to sustain productive fishing grounds, which may be created close to markets (Kirke, 2003), and local aquaculture, especially seaweed growth, although some studies determined that the level of nutrients injected would be maintained at levels far below those needed to sustain aquaculture. It has also been proposed as a means of providing energy and cooling (National Academies of Sciences, Engineering, and Medicine, 2022). |
| Maintenance needs | To date, there is not enough information about the long-term operation and efficacy of artificial upwelling (National Academies of Sciences, Engineering, and Medicine, 2022).<br>Artificial upwelling has a long, multi-decadal period of implementation (GESAMP, 2019). If artificial upwelling stops, the additional heat can return to the surface and lead to an increase in surface temperatures exceeding the previous status (GESAMP, 2019). |
| Stakeholders' engagement | Ocean Carbon Direct Removal (CDR) projects are expected to face public acceptability challenges. Stakeholders and the public will be concerned on how to govern the perceived high, novel risks. Hence, extensive consultation of affected communities is recommended (National Academies of Sciences, Engineering, and Medicine, 2022). |
| Success and/or limiting factors | + The optimum depth from which to extract water is approximately 100-200 m (Pan et al., 2018).<br>+ The design of the seamount as composed of blocks piled up to form a planned conic shape showed to be advantageous in terms of both function and deployment (Suzuki and Hashimoto, 2011).<br>+ The efficiency of carbon sequestration may vary depending on the local characteristics, the season, and the technical parameters of the technique employed (Pan et al., 2018).<br>- Current wave pump technology may not be adequate for open ocean applications; new, more durable tube materials must be developed, while keel design must be re-engineered to enhance the endurance of wave pumps (White et al., 2010).<br>- The scale and duration of the biological response to upwelling varies depending on the variability and unpredictability of the physical environment (wave height and |

| Name/type | Construction of artificial structures to increase primary production through upwelling |
|---|---|
| | frequency, storms, etc.), as well as across seasons and spatial locations (White et al., 2010).<br>- The success of the pilot interventions, performed in various locations and at different scales, has not been proved yet (Riisager-Simonsen et al., 2022). |
| Trade-offs | Although applied in small-scale pilot experiments, the technology behind artificial upwelling is not yet robust enough to be applied in the open ocean over the timescales needed for carbon removal (National Academies of Sciences, Engineering, and Medicine, 2022).<br>The use of this technology has the potential to pose threats to fisheries, ecological cycles, and the climate (Riisager-Simonsen et al., 2022), which are strongly influenced by certain technical parameters, the applied region, and the season (Pan et al., 2018):<br>• The reduction of outgoing long-wave radiation of the planet would be decreased, resulting in the accumulation of energy during artificial upwelling, stored as heat in subsurface waters, and the consequent disturbance of the thermocline, leading on longer timescales to higher global mean temperatures (Kwiatowski et al., 2015; GESAMP, 2019).<br>• Some studies report a small or even negative effect of artificial upwelling on atmospheric $CO_2$ uptake (Pan et al., 2018).<br>• There may be substantial changes in the species composition of phytoplankton, shifting towards larger cells, and those communities that prefer a eutrophic environment would be favoured.<br>• The enhancement of the quantity of carbon flux reaching the seafloor may increase the amount of seafloor biomass and change the balance among different organisms, with uncertain effects on seafloor biodiversity (Pan et al., 2016).<br>• The increase in biological production at wide scale may lead to enhanced remineralisation of organic material in the water column, depleting mid-water oxygen levels and increasing methane and nitrous oxide release (GESAMP, 2019).<br>• There may be an exacerbation of surface acidification through the uplift of low-pH sea water, leading to an estimated decrease of pH of up to 0.15, with negative effects on marine organisms with calcium carbonate structure (Pan et al., 2016).<br>A theoretical application of this measure to all the areas of the tropics with a carbon fixation efficiency of 2.2% relative to air-sea uptake, would require the deployment of 189-776 million pumps to increase ocean carbon sequestration by 1 Pg/year above current rates. This would inevitably generate conflicts with transatlantic shipping routes and fishing activity (National Academies of Sciences, Engineering, and Medicine, 2022). |
| Links to MSFD drivers-pressures | Pressures:<br>• Biological:<br>  ○ Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities);<br>Contribution to achieve GES: D1, D3, D4, D5, D6 |

| Name/type | Construction of artificial structures to increase primary production through upwelling |
|---|---|
| Links to other policy objectives | Global: UNFSA; Paris Agreement.<br>EU: CFP; EU Climate Law. |
| References | Kirke, B., 2003, Enhancing fish stocks with wave-powered artificial upwelling. *Ocean and coastal management*, *46*(9-10), 901-915.<br>Kwiatkowski, L.; Ricke, K.L.; Caldeira, K., 2015, Atmospheric consequences of disruption of the ocean thermocline. Environ. Res. Lett., 10, 1–9.<br>GESAMP, 2019, "High level review of a wide range of proposed marine geoengineering techniques". (Boyd, P.W. and Vivian, C.M.G., eds.). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 98, 144 p.<br>National Academies of Sciences, Engineering, and Medicine, 2022, A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration. Washington, DC: The National Academies Press.<br>Oschlies, A., Pahlow, M., Yool, A., and Matear, R. J., 2010, Climate engineering by artificial ocean upwelling: Channelling the sorcerer's apprentice. Geophysical Research Letters, 37(4).<br>Pan, Y., Fan, W., Zhang, D., Chen, J., Huang, H., Liu, S., ... and Chen, Y., 2016, Research progress in artificial upwelling and its potential environmental effects. *Science China Earth Sciences*, *59*(2), 236-248.<br>Pan, Y., You, L., Li, Y., Fan, W., Chen, C. T. A., Wang, B. J., and Chen, Y., 2018, Achieving highly efficient atmospheric CO2 uptake by artificial upwelling. Sustainability, 10(3), 664.<br>Riisager-Simonsen, C., Fabi, G., van Hoof, L., Holmgren, N., Marino, G., and Lisbjerg, D., 2022, Marine nature-based solutions: Where societal challenges and ecosystem requirements meet the potential of our oceans. *Marine Policy*, *144*, 105198.<br>Sawall, Y., Harris, M., Lebrato, M., Wall, M., and Feng, E. Y., 2020, Discrete pulses of cooler deep water can decelerate coral bleaching during thermal stress: Implications for artificial upwelling during heat stress events. Frontiers in Marine Science 7:00720. https://doi:10.3389/fmars.2020.00720<br>Suzuki, T., and Hashimoto, O., 2011), Enhancing food production on the continental shelf by artificial seamounts. In Artificial reefs in fisheries management (pp. 297-309). CRC Press.<br>Webb, R. M., Silverman-Roati, K., and Gerrard, M. B., 2022, Removing carbon dioxide through artificial upwelling and downwelling: Legal challenges and opportunities.<br>White, A., Björkman, K., Grabowski, E., Letelier, R., Poulos, S., Watkins, B., and Karl, D., 2010, An open ocean trial of controlled upwelling using wave pump technology. Journal of Atmospheric and Oceanic technology, 27(2), 385-396. |

### *CDR – Enhancing ocean alkalinity*

| Name/type | Enhancing ocean alkalinity |
|---|---|
| Spatial scale | Local, national, transnational |
| Spatial and temporal scope of implementation | The first ideas to emulate the natural weathering process and enhance ocean alkalinity were proposed in the 1990s. Recently, some small-case tests have been performed globally, and several large funders have proposed to mobilise significant amounts of investments into this type of projects (Nawaz et al., 2023). |
| Objective of the measure and main actions implemented | This measure consists of adding additional chemical base to seawater to increase the alkalinity of the ocean, so that the surface water partial pressure of $CO_2$ decreases and the $CO_2$ uptake increases. Several methods have been proposed in literature: (1) adding lime directly to the ocean, which consumes ocean and air $CO_2$; (2) adding carbonate minerals to undersaturated subsurface waters; (3) accelerating the weathering of limestone, by reacting carbonate minerals with waste flue gas $CO_2$ and seawater; (4) electrochemical enhancement of carbonate and silicate mineral weathering; (5) thermal decomposition of desalination reject brine; (6) dissolution of olivine or other silicate mineral particles in the open ocean or in coastal areas; (7) enhanced weathering of crushed mine waste (GESAMP, 2019). |
| Estimated economic cost | Costs depend on the technique employed: ocean liming has an estimated cost of 72-159 USD per tonne of $CO_2$ sequestered; electrochemical weathering may cost 14-190 USD per tonne of $CO_2$; and accelerated weathering of limestone may cost 10-40 USD per tonne of $CO_2$. These costs are considered as comparable with other alternative carbon capture and storage techniques. However, there are no widely employed or transparent decision-making frameworks for investment in technology development, and the predicted future costs, the required resources to progress development, and the lead time for implementation are still unassessed (Renforth and Henderson, 2017). |
| Environmental Benefits | The benefits of this measure require further study. In general, by helping to decrease surface water partial pressure of $CO_2$, this measure can increase ocean $CO_2$ uptake and provide a stable storage for anthropogenic $CO_2$. Renforth and Henderson (2017) estimate the possibility to sequester hundreds of billions to trillions of tonnes of carbon for around 100,000 years, which is the residence time of dissolved inorganic carbon in the ocean.<br>Moreover, this measure may counter seawater acidity generated by excess $CO_2$ and, therefore, help reverse the effects of ocean acidification (GESAMP, 2019).<br>However, the effects of the increase in alkalinity on marine ecosystems are currently poorly understood and require further research. |
| Social and economic co-benefits | The socioeconomic benefits of this measure are currently very poorly understood or considered in the pilot implementation phase. Nawaz et al. (2023) identify the following potential social impacts:<br>• Direct impacts – Increases to local shellfish production and income, and job creation from the project supply chain;<br>• Indirect impacts – Changes in food provisioning from aquaculture or fisheries in surrounding areas, social impacts of the expansion of mining activities;<br>• Cumulative impacts – Health effects of additional elements, and impacts on local tourism and aesthetics from industrial infrastructure and vessel traffic. |
| Maintenance needs | The deployment must be continuous to achieve sustained $CO_2$ removal and/or mitigation of ocean acidification (GESAMP, 2019). |

| Name/type | Enhancing ocean alkalinity |
|---|---|
| Stakeholders' engagement | The public acceptability of this measure should be thoroughly assessed and considered before deployment (GESAMP, 2019). Rayner et al. (2013) proposed some principles for the effective governance of this measure, including public participation in decision-making, the disclosure of research and open publication of results. |
| Success and/or limiting factors | + Waste mineral dissolution should be done near the site of surface ocean addition, to prevent in situ precipitation of minerals releasing $CO_2$ again.<br>- The precipitation of carbonate minerals decreases the efficacy of this measure (GESAMP, 2019).<br>- Ocean liming, the electrochemical enhancement of carbonate and silicate mineral weathering, and the crushing of olivine to the very small required dimensions (≤1µm) need great quantities of energy; hence, it is important that they are implemented using renewable sources, to avoid offsetting the advantages of this method for carbon sequestration (GESAMP, 2019).<br>- The accelerated weathering of limestone seems to have low impact, although it requires thousands of tonnes of seawater per tonne of $CO_2$ sequestered; further research is needed to assess the environmental impacts of this measure (GESAMP, 2019). |
| Trade-offs | The biogeochemical and ecological responses to this measure are not yet fully understood, and further research and testing are required. In fact, rapid, uncontrolled changes in pH, carbon saturation state, and dissolved aqueous $CO_2$ may have negative effects on ecosystems. This measure could enhance biologically-mediated precipitation of calcium carbonate, which would release $CO_2$ and reduce the efficacy of this measure. Also, the introduction of other ions could impede or enhance carbon fixation and other biogeochemical processes, with possible impacts on marine ecosystems (GESAMP, 2019). More in detail, the introduction of silicon and iron could have negative effects comparable to those of active ocean fertilisation (e.g., increase in nitrous oxide and methane emissions, lower dissolved oxygen, nutrient-driven ecosystem structural changes). Moreover, the reduction of dissolved carbon could inhibit photosynthesis and alter the function and structure of phytoplankton communities (Renforth and Henderson, 2017).<br>The potential negative consequences of introducing olivine or other silicate mineral particles are currently unknown; these may relate to disturbances of food-web interactions, the biochemical effects and fate of other metal impurities released from silicate minerals, and possible pore water saturation in the seabed of coastal areas (GESAMP, 2019). |
| Links to MSFD drivers-pressures | Pressures: N/A<br>Contribution to achieve GES: N/A |
| Links to other policy objectives | Global: Paris Agreement.<br>EU: EU Climate Law. |
| References | GESAMP, 2019, "High level review of a wide range of proposed marine geoengineering techniques". (Boyd, P.W. and Vivian, C.M.G., eds.). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 98, 144 p. |

| Name/type | Enhancing ocean alkalinity |
|---|---|
| | Nawaz, S., Lezaun, J., Valenzuela, J. M., and Renforth, P., 2023, Broaden research on ocean alkalinity enhancement to better characterize social impacts. *Environmental Science and Technology*, *57*(24), 8863-8869.<br>Rayner, S., Heyward, C., Kruger, T., Pidgeon, N., Redgwell, C., and Savulescu, J., 2013, The Oxford principles, Clim. Chang., 121, 499–512, doi:10.1007/s10584-012-0675-2.<br>Renforth, P., and Henderson, G., 2017, Assessing ocean alkalinity for carbon sequestration. Reviews of Geophysics, 55(3), 636-674. |

### *CDR – Ocean thermal energy conversion*

| Name/type | Ocean thermal energy conversion |
|---|---|
| Spatial scale | Local |
| Spatial and temporal scope of implementation | First proposed in the 1880s, this measure has been developed and piloted in the last 40 years in Japan, Hawaii, and Martinique (GESAMP, 2019; Herrera et al., 2021). The most suitable areas are those between 20- and 24-degrees latitude. To date, the only pilot that is still operational is in the Hawaii, USA, producing 105kW (GESAMP, 2019). |
| Objective of the measure and main actions implemented | This process aims to generate electrical power by exploiting the difference in temperature between the surface and the deep layers of the ocean. A working fluid with low boiling temperature (e.g., ammonia) is heated, and vapour is used to drive a turbine and electricity generator, while cold water is used to re-condense the vapour. For a 100MW power plant, it has been calculated that about 50,000$m^3$ per minute of water are needed. This technology may be employed also to cool ocean surface waters, transferring heat into deeper waters (GESAMP, 2019). |
| Estimated economic cost | This measure has high investment and implementation costs, especially of the cables, and a low conversion efficiency, of about 2.5-5.3% (Aresti et al., 2023); therefore, government support is advised. Plants below 300 kW are not commercially viable, at least in developed countries (Herrera et al., 2021). The levelised cost of energy ranges from 0.05 to 0.45 USD/kWh (Aresti et al., 2023). Other estimates by Olim et al. (2025) indicate that by combining ocean thermal energy conversion with DACCS in tropical depleted or semi-depleted oil and gas fields, a total of 33,000 90MW plants would be necessary to sequester 2,446Gt $CO_2$ over a 70-year period, corresponding to USD 166-398 per tonne of $CO_2$ sequestered.<br>However, there is still uncertainty over the capital costs at both system and component level, and on the operational costs and useful lifetime (Langer et al., 2020). |
| Environmental Benefits | This measure allows to produce carbon-neutral or even carbon-negative energy, with a global theoretical potential of up to 30TW (Langer et al., 2020). In fact, this measure may sequester carbon directly, i.e., by altering the surface temperature and circulation of the ocean, and indirectly, by moving nutrients from deep waters to the surface, increasing primary production.<br>The presence of nutrients and the functioning of the installation as artificial reef may contribute to attract fauna (GESAMP, 2019). |
| Social and economic co-benefits | The following potential socioeconomic benefits of this measure have been identified:<br>• These installations can convert seawater vapour into drinking water, thus contributing to water access and availability, especially on small islands.<br>• The flow of cold seawater can be used to cool soil and allow the cultivation of temperate plants in tropical areas (refrigerated soil agriculture). |

| Name/type | Ocean thermal energy conversion |
|---|---|
| | • The nutrient-rich water pumped from ocean depths may be used to feed aquaculture systems, contributing to lower the costs associated with feeding.<br>• The fauna attracted by nutrients and by the use of installations as reefs, may support local fisheries (Herrera et al., 2021). |
| Maintenance needs | This measure can be implemented continuously. |
| Stakeholders' engagement | Based on experience in the USA, Copping and Farr (2024) argue that community involvement is key to ensure social licence and stewardship of ocean thermal energy conversion projects. Communities should be involved in the choice of location of the infrastructure components and be informed on the health and safety issues. Moreover, their concerns in relation to the possible loss of cultural services related to the sea, possible restrictions to economic activities and increased competition and conflicts of use, should be addressed, possibly through maritime spatial planning (Kim and Kim, 2020). |
| Success and/or limiting factors | + Facilities may be built: (i) onshore – they are protected by storms, do not require a robust lashing system, and maintenance is cheaper; however, they need significant investment in pipes; (ii) offshore – they should be located at about a depth of 100 m, to avoid influence from waves; however, they are subject to stress from open sea conditions and require submarine cables to reach the distribution network; (iii) floating, e.g. on a ship, with low implementation costs and less difficulty in design, but with difficulties related to anchoring in deep waters, possible damage to cables from continuous wave movement, and not easy maintenance (Herrera et al., 2021).<br><br>+/- While its efficiency is very low, the energy source is almost unlimited, and plants can generate electricity continuously, without interruptions (Herrera et al., 2021).<br><br>- The temperature differential is key to the efficiency of this measure (Herrera et al., 2021); to function, the difference in temperature between the surface and deep water must be at least 20°C to achieve net power generation. Globally, this corresponds to areas between 20- and 24-degrees latitude (GESAMP, 2019).<br><br>- This measure is more viable for small islands, where the benefits of obtaining electricity from cleaner sources and the production of desalinated waters would be profitable under current costs, and for middle-income island countries, where up to 10 MW open-cycle systems could be installed, generating desalinated water at competitive prices. Industrialised countries should implement systems of up to 50 MW, which would be viable under the scenario of the high prices of fossil fuels (Herrera et al., 2021).<br><br>- Because of the high implementation costs and low efficiency, a comprehensive vision is necessary to develop such systems, considering the generation of drinking water, the design of appropriate spaces, the generation of food, and correctly involving the local community to develop a sense of appropriation (Herrera et al., 2021). |
| Trade-offs | The discharge of nutrient-rich water at surface could shift community species composition, enhance phytoplankton growth or cause algal blooms. Some modelling studies showed that this shift could be within naturally occurring variability; however, the possible cumulative impacts are not taken into consideration yet. |

| Name/type | Ocean thermal energy conversion |
|---|---|
| | Also, impingement of fish and entrainment of plankton and other small organisms may occur in both surface and deep waters, while the noise produced by the installations may disturb local fauna.<br>The effects of using this measure to cool surface waters are estimated to be temporary, regionally heterogeneous, and present termination risks (GESAMP, 2019). |
| Links to MSFD drivers-pressures | Pressures: N/A<br>Contribution to achieve GES: N/A |
| Links to other policy objectives | Global: Paris Agreement.<br>EU: EU Climate Law. |
| References | Aresti, L., Christodoulides, P., Michailides, C., and Onoufriou, T., 2023, Reviewing the energy, environment, and economy prospects of Ocean Thermal Energy Conversion (OTEC) systems. Sustainable Energy Technologies and Assessments, 60, 103459.<br>Copping, A., and Farr, H., 2024, Feasibility of Ocean Thermal Energy Conversion (OTEC) Development for US Islands. In InPan-American Marine Energy Conference.<br>GESAMP, 2019, "High level review of a wide range of proposed marine geoengineering techniques". (Boyd, P.W. and Vivian, C.M.G., eds.). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 98, 144 p.<br>Herrera, J., Sierra, S., and Ibeas, A., 2021, Ocean thermal energy conversion and other uses of deep sea water: A review. Journal of Marine Science and Engineering, 9(4), 356.<br>Kim, H. J., and Kim, A. S., 2020, Ocean thermal energy conversion (OTEC): Past, present, and progress. IntechOpen.<br>Langer, J., Quist, J., and Blok, K., 2020, Recent progress in the economics of ocean thermal energy conversion: Critical review and research agenda. Renewable and Sustainable Energy Reviews, 130, 109960.<br>Olim, S. T., Nickoloff, A., Moffat, L. J., Weaver, A. J., and Eby, M., 2025, Mitigating anthropogenic climate change with aqueous green energy. Scientific Reports, 15(1), 1700. |

### *SRM – Increasing ocean albedo*

| Name/type | Increasing ocean albedo |
|---|---|
| Spatial scope | Anywhere in the ocean |
| Spatial scale | Local, National, Transnational |
| Spatial and temporal scope of im-plementation | Cloud brightening was first proposed in the 1990s. It is considered as more applicable in the north-east or south-east Tropical Pacific, due to the frequent occurrence of marine stratocumulus clouds.<br>However, to date, there are no recorded pilot implementations of this measure. |
| Objective of the measure and main | The idea behind this approach is to increase ocean albedo, i.e., the capacity of the ocean surface to reflect sunlight and scatter it from the interior, thereby altering the Earth's radiation balance and counteract the effects of global warming. There are |

| Name/type | Increasing ocean albedo |
|---|---|
| actions implemented | two main groups of strategies: (i) the injection of microbubbles, for example by commercial ships, foams, ice, reflective algal blooms (e.g., coccolithophores, or the foam-generating nuisance alga *Phaeocystis globosa*) and other materials; and (ii) cloud brightening, i.e., the seeding of marine stratocumulus clouds with sub-micrometre sea water particles pumped in the air from ships, to make them denser and enhance cloud albedo (GESAMP, 2019). |
| Estimated economic cost | There are no comprehensive estimates of costs of this measure. Gattuso et al. (2018) indicate that increasing ocean albedo has a low cost-efficiency. Seitz (2010) estimated that the cost of surfactants to ensure artificial microbubble stabilisation would be less than USD 10 per kg, corresponding to less than USD 100 per $km^2$. Claudel et al. (2024) estimated a cost of marine cloud brightening using UAV of USD 40 billion per year. |
| Environmental Benefits | Modelling experiments suggest that the increased reflection of sunlight would generate a net cooling of the ocean surface, counteracting the retention of energy by GHG. It has been estimated that the global use of foams would increase ocean albedo (normally about 0.6) by an additional 0.05-0.06, resulting in a decrease of average global surface temperatures by about 2.7°C. Another estimation calculated that an increase in the duration of microbubbles from global shipping traffic from 7-15 minutes to 6-13 days, would lead to a reduction of 0.5°C in global mean temperature (GESAMP, 2019).<br>As for cloud brightening, modelling showed that, if implemented at a large enough scale, it could offset a large fraction of, or even all of the impacts of global warming (although not addressing the root cause). Some authors suggested that this could lower sea surface temperature and reduce the energy available to tropical cyclones and, hence, their power and intensity (GESAMP, 2019). |
| Social and economic co-benefits | There are no studies assessing the direct socioeconomic benefits of this measure. General claims about positive impacts on fisheries, tourism, public health or agriculture are not backed up by practical evidence, but only by simulations and modelling. |
| Maintenance needs | Deployments can be continuous; algal blooms typically last for about 3 weeks. However, any termination before the reduction of GHG concentrations could result in rapid warming (GESAMP, 2019). |
| Stakeholders' engagement | Gattuso et al. (2018) indicate that this measure has a low governability, because its implementation involves international cooperation to solve the free-riding dilemma with regard to global public goods. |
| Success and/or limiting factors | + Potential deployment zones of foam are high-nutrient low-chlorophyll regions, because they support low levels of marine life due to iron deficiency, hence minimising the potential impact on marine life.<br>+ Experiments with foams were held in laboratory, and there are no proofs of concept in a real-life situation to date (GESAMP, 2019).<br>+ Some initial testing of the use of reflective floating silica sphered to preserve Arctic ice showed no adverse impact on wildlife; however, these results are not definitive (GESAMP, 2019).<br>- While several modelling studies showed the positive effect of cloud brightening on reducing global warming at small scale, and the proof of concept was observed from ship tracks, the efficacy of this measure over large areas and extended time periods is still uncertain (GESAMP, 2019). |

| Name/type | Increasing ocean albedo |
|---|---|
| | - For cloud brightening, the capacity to produce routinely fine sprays has not been demonstrated yet (GESAMP, 2019).<br>- There are significant knowledge gaps in several aspects of implementation of this measure, related to cloud microphysics, meteorological-aerosol co-variability, as well as the lack of adequate tools to assess the impact of small-scale perturbations on larger-scale circulation and their contribution to regional changes in precipitation and radiative forcing of the climate, and detection-related knowledge gaps (Feingold et al., 2022).<br>- The use of algal blooms requires a detailed knowledge of the environmental conditions and triggers to initiate and terminate the bloom (GESAMP, 2019). |
| Trade-offs | There is considerable uncertainty on the possible negative environmental effects of this measure, as no assessment has been made to date. Modelling indicates several indirect effects on climate, including altered distribution of temperature and precipitation, and the potential for biologically mediated changes in the ocean sink for atmospheric carbon. Also, the introduction of foams or bubble would require the use of surfactants or other stabilising materials, which could cause the retardation of the air-sea exchange of gases, including $CO_2$ and aerosol precursors, and reduce the natural oceanic source of planetary albedo. Moreover, their interaction with existing organic constituents of surface water could influence carbon cycling. Other possible impacts include alterations of ocean circulation and ocean chemistry, the enhancement of ocean acidification, uncertainties on how the introduced substances could interact with microplastics and their potential impacts on biota, negative impacts on the surface water ecosystem, on fisheries and fishing, and the economic and social consequences of accumulating foams in coastal areas or on aquaculture sites (GESAMP, 2019).<br>As for cloud brightening, there could be effects on regional temperatures and hydrological cycles over land, with possible positive consequences on crop failures and coal bleaching events, and uncertain impacts on tropical rainforests. Few studies quantified the impacts of this measure on the marine ecosystem. A reduction in sea surface temperature and photosynthetically active radiation could generate changes in upwelling and mixing. Also, the use of sea salt could increase salt deposition around the deployment location, influencing primary production, altering the vertical structure of the water column and modifying food webs and biogeochemical cycling, with unpredicted consequences on carbon sequestration (GESAMP, 2019). |
| Links to MSFD drivers-pressures | Pressures: N/A<br>Contribution to achieve GES: N/A |
| Links to other policy objectives | Global: Paris Agreement.<br>EU: EU Climate Law. |
| References | GESAMP, 2019, “High level review of a wide range of proposed marine geoengineering techniques”. (Boyd, P.W. and Vivian, C.M.G., eds.). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 98, 144 p.<br>Claudel, C., Lockley, A., Hoffmann, F., and Xia, Y., 2024, Marine-cloud brightening: an airborne concept. Environmental Research Communications, 6(3), 035020. |

| Name/type | Increasing ocean albedo |
|---|---|
| | Feingold G., V. P. Ghate, L. M. Russell, et al., 2022, DOE-NOAA Marine Cloud Brightening Workshop. U.S. Department of Energy and U.S. Department of Commerce NOAA; DOE/SC-0207; NOAA Technical Report OAR ESRL/CSL-1.<br><br>Gattuso, J. P., Magnan, A. K., Bopp, L., Cheung, W. W., Duarte, C. M., Hinkel, J., ... and Rau, G. H., 2018, Ocean solutions to address climate change and its effects on marine ecosystems. Frontiers in Marine Science, 5, 337.<br><br>Seitz, R., 2011, Bright water: hydrosols, water conservation and climate change. Climatic Change, 105(3), 365-381. |

# 4. Analysis of the findings

Compared to terrestrial and freshwater ecosystems, there are limited examples of marine NbS practices, and, of these, few have been developed to explicitly achieve the Good Environmental Status as set out in the MSFD (Riisager-Simons et al., 2022). In Europe, although large-scale active restoration is less developed than in other areas such as North America and Australia, the gap is narrowing, with several ongoing projects having a wide coverage (from coasts to deep sea) also in terms of habitat forming species, habitat types and target organisms (ICES, 2025).

Table 4.1 provides a short comparison of the main features of the marine NbS reviewed in this report. The findings for each category are discussed in the following sub-sections.

## 4.1 Location and scale of implementation

The majority of place-based NbS target coastal or offshore areas. However, as the marine environment is the sink of all anthropogenic activities taking place on land, many of the NbS are targeted to the transition zone between land and sea. These include, for instance, the restoration of lagoons, estuaries and wetlands, with the aim to capture substance flows by creating natural buffer zones and to protect them as significant habitats for marine life.

The scale of implementation of the NbS reviewed may vary (Figure 4.1). NbS aiming at the conservation, restoration and creation of specific ecosystems normally have a local scale of implementation, while geo-engineering techniques may also be implemented at a national and transnational scale.

**Figure 4.1 Number of marine NbS for each implementation scale (local, national, transnational)**

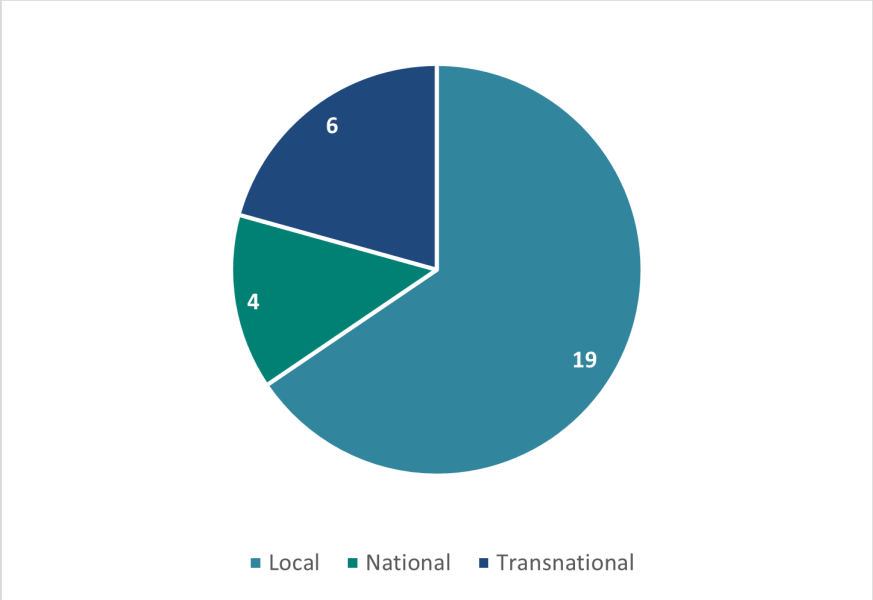


**Table 4.1 Summary of the main characteristics of marine NbS**

| Category | Name of the NbS | Scale of implementation | Estimated economic cost (values) | Estimated economic cost (label) | Benefits (including risk reduction) | | | Maintenance needs | Possible trade-offs |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Environmental | Social | Economic | | |
| Protect | MPAs | Local | Very variable; establishment: 0.8-2.5 million USD/ha; annual maintenance: 0.5 million USD/ha | €-€€-€€€ | Biodiversity; Climate Change Adaptation; Nutrients cycling; Physical disturbance; Pollution; Litter | Food security; coastal protection; tourism jobs; cultural value | Fisheries; tourism | Continuous, long-term | Environmental: impacts from increased tourism, shift of fishing from one species to another<br>Social: increased prosocial/antisocial behaviour, exacerbated social stratification<br>Economic: increase of costs and losses in fisheries revenue |
| Protect | Passive seagrass/ seaweed restoration | Local | 26,000-130,000 USD/ha | € | Biodiversity; Nutrients cycling | Coastal protection; Pathogens reduction | Fisheries; tourism | Continuous, long-term | Social: spatial conflicts of use, negative impact on livelihoods<br>Economic: losses in fisheries revenue<br>Other: long-term large-scale passive restoration vs small-scale, quick-gain active restoration |
| Protect | Passive coastal wetlands restoration | Local | 26,000-180,000 USD/ha | €-€€ | Biodiversity; Climate change mitigation; Nutrients cycling; Pollution; Water cycle | Coastal protection; Water quality improvement | Fisheries; tourism | Continuous, long-term | Environmental: adverse impacts on non-targeted species |

| Category | Name of the NbS | Scale of implementation | Estimated economic cost (values) | Estimated economic cost (label) | Benefits (including risk reduction) | | | Maintenance needs | Possible trade-offs |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Environmental | Social | Economic | | |
| Restore | Active seagrass/ seaweed restoration | Local | 590,000-910,000 USD/ha | €€€ | Biodiversity; Climate change mitigation; Nutrients cycling | Coastal protection | Fisheries; tourism | Shorter for fast-growing species, longer for slow-growing species (*P. oceanica*) | Environmental: seagrass disruptions by engineered solutions, possible regime shifts<br>Social: conflicts triggered by regime shifts |
| Restore | Restoration of sub-tidal boulder structures | Local | 0.5-1 million USD/ha | €€€ | Biodiversity; Climate change mitigation; Climate change adaptation; Upwelling | Coastal protection | Fisheries; tourism | One-off, but need to monitor effectiveness | Environmental: increased coastal erosion and deposition, impact on development of assemblages depending on material used |
| Restore | Lagoon restoration | Local | EUR 4,500 – 25,000 | € | Biodiversity | Recreational opportunities | Fisheries | One-off | Economic: Restrictions/bans to dredging of boating routes. Marinas can be built outside, or specific designs to boat access can be made |
| Restore | Shellfish reefs/beds restoration | Local | 190,000 USD/ha | €€ | Biodiversity; Nutrients cycling; Pollution | Coastal protection; Water quality improvement; Cultural values; Jobs | Fisheries | One-off | Environmental: competition with native species, impacts on food webs and new diseases<br>Social: conflicts by restricted access to oyster bottoms, impacts of ingested pathogens on human health |

| Category | Name of the NbS | Scale of implementation | Estimated economic cost (values) | Estimated economic cost (label) | Benefits (including risk reduction) | | | Maintenance needs | Possible trade-offs |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Environmental | Social | Economic | | |
| Restore | Active coastal wetlands restoration | Local | 52,000-151,000 USD/ha | €€€ | Biodiversity; Climate change mitigation; Nutrients cycling; Pollution; Water cycle | Coastal protection; Water quality improvement; Jobs | Fisheries; tourism | Continuous, long-term | Environmental: adverse impacts on non-targeted species |
| Restore | Restoration of polluted/ hypoxic seabed | Local | EUR 482,000–1,774,000 | €€€ | Physical disturbance | Human health | Fisheries | One-off | Environmental: Risk of spread of hazardous substances |
| Create | Creation of artificial reefs | Local | As high as 1.5 million USD | €€€ | Biodiversity | Food security; Coastal protection; Cultural value | Fisheries | Continuous, long-term | Environmental: overfishing, increase in accidental captures, introduction and dispersion of exotic species, pollution, toxicity, changes in local hydrodynamics |
| Create | Greening grey/hard infrastructure | Local | Little or no extra cost, if included in design | € | Biodiversity | Cultural and aesthetic value | Fisheries | One-off or limited maintenance depending on the material | Environmental: spread of invasive species, act as ecological trap or environmental filter, trade-offs between species richness and functional outcomes, impacts on marine food webs beyond structure's footprint<br>Social: use of the measure for 'greenwashing', misuse to increase support for land reclamation |

| Category | Name of the NbS | Scale of implementation | Estimated economic cost (values) | Estimated economic cost (label) | Benefits (including risk reduction) | | | Maintenance needs | Possible trade-offs |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Environmental | Social | Economic | | |
| Create | Low-trophic aquaculture | Local | Seaweed: 30-2,618 USD/tonne produced Bivalves: 520-8,520 EUR/tonne produced | € | Biodiversity; Nutrients cycling; Pollution; Climate change mitigation; Deforestation* | Coastal protection; cultural value; human health | Fisheries; Agriculture; Construction ; Renewable products | Continuous | Environmental: use of shells for agriculture hinders capacity to act as carbon storage, local nutrient enrichment and eutrophication Social: conflicts of use, impacts on human health by accumulated pathogens |
| Create | Integrated multi-trophic aquaculture | Local | Seaweed: 30-2,618 USD/tonne produced Bivalves: 520-8,520 EUR/tonne produced | € | Nutrients cycling; Climate change mitigation; Pollution; Water transparency | Food security; jobs | Fisheries | Continuous | Environmental: use of shells for agriculture hinders capacity to act as carbon storage, local nutrient enrichment and eutrophication Social: conflicts of use, impacts on human health by accumulated pathogens |
| Nature-inspired | Decarbonise transport | Transnational | High initial investments, lower costs when scaled | €€€ | Air and water pollution | Clean air and water | Maritime transport | One-off investment | Economic: not convenient for lo fossil fuel prices |
| Nature-inspired | Constructed wetland designs | Local | Low | € | Nutrients, organic matter, hazardous substances, litter | Clean water | Fisheries, recreation, tourism | One-off investment, regular maintenance | Other: Careful planning needed to build a design that can treat all the inflow water. May require integration with other measures. |

| Category | Name of the NbS | Scale of implementation | Estimated economic cost (values) | Estimated economic cost (label) | Benefits (including risk reduction) | | | Maintenance needs | Possible trade-offs |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Environmental | Social | Economic | | |
| Nature-inspired | Bio-anti-fouling agents | Transnational | No estimates | N/A | Water pollution | Water quality | N/A | Continuous | Environmental: possible toxicity for non-target organisms |
| Geo-engineering | Ocean iron/macro-nutrients fertilisation | Local, National, Transnational | 200 USD/$tCO_2$ | €€€ | Climate change mitigation | Not explored | Not explored | Continuous, long-term | Environmental: production of Nox, $CH_4$ offsetting $CO_2$ sequestration, impacts on productivity, changes in spatial patterns of ocean acidification, negative impacts on seafloor ecosystems, toxic algal blooms |
| Geo-engineering | Artificial upwelling | Local, National, Transnational | 100-240 USD/$tCO_2$ | €€€ | Biodiversity; Climate change mitigation | Energy supply | Fisheries | Continuous, long-term, reversal of benefits if stopped | Environmental: disturbance of thermocline and increase in global temperatures, changes in phytoplankton species composition, changes in seafloor biomass and uncertain effects on biodiversity, increase of NOx and $CH_4$ release offsetting $CO_2$ sequestration, surface acidification and impacts on calcium carbonate shell species |
| Geo-engineering | Enhancing ocean alkalinity | Local, National, Transnational | 10-190 USD/$tCO_2$ | €€€ | Climate change mitigation | Jobs | Fisheries | Continuous, long-term | Environmental: unintended $CO_2$ release, disturbance of carbon fixation and other biogeochemical processes and related impact on ecosystems, alteration of |

| Category | Name of the NbS | Scale of implementation | Estimated economic cost (values) | Estimated economic cost (label) | Benefits (including risk reduction) | | | Maintenance needs | Possible trade-offs |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Environmental | Social | Economic | | |
| | | | | | | | | | structure of phytoplankton communities, disturbance of food-web interactions |
| Geo-engineering | Ocean thermal energy conversion | Local | 166-398 USD/$tCO_2$ | €€€ | Biodiversity; Climate change mitigation | Drinking water availability and access | Fisheries; Agriculture | Continuous, long-term | Environment: shift in community species composition, enhancement of phytoplankton growth, algal blooms, impingement of fish, entrainment of plankton, disturbance to local fauna from noise |
| Geo-engineering | Increasing ocean albedo | Local, National, Transnational | No estimates | ? | Climate change mitigation | Not explored | Not explored | Continuous, long-term; reversal of benefits if stopped before GHG concentration reduction | Environment: altered temperature/precipitation patterns and hydrological cycles on land, changes in upwelling and mixing, biologically-mediated changes in $CO_2$ ocean sink, influences in carbon cycling, alterations of ocean circulation and chemistry, increase in ocean acidification, impacts of possible interactions with microplastics on biota, impact on food webs<br>Economic: impacts on fisheries, impact of accumulating foams in coastal areas |

## 4.2 Economic costs

The economic costs of the marine NbS investigated are not immediately comparable. In fact, three main units of measure have been normally employed:

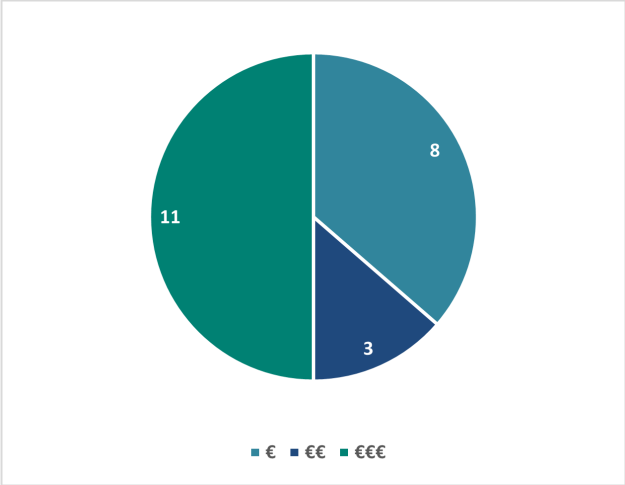
- The cost per hectare (ha), which is normally employed to express the expenses needed for place-based conservation or restoration. This applies to all Category 1 and 2 NbS, and to the majority of Category 3.
- The cost per weight of product (tonne), which applies to low-trophic aquaculture and Integrated Multi-Trophic Aquaculture.
- The cost per quantity of $CO_2$ sequestered, which applies to geo-engineering techniques for climate change mitigation.

In general, the restoration of marine coastal ecosystems is more expensive than for other ecosystems. According to Bayraktarov et al. (2016), the total (median) cost estimates for marine coastal restoration measures are 10–400 times higher than the maximum cost reported for the restoration of inland wetlands (USD 40,000/ha, 2007), freshwater systems (USD 16,000/ha, 2007), tropical (USD 7,000/ha, 2007) and temperate forest (USD 3,000/ha, 2007), woodlands (USD 1,000/ha, 2007), and grasslands (USD 1,500/ha, 2007; De Groot et al., 2013).

As shown in Table 4.1, a tentative comparison was performed by classifying the cost estimations as 'low' (€) (0-100,000 USD/hectare, tonne produced, or $tCO_2$), 'medium' (€€) (100,000-500,000 USD/hectare, tonne produced, or $tCO_2$), and 'high' (€€€) (500,000-1,500,000 USD/hectare, tonne produced, or $tCO_2$). Figure 4.2 shows how these are divided among the reviewed NbS.

It seems that there are several low-cost methods available, but the large-scale geo-engineering ones have high price tags. Also, MPAs were assigned a wide range of costs (€-€€-€€€) because they have a wide range of establishment and maintenance costs, depending on several factors including the location, the extension, and maintenance needs.

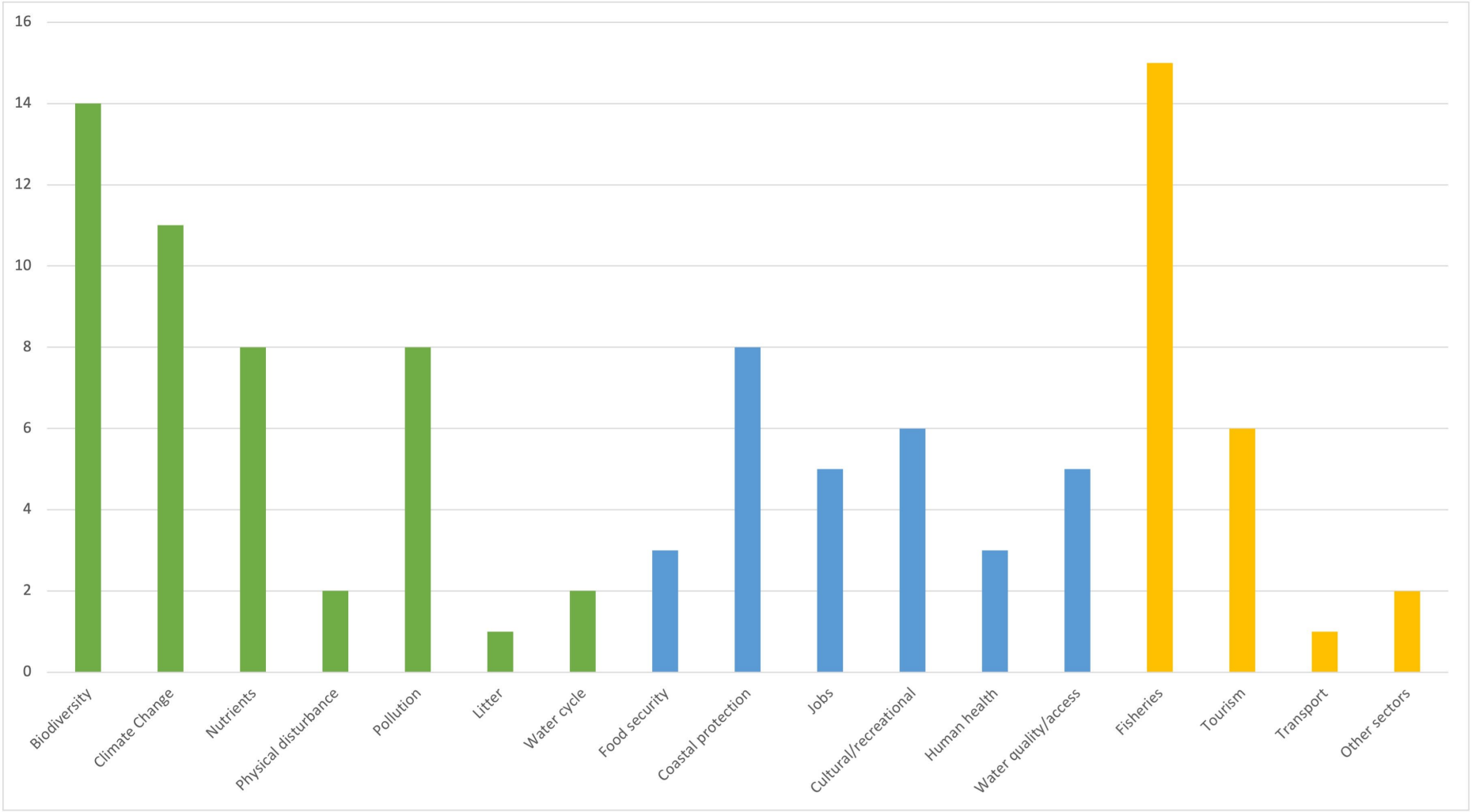
**Figure 4.2 Number of marine NbS for each cost category.**




## 4.3 Environmental, Economic, and Social Benefits

Marine NbS provide a wide range of environmental, social and economic benefits. The majority of the NbS reviewed contribute to biodiversity (14) and climate change mitigation (11), while only 2 were found to improve the water cycle and reduce physical disturbance, and only 1 targeted marine litter. The main social benefit provided is coastal protection (8), followed by cultural, recreational and aesthetic values (6) and water quality or access improvement (5). At the economic level, fisheries (15) and tourism (6) are the two main sectors that the marine NbS contribute to.

**Figure 4.3 Frequency of the environmental, social, and economic benefits of marine NbS. In green: environmental benefits. In blue: social benefits. In yellow: economic benefits.**



## 4.4 Maintenance needs

The majority of NbS require a certain level of maintenance, which is recommended to be continuous and in the long term (13), while 7 are a one-off intervention that requires low or no maintenance, and 1 with variable needs depending on the species selected for restoration.

## 4.5 Stakeholders' engagement

Experience consistently highlights the importance of local participation in conservation and restoration initiatives. In fact, over the last 20 years, any conservation and restoration action that includes local communities in the decision-making and management process proved to be more sustainable and successful in meeting the set goals, while externally controlled interventions often produced negative results (Moore and Kumble, 2024).

The level and type of stakeholder engagement required, however, varies across NbS. For example, Category 4 "Nature-inspired" measures (Section 3.4) can be implemented by private with limited interaction with other stakeholders, while certain site-specific interventions (e.g. removing polluted sediments) may be implemented in public areas like ports where broader stakeholder inputs are not as critical. In contrast, other measures—such as the establishment of MPAs—require engagement at the community level, whereas some interventions (e.g. artificial wetlands) may involve negotiations with a limited number of stakeholders, such as individual landowners.

Where public engagement is required, a key objective is to build trust between scientists, practitioners, and the wider community. This is particularly important for geo-engineering approaches (Section 3.5), where public acceptance is essential for implementation (Williamson and Bodle, 2016).

Careful consideration is therefore needed in designing stakeholder engagement processes. Ibrahim et al. (2025) emphasise the importance of clearly defining stakeholder roles and tailoring engagement strategies accordingly into NbS planning and implementation. Suitable criteria for the engagement can be (1) "why engage", (2) "who is invited", (3) "when each group is invited", and (4) "how stakeholders are engaged".

While inclusivity, equity, and transparency are fundamental principles, the effective implementation of NbS also depends on adequate political support, sufficient resources, and institutional capacity to ensure that engagement processes are fit for purpose (Ibrahim et al., 2025).

## 4.6 Trade-offs

Trade-offs may arise in the implementation of NbS. The following types of trade-offs were identified for the marine NbS reviewed:

- Environmental: measures targeting specific habitats, species, or group of species, may generate unintended impacts such as pressure displacement (e.g., from overfishing outside a protected area), negative effects on non-target habitats and species, potentially altering food webs. Additional risks include increased physical impacts (erosion, deposition, changes in hydrodynamics), the risk of the spread of hazardous substances or invasive species, increased GHG emissions, disturbance to water or carbon cycles, and altered local climate patterns.
- Social: spatial conflicts may arise from the implementation of spatial restrictions (e.g., no-fishing zones), or conflicts over restricted access to resources.
- Economic: Some NbS may result in reduced revenues for specific sectors.

## 4.7 Success factors for NbS

Several success and failure criteria have been identified for each NbS. Previous studies identified common success criteria to all Nbs, which include the setting of SMART goals and project's performance criteria in addition to careful site selection, supported by community assessment, and considering environmental factors (Smith and Pruett, 2025). In addition, ICES (2025) listed the following success and limit factors that are common to all NbS:

- Restoration is possible only if the pressures that caused degradation are removed or mediated, and the physical environment is in a suitable condition;
- Often, hysteresis (i.e., the existence of different stable states under the same variables or parameters) can prevent the natural recovery of a system to its original state, even after removing the stressors;
- Suitable habitats are the key factor to determine the success of species recovery;
- Monitoring is fundamental to assess the effectiveness of action, and should match the spatial/temporal scale of the key habitat feature and/or target species;
- Objectives and targets of action should be clearly defined, and monitoring should be formulated accordingly;
- the timeline for restoration is usually longer than the timeframes of policy evaluation, and it may be difficult to evaluate policy or intervention effectiveness;
- A strategic and inclusive approach is important for successful restoration, including a top-down approach to planning, which is necessary to ensure adherence to scientific methodology, and the buy-in of stakeholders and the wider society, especially through early engagement for implementation and support throughout the whole duration.

Some social, economic, cultural, and ethical considerations are common to all the geo-engineering techniques presented (Williamson and Bodle, 2016):

- Geo-engineering solutions may reduce efforts on climate change mitigation;
- Their large-scale application may have unintended side-effects and increase socio-political tensions;
- There may be technological, political and social "lock in";
- The distribution of resources and impacts within and among societies and across time is unclear;
- Geopolitical considerations may arise in cases involving transboundary impacts or activities in areas beyond national jurisdiction.

## 4.8 Combination of NbS

While some NbS are effective as stand-alone measures, there are cases when this is not sufficient and combined solutions are necessary. This is particularly relevant in areas with multiple uses, complex local geography (e.g. fragmented coastlines or archipelagos), or where land-based activities generate multiple pressures on the marine environment. In such contexts, it is essential to assess the potential synergistic effects—both positive and negative—of combined measures.

Success of some NbS require prior actions. For example, revegetation efforts are unlikely to succeed if organic enrichment is not first reduced. Similarly, constructed wetlands may fail to capture target effluents if inflow volumes are too high or if the system is undersized, requiring upstream measures to reduce nutrient loads or adjustments in wetland design and scale. Scale is a critical factor, as most NbS are implemented locally and may be insufficient to achieve large-scale effectiveness. This limitation can be addressed by deploying a sufficient number of NbS across the targeted area.

Combining passive and active restoration with MPAs, or for historically polluted and abandoned sites, has proven to be particularly effective in rehabilitating marine sites degraded by historical industrial activities (Puig et al., 2024). In this context, success is dependent on three principles: (i) the re-establishment and maintenance of protected area values, drawing on the original purpose and conservation and/or cultural objectives of the protected area; (ii) the maximisation of ecological, socioeconomic and cultural benefits and the minimisation of costs; and (iii) the involvement of partners, rights holders, and stakeholders in planning and implementation, fostering mutual learning, and ensuring the incorporation of the perspectives and knowledge of local communities (ICES, 2025).

However, MPAs alone are generally insufficient to prevent pollution beyond their boundaries, making complementary preventive measures necessary. This can be achieved by (i) passive or (ii) active wetland designs, or by (iii) removing historically polluted sediments or by (iv) actively restoring anoxia on the seabed. Although, evidence for the latter remains limited in marine environments. These can be further enhanced by catchment area measures to reduce pollution, such as sedimentation pools, buffer zones and restored wetlands.

Finally, habitat restoration or the reintroduction of habitat-forming species is unlikely to succeed if the underlying drivers of degradation persist, such as bottom trawling, dredging, high-speed vessel traffic, aquaculture, or excessive nutrient inputs. Therefore, prior actions are needed to reduce or eliminate such pressures and, in some cases NbS can contribute to this. For example, the restoration of a coastal lagoon may require a sequence of measures to ensure success: (i) restore the lagoon entrance, (ii) ban, reduce or re-route boating, (iii) restore wetlands (or use other measures) to capture nutrients and (iv) re-plant the original lagoon species (Arnkil et al., 2024).

## 4.9 Contribution of NbS to address MSFD marine pressures and GES

A synthesis of the contribution of the marine NbS reviewed in this report to address the marine pressures listed in Annex II of the MSFD is provided in Table 4.2, while a summary with the frequencies is presented in Figure 4.4.

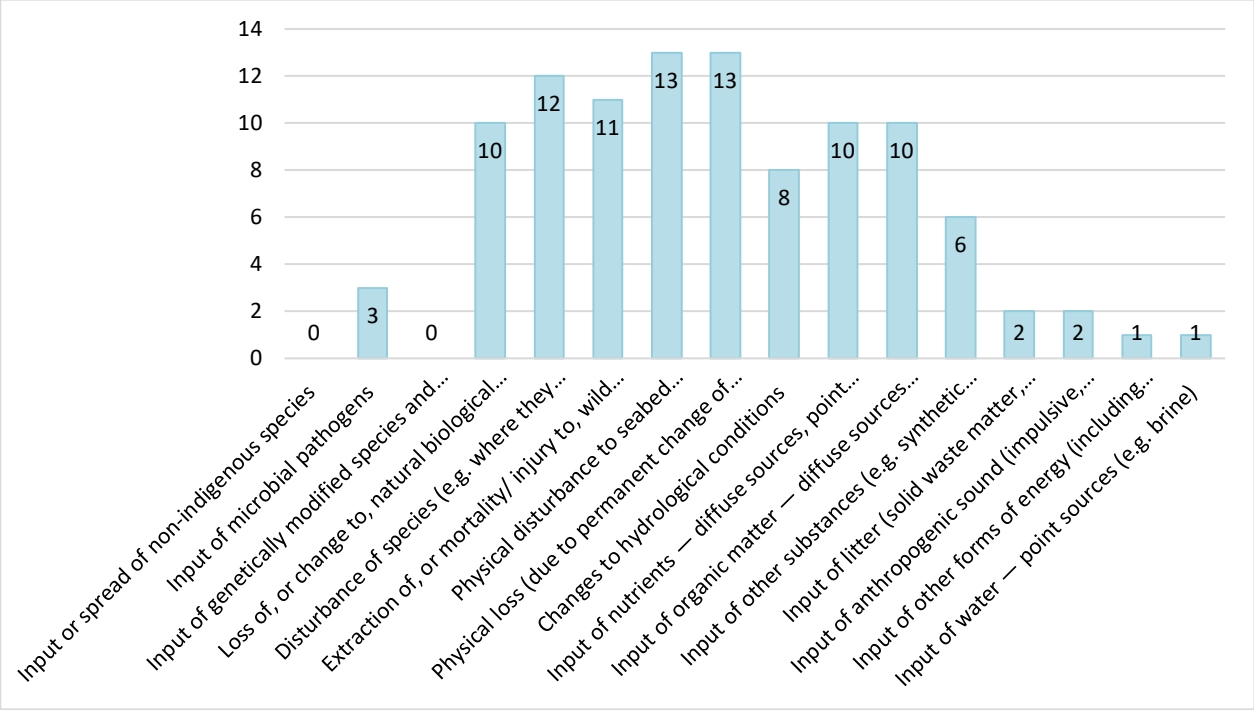
As shown in Table 4.2 and Figure 4.4, the reviewed NbS primarily address pressures related to physical disturbance to the seafloor, physical loss of the seafloor and disturbance of the species due to human presence. In addition, several NbS target pressures associated with species mortality due to population extraction, fisheries bycatch or cultivation of other species as well as inputs of nutrient and organic matter. By contrast, significantly less or no coverage is given to pressures such as underwater noise, marine litter, and the introduction of alien or genetically modified species.

**Table 4.2 Contribution of NbS to address the anthropogenic pressures listed in Annex II of the MSFD.**

| | MPAs | Passive seagrass/seaweed restoration | Passive coastal wetlands restoration | Active seagrass/seaweed restoration | Restoration of sub-tidal boulder structures | Lagoon restoration | Shellfish reefs/beds restoration | Active coastal wetlands restoration | Restoration of polluted/hypoxic seabed | Creation of artificial reefs | Greening of grey/hard infrastructures | Low-trophic aquaculture | Integrated multi-trophic aquaculture | Decarbonise transport | Constructed wetland designs | Bio anti-fouling agents | Ocean iron/macro-nutrients fertilisation | Artificial upwelling | Enhancing ocean alkalinity | Ocean thermal energy conversion | Increasing ocean albedo |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Input or spread of non-indigenous species | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | | - | - | - | - | - |
| Input of microbial pathogens | - | - | - | - | - | - | - | - | - | - | - | X | X | - | X | | - | - | - | - | - |
| Input of genetically modified species and translocation of native species | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | | - | - | - | - | - |
| Loss of, or change to, natural biological communities due to cultivation of animal or plant species | X | X | X | X | - | - | X | X | - | X | X | X | X | - | - | | - | - | - | - | - |
| Disturbance of species (e.g. where they breed, rest and feed) due to human presence | X | X | X | X | X | X | X | X | - | X | X | X | X | - | - | | - | - | - | - | - |
| Extraction of, or mortality/ injury to, wild species (by commercial and recreational fishing and other activities) | X | X | X | X | X | - | X | X | - | X | X | X | X | - | - | | - | - | - | - | - |
| Physical disturbance to the seabed (temporary or reversible) | X | X | X | X | X | X | X | X | - | X | X | X | X | - | X | | - | - | - | - | - |
| Physical loss (due to permanent change of seabed substrate or morphology and to extraction of seabed substrate) | X | X | X | X | X | X | X | X | X | X | X | X | X | - | - | | - | - | - | - | - |
| Changes to hydrological conditions | X | X | X | X | X | X | X | X | - | - | - | - | - | - | - | | - | - | - | - | - |
| Input of nutrients — diffuse sources, point sources, atmospheric deposition | X | X | X | X | - | - | X | X | X | - | - | X | X | - | X | | - | - | - | - | - |
| Input of organic matter — diffuse sources and point sources | X | X | X | X | - | - | X | X | X | - | - | X | X | - | X | | - | - | - | - | - |

| | MPAs | Passive seagrass/seaweed restoration | Passive coastal wetlands restoration | Active seagrass/seaweed restoration | Restoration of sub-tidal boulder structures | Lagoon restoration | Shellfish reefs/beds restoration | Active coastal wetlands restoration | Restoration of polluted/hypoxic seabed | Creation of artificial reefs | Greening of grey/hard infrastructures | Low-trophic aquaculture | Integrated multi-trophic aquaculture | Decarbonise transport | Constructed wetland designs | Bio anti-fouling agents | Ocean iron/macro-nutrients fertilisation | Artificial upwelling | Enhancing ocean alkalinity | Ocean thermal energy conversion | Increasing ocean albedo |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Input of other substances (e.g. synthetic substances, non- synthetic substances, radionuclides) — diffuse sources, point sources, atmospheric deposition, acute events | X | - | - | - | - | - | X | - | X | - | - | X | X | - | X | | - | - | - | - | - |
| Input of litter (solid waste matter, including micro-sized litter) | X | - | - | - | - | - | - | - | - | - | - | - | - | - | X | | - | - | - | - | - |
| Input of anthropogenic sound (impulsive, continuous) | X | - | - | - | - | - | - | - | - | - | - | - | - | X | - | | - | - | - | - | - |
| Input of other forms of energy (including electromagnetic fields, light and heat) | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | | - | - | - | - | - |
| Input of water — point sources (e.g. brine) | X | - | - | - | - | - | - | - | - | - | - | - | - | - | - | | - | - | - | - | - |

**Figure 4.4 Number of NbS addressing each of the pressures listed in Annex II of the MSFD. See Table 4.1 for the full names of the pressures.**




The contribution of marine NbS to achieve MSFD GES is summarised in Table 4.3 and Figure 4.5.

As shown in Table 4.3 and Figure 4.5, the highest contribution is for Descriptors related to biodiversity (D1 and D4) and seafloor integrity (D6), while there is indirect contribution to marine food webs (D4). A smaller number of NbS were found to benefit the achievement of D10 (marine litter, 1 direct and 1 indirect) and D11 (underwater noise, indirectly benefiting from the reduction of noise from the use of wind-assisted ship propulsion). No contribution was found for the achievement of D2 on non-indigenous species.

**Figure 4.5 Number of NbS addressing the MSFD GES descriptors. Direct (blue) and indirect (orange) benefits to descriptors are shown separately. See Table 2.2 for the entire descriptor names.**

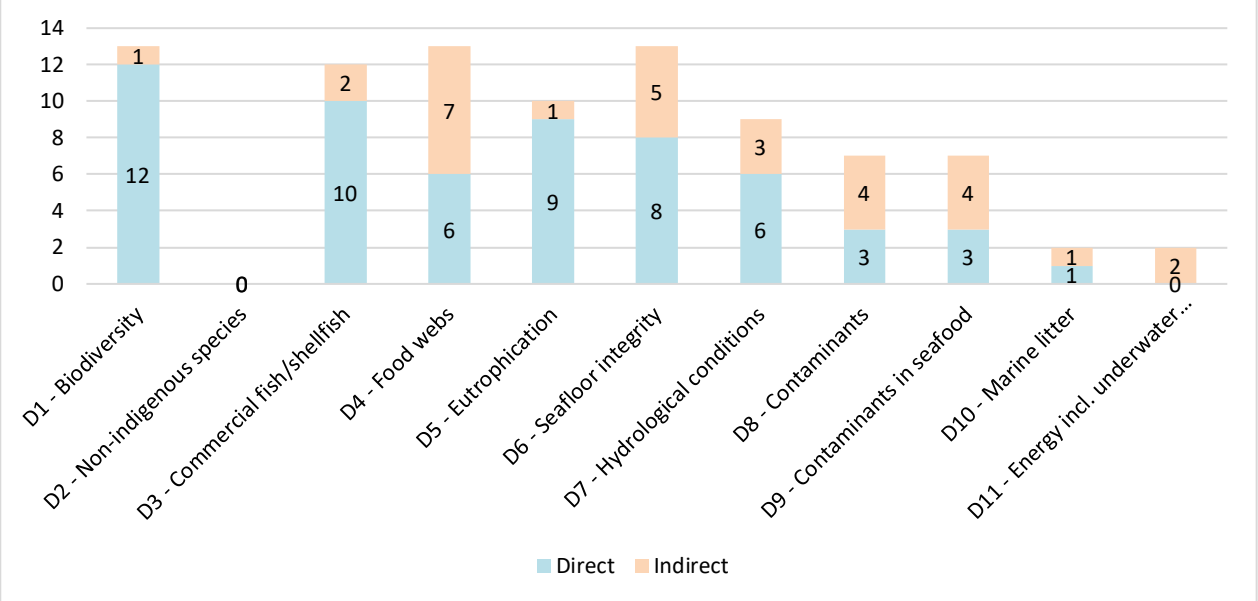


**Table 4.3 Contribution of NbS to achieve GES for each MSFD Descriptor.**

| | MPAs | Passive seagrass/seaweed restoration | Passive coastal wetlands restoration | Active seagrass/seaweed restoration | Restoration of sub-tidal boulder structures | Lagoon restoration | Shellfish reefs/beds restoration | Active coastal wetlands restoration | Restoration of polluted/hypoxic seabed | Creation of artificial reefs | Greening of grey/hard infrastructures | Low-trophic aquaculture | Integrated multi-trophic aquaculture | Decarbonise transport | Constructed wetland designs | Bio anti-fouling agents | Ocean iron/macro-nutrients fertilisation | Artificial upwelling | Enhancing ocean alkalinity | Ocean thermal energy conversion | Increasing ocean albedo |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D1 | XX | XX | XX | XX | XX | XX | XX | XX | - | XX | XX | XX | XX | - | - | X | - | - | - | - | - |
| D2 | - | - | | - | - | - | - | - | - | - | * | - | - | - | - | - | - | - | - | - | - |
| D3 | XX | XX | XX | XX | XX | - | XX | X | - | XX | XX | XX | XX | - | - | X | - | - | - | - | - |
| D4 | XX | XX | X | X | X | X | XX | XX | - | XX | XX | X | X | - | - | X | - | - | - | - | - |
| D5 | XX | XX | XX | XX | - | - | X | XX | XX | - | - | XX | XX | - | XX | - | - | - | - | - | - |
| D6 | XX | XX | XX | XX | - | XX | XX | XX | X | XX | X | X | X | - | X | - | - | - | - | - | - |
| D7 | XX | XX | XX | XX | XX | XX | X | X | - | - | - | X | - | - | - | - | - | - | - | - | - |
| D8 | X | - | - | - | - | - | X | - | XX | - | - | X | X | - | XX | XX | - | - | - | - | - |
| D9 | X | - | - | - | - | - | XX | - | X | - | - | X | X | - | XX | XX | - | - | - | - | - |
| D10 | X | - | - | - | - | - | - | - | - | - | - | - | - | - | XX | - | - | - | - | - | - |
| D11 | X | - | - | - | - | - | - | - | - | - | - | - | - | X | - | | - | - | - | - | - |

Notes XX=direct contribution; X=indirect contribution

## 4.10 Contribution to Global and EU Policies

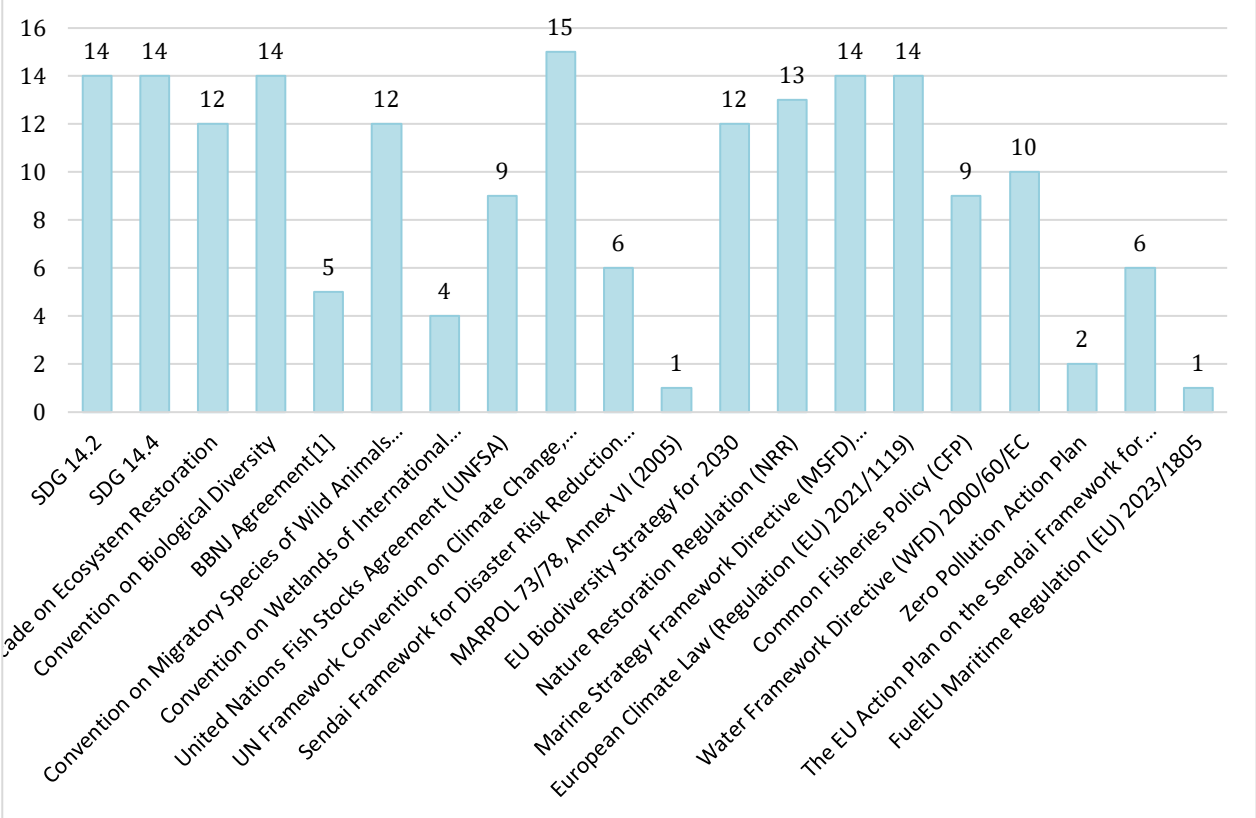
The number of NbS contributing to the global and EU policies considered in this review is presented in Figure 4.6.

Many restoration measures aim to enhance biodiversity or specific habitats or species populations, thus contributing not only to SDGs 14.2 and 14.4, but also to the CBD-Global Biodiversity Framework and, some of them, to the UN Decade for Ecosystem Restoration at global level, while contributing to the EU Biodiversity Strategy and related Directives (Habitats and Birds Directives) at EU level. For example, the re-establishment of seagrass meadows, seaweeds, or reefs exert direct benefits to the respective Habitats Directive objectives, but indirectly also enhance food webs and ecosystem functioning, which are required by the EU MSFD. As expected, geo-engineering techniques and measures to restore natural carbon sinks (e.g., mangroves and other types of wetlands) were found to contribute to the objectives of the UNFCCC Paris Agreement and related EU Climate Law. The only NbS contributing to MARPOL Annex VI and the FuelEU Directive was the decarbonisation of maritime transport using wind-propelled cargo ships.

Some measures have an added value for the source-to-sea approach, such as passive and active restoration in coastal wetlands to reduce substance flows. These mainly address the WFD and MSFD, but also the global Ramsar Convention objectives. A different method with the constructed wetland designs may be more appropriate for treating point-source effluents from small industrial or municipal sites. Such a design may respond to the environmental impact assessments (the EIA Directive) and permit requirements.

MPAs are a measure that touches several policies depending on the conservation objectives and the management plan. The benefit of this measure entirely depends on the implementation and enforcement of the management plan.

**Figure 4.6 Number of NbS contributing to the major global and EU policies considered.**



## 5. Concluding remarks

The results highlight the importance of prioritising context-specific, well-designed NbS, underpinned by robust planning, long-term monitoring, and effective stakeholder engagement. Their effectiveness depends on being implemented as part of integrated, multi-measure strategies that address the root causes of environmental degradation, rather than as stand-alone actions. Strengthening the evidence base—particularly regarding costs, performance, and long-term outcomes—together with scaling up proven approaches and improving integration within existing policy and regulatory frameworks, will be essential to maximise their effectiveness. Furthermore, addressing key knowledge gaps and implementation barriers will be critical to fully realise the potential of marine NbS in contributing to EU and global environmental objectives.

Marine NbS have the potential to provide significant co-benefits across multiple EU and global policy frameworks—particularly biodiversity, climate, and water policies—demonstrating their potential as effective, cross-sectoral solutions for integrated marine management.

## List of abbreviations

| Abbreviation | Name |
|---|---|
| BBNJ Agreement | Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction |
| CBD | Convention on Biological Diversity |
| CDR | Carbon Direct Removal |
| CFP | Common Fisheries Policy |
| CMS | Convention on the Conservation of Migratory Species of Wild Animals |
| DACCS | Direct Air Carbon Capture and Storage |
| EU | European Union |
| GES | Good Environmental Status |
| GHG | Greenhouse gas |
| IMO | International Maritime Organisation |
| MARPOL | International Convention for the Prevention of Pollution from Ships |
| MPA | Marine Protected Area |
| MSFD | Marine Strategy Framework Directive (2008/56/EC) |
| NbS | Nature-based Solutions |
| NGO | Non-Governmental Organisation |
| NRR | Nature Restoration Regulation (Regulation (EU) 2024/1991) |
| POC | Particulate organic carbon |
| SDG | Sustainable Development Goals |
| SRM | Solar Radiation Management |
| UN | United Nations |
| UNEA | United Nations Environment Assembly |
| UNESCO-IOC | United Nations Educational, Scientific and Cultural Organisation – Intergovernmental Oceanographic Commission |
| UNFCCC | United Nations Framework Convention on Climate Change |
| UNFSA | United Nations Fish Stocks Agreement |
| WFD | Water Framework Directive (2000/60/EC) |

## References


Arnkil, A., Bäck, A., Haavisto, F., Keskinen, E., Kuningas, S., Laine, A., Nieminen, A., Puttonen, I., Raitanen, H. ja Salovius-Laurén, S., 2024, *A Review of Marine Nature Restoration Work and Methods Used in Finland*. Nature Protection Publication in Metsähallitus. Series A 252, 139 p., Available at: https://julkaisut.metsa.fi/julkaisu/a-review-of-marine-nature-restoration-work-and-methods-used-in-finland/ (last access: 20 April 2026).

Benyus, J. M., 1997, *Biomimicry: Innovation inspired by nature (Vol. 688136915).* New York: Morrow.

Brooker, E. E., Midgley, G., Burns, N., Trotman, C. E., Gregory, A., & Hopkins, C. R., 2025, Defining marine rewilding can help guide theory and practice in marine conservation. Communications Earth & Environment, 6(1), 241.

Duarte, C.M., Apostolaki, E.T., Serrano, O., Steckbauer, A., Unsworth, R.K.F., 2025, *Conserving seagrass ecosystems to meet global biodiversity and climate goals.* Nature Reviews Biodiversity, 1: 150-165, Available at: https://www.nature.com/articles/s44358-025-00028-x (last access: 20 April 2026).

European Commission, 2021, *Science for Environment Policy: "The Solution is in Nature".* Future Brief 24. Brief produced for the European Commission DG Environment. Bristol: Science Communication Unit, UWE, Bristol. Available at: https://op.europa.eu/en/publication-detail/-/publication/c08abcf1-8087-11eb-9ac9-01aa75ed71a1/language-en (last access: 20 April 2026).

ICES, 2025, *Workshop on Nature Restoration and Recovery (WKREST)*. ICES Scientific Reports. 7:46. 172 pp., Available at: https://doi.org/10.17895/ices.pub.28759463 (last access: 20 April 2026).

Ibrahim, A., Marshall, K., Carmen, E., Blackstock, K. L., and Waylen, K. A., 2025*, Raising standards for stakeholder engagement in Nature-based Solutions: Navigating the why, when, who and how.* Environmental Science and Policy, 163, 103971.

Moore, A. C., and Kumble, S., 2024, *Community-based conservation and restoration in coastal wetlands: A review.* Wetlands, 44(5), 62.

Royal Society, 2009, *Geoengineering the climate.* Geoengineering the climate: Science, governance and uncertainty, Available at: https://doi.org/10.1007/s10098-010-0287-3 (last access: 20 April 2026).

Smith, R. S., and Pruett, J. L., 2024, *Oyster restoration to recover ecosystem services.* Annual Review of Marine Science, 17.

Williamson, P., and Bodle, R., 2016, *Update on climate geoengineering in relation to the Convention on Biological Diversity: Potential impacts and regulatory framework.* Montreal: Secretariat of the Convention on Biological Diversity.

European Topic Centre on
Biodiversity and Ecosystems
https://www.eionet.europa.eu/etcs/etc-be

The European Topic Centre on Biodiversity and Ecosystems (ETC-BE) is a consortium of European institutes under contract of the European Environment Agency.

European Environment Agency
European Topic Centre
Biodiversity and ecosystems