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Ecological restoration measures for shallow coastal habitats of the Baltic Sea and the Skagerrak – effectiveness, costs and knowledge gaps

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ABSTRACT

Human-induced pressures are interfering with the environmental status of marine and coastal areas impacting their ability to maintain ecosystem functions and services. In combination with planning and conservation measures to halt ongoing biodiversity loss, there is a need for developing and adapting toolboxes for active and passive restoration. Such habitat-specific restoration measures need to be tailor-made to strengthen the ecosystem services we depend on and to increase the resilience to climate change and other pressures. Today, there is a knowledge gap both regarding potential restoration measures and in the follow-up and evaluation of the effectiveness of existing measures. There is also a lack of general guidance about which measures are the most functional ones. Such knowledge is of utmost importance for implementation of the EU nature restoration law.

Here, we provide an overview of eight marine/coastal active and passive restoration measures relevant and applicable for the Northeast Atlantic, focusing on the Baltic Sea and the Skagerrak region. The measures reviewed foremostly aim at reversing negative impacts from physical disturbance on coastal habitats, focusing on active restoration of eelgrass beds, macrophyte beds on soft sediment, rocky-shore macroalgal beds, blue mussel reefs, stony reefs, as well as coastal wetlands and flads/lagoons. Two passive restoration methods are also reviewed, including strengthening populations of predatory fish and undertaking habitat protection. When relevant, these measures are reviewed with regard to type of restoration target, threats, benefits from restoration, restoration measures/methodologies and documented effects, pertinent geographical areas, approximate costs and possible additional information/key knowledge gaps. Among the measures reviewed, three stand out as having especially low costs per area/effort, i.e., 1) restoration of coastal wetlands and flads/lagoons, 2) strengthening populations of predatory fish and 3) habitat protection. We further conclude that there is a general lack of evidence for the cost-effectiveness of measures and that even the more costly measures may still bring more benefits than costs. Nevertheless, many measures are still understudied, provide limited positive effects in relation to their costs, are hard to upscale, have geographical limitations for a broader use or are sensitive to poor environmental status and continued environmental degradation. Additionally, all measures continuously need various degrees of development and fine tuning in order to improve success rates and value for money. The results are intended to support management in this maritime region and they are also applicable to other areas where the studied or similar habitat types exist.

1. Introduction

The interest in ecological restoration measures is increasing, along with deepened societal insights on the ongoing deterioration of ecosystems and associated impacts, accentuated by climate change effects. The 2020s have been announced as the UN Decade on Ecosystem Restoration (United Nations Environment Agency, 2019; Waltham et al., 2020; Saunders et al., 2024), and ambitious restoration proposals are presented in many parts of the world. Responding to urgent biodiversity losses and climate change demands for restoration measures. This is

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departing from the UN biodiversity convention (UN, 1992) and is today included in many international environmental directives, agreements and proposals (Water Framework Directive, 2000; Marine Strategy Framework Directive, 2008; Aronson et al., 2020; Waltham et al., 2020; Singh et al., 2022; EC, 2024). For example, the European Union has recently passed a nature restoration law (2022/869), aiming at covering at least 30 % of its degraded land and sea areas with restoration measures by 2030 and, ultimately, all habitats in need of restoration by 2050 (EC, 2024). This law defines restoration as "the process of actively or passively supporting the recovery of an ecosystem in order to improve its structure and functions, with the aim of conserving or enhancing biodiversity and ecosystem resilience, through improving an area of a habitat type to good condition, re-establishing favourable reference area, and improving a habitat of a species to sufficient quality and quantity (…)" (EC, 2024). Active restoration is the process of directly intervening to assist the recovery of an ecosystem to a good condition. Passive restoration is the process of removing or preventing anthropogenic sources of disturbance, thereby allowing natural recovery of ecosystem structure and function (EC, 2024).

Several types of restoration tools are potentially available to halt or reverse a negative development. The practical aim of restoration could vary between full restoration, aiming to achieve the conditions that were present before the damage, to achieving a certain desired level of improvement in relation to perceived feasibility or prevailing needs (Gann et al., 2019). For example, Clewell et al. (2000) defined the purpose of ecological restoration as to recreate functioning ecosystems with sufficiently high biodiversity for natural recovery over longer time perspectives, rather than to recreate a pristine historical state. Nevertheless, learning how to recreate the structure and function of damaged ecosystems through restoration measures has been characterized as one of the greatest challenges within marine ecosystems ecology (Borja, 2014). Within this process, questions of costs are also of utmost importance (Kimball et al., 2015; Eger et al., 2016; Trouth and Laingui, 2025). We need to have as low costs as possible to enable as many projects as possible within a limited budget, but we also need cost-efficiency to have good outcomes for nature in terms of both how much area is actually restored and how soon.

Coastal and marine restoration is still in its infancy both scientifically and managerially despite the increasing interest within both research and management (Borja, 2014; Bas et al., 2016; France, 2016, United Nations Environment Agency, 2019; Duarte et al., 2020; EC, 2024). Examples of unequivocal marine restoration successes are scarce (Bayraktarov et al., 2016; Zerbe, 2023). Most of the experiences, so far, come from restoration projects targeting seagrass beds (Fonseca, 2011; Orth et al., 2011; Matheson et al., 2023), oyster reefs (Brumbaugh et al., 2000; Coen et al., 2007; Cannon et al., 2022), mangrove forests (Ellison, 2000; Lewis, 2005; Arifanti et al., 2022) and coral reefs (Epstein et al., 2001; Meesters et al., 2015; Quigley et al., 2022). The demand for a broader knowledge base regarding coastal restoration is increasing rapidly, including for typical habitats of northern temperate areas (Defeo and Elliott, 2021; Zerbe, 2023; EC, 2024).

Shallow coastal and nearshore habitats do, in many cases, not reach good environmental status (EEA, 2020). They are thus in particular need of restoration measures as they are subjected to high pressure levels from various current and historical human marine and terrestrial activities (Borja and Dauer, 2008; Crain et al., 2008; Halpern et al., 2008; Timmerman et al., 2021; Helcom, 2023; Arkema et al., 2024; Saunders et al., 2024). Major activities causing losses and reduced environmental status of these essential habitats include coastal construction, disturbance from marine transport and recreation, inputs of nutrients or other pollutants, fishing, introduction of non-indigenous species and climate change (Korpinen et al., 2012; Worm, 2016; Gao et al., 2022; Hodapp et al., 2023). The pressures may act both individually and additively (Andersen et al., 2015, 2020), leading to a loss of habitats, fragmentation altering connectivity and process dynamics within and between natural communities, decreases in the abundance and size structure of key species, and homogenisation of biological communities (Airoldi and Beck, 2007; Seitz et al., 2014; Geist and Hawkins, 2016; Berkström et al., 2022). This environmental deterioration is closely connected to a reduced potential of coastal habitats to deliver supporting and regulating ecosystem services, leading to a downward spiral of continued environmental degradation (Bryhn et al., 2020; Beheshti et al., 2022).

The purpose of this paper is to evaluate current empirical knowledge on the costs, effectiveness and applicability of restoration measures for shallow coastal habitats in the Baltic Sea and the Skagerrak area in the northeast Atlantic. This sea area is a unique system with the transmission from fully marine conditions to a broad semi-enclosed estuary with brackish water. Baltic Sea is also an exceptionally shallow sea where the coastal areas are of great significance for ecosystem function while simultaneously hosting most of the ecosystem services that are present. At the same time, the Baltic Sea and the Skagerrak have hot spots for environmental impacts and are presenting some of the worst habitat states among marine areas in Europe (EEA, 2020) and can thus serve well as a case example for sea/coastal areas globally. We do this knowledge evaluation by perfoming a literature review of eight applied types of coastal restoration measures in this region. Quite strong focus in the review is set on fish, and a bit less emphasis on other environmental and societal issues. This reflects the management priorities around the Baltic Sea and the Skagerrak, where depleted fish stocks is seen as a major focus for management, partly because stronger fish populations have been shown to benefit also habitat health and ecosystem functioning. The study is intended to guide the prioritization of management actions in relation to coastal conservation and restoration, as well as to inform on needs for further development to strengthen national and regional restoration toolboxes, as requested by, for example, EC (2024).

2. Material and methods

2.1. Study area

The Baltic Sea and the Skagerrak include waters with a surface salinity gradient ranging from close to 0 in the northernmost river mouths of the Baltic Sea to close to fully marine conditions in the Skagerrak.

The Baltic Sea is a semi-enclosed estuarine sea and among the largest brackish water areas in the world (Voipio, 1981). It is bordered by nine European countries and can be divided into several different sub-basins (Fig. 1). This non-tidal sea is shallow (average depth: 54 m) in relation to its size (surface area: 420,000 km^2). The coastal zone is topographically complex with vast archipelago areas that constitute large and important parts of the ecosystem. The gradient in surface salinity drives strong differences in species composition, with freshwater species in the inner parts and marine species in the outer parts (Helcom, 2023). Other gradients in background conditions are also present, for instance, with regard to hydromorphological, chemical, physical and biological variables, but also to the density of the coastal population, to the intensity and type of pressures relating to coastal development and to non-physical pressures such as pollution levels (Leppäkoski and Bonsdorff, 1989; Kraufvelin et al., 2021b).

The Skagerrak, in turn, between western Sweden, southern Norway and northern Denmark, is a transition area connecting the North Sea to the Baltic Sea. The salinity in the surface water of the Skagerrak ranges between around 15 in inner bays and estuaries to well above 30 in more open areas offshore. The tidal amplitude in the Skagerrak is narrow with spring tide amplitudes usually being lower than 40 cm (Fonselius, 1990).

2.2. Selection of measures

Literature for this review was gathered through searches on ISI Web of Science Database and Google Scholar (until spring 2025) using the central keywords “marine restoration” focusing on both active and

Fig. 1. The Baltic Sea and the Skagerrak in northern Europe.

passive restoration measures as defined by EC (2024) and screening mainly material from countries surrounding the Baltic Sea and the Skagerrak (both scientific articles and grey literature). The resulting review also builds on a Swedish national report on marine restoration in Swedish (Kraufvelin et al., 2021a).

The results were synthesised in dedicated evaluations for eight measures that were identified as having so far been more broadly applied or considered for shallow temperate coastal areas of the Baltic Sea and the Skagerrak area. Another key criterion for including a measure was that there was at least some information available on the focal themes of the evaluation applicable to the study area, i.e., on methodology, success rates, challenges in achieving positive environmental effects, as well as costs (see also Table 1 and more details below). To some extent, all chosen measures also represented ways to counteract and remediate negative impacts from physical disturbance. Six of the measures were active measures to restore (or rehabilitate) habitats and habitat-forming species. In addition, two of the measures were typically passive, i.e., strengthening populations of predatory fish as well as habitat protection were included as two complementary or alternative passive restoration measures. Hence, in order to focus on ecological restoration aspects (Martin, 2017), measures to reduce pollution levels, such as inputs of nutrient or contaminants, and other measures to reduce pressures affecting water quality were not included.

Thus, the review focused on six active (1–6) and two passive (7–8) measures.

1. restoration of eelgrass beds (Fig. 2a),
2. restoration of macrophyte beds on soft sediments,
3. restoration of rocky-shore macroalgal beds (Fig. 2b),
4. restoration of blue mussel reefs (Fig. 2c),
5. restoration of stony reefs in areas where they have been lost,
6. restoration of coastal wetlands and flads/lagoons (enclosed and semi-enclosed bays, Fig. 2d),
7. strengthening populations of predatory fish (Fig. 2e),
8. protection of habitats.

2.3. Synthesis and evaluation

With regard to the focal themes of the evaluation, all eight restoration measures selected after the literature search were presented in general ways and then described in relation to the following characteristics.

- threats,
- benefits from restoration,
- restoration measures and their effectiveness,
- geographical applicability,
- costs,
- additional information and key knowledge gaps.

The overall feasibility of each measure was qualitatively evaluated with respect to available restoration techniques and their applicability in shallow coastal areas of the Baltic Sea and the Skagerrak. Costs were evaluated with regard to reported projects costs, but also considering known methodological difficulties and weaknesses, risks, as well as the potentials for biological recovery to take place over reasonable time intervals.

3. Eight potential restoration measures for the Baltic Sea and the Skagerrak

This section describes and reviews the various restoration measures examined for the different focal themes evaluated (see section 2.2). For a summary of the results, see Table 1.

3.1. Restoration of eelgrass beds (*Zostera marina*)

Eelgrass is a characteristic seagrass species for shallow sandy substrates in the western, southern and central Baltic Sea and the Skagerrak. It is considered an engineering species - generating a wide range of important ecosystem services (Boström et al., 2014; Cole and Moksnes, 2016; Cole et al., 2021). It offers a three-dimensional benthic structure which serves as nursery habitats, feeding areas and refuges or shelter from predation for many animal species, including fish (Kraufvelin et al., 2018; Steinfurth et al., 2022; Gagnon et al., 2023; Castro-Fernàndez et al., 2025). Eelgrass is rare or absent in the northern and easternmost parts of the Baltic Sea due to low salinity (<5). It predominantly reproduces asexually in the Baltic Sea, with a high degree of clonality observed in many populations (Boström et al., 2014).

Threats. Eelgrass distribution has been decreasing on soft and sandy substrates in many parts of the Baltic Sea and in the Skagerrak (Boström et al., 2014; Moksnes et al., 2018; Rinde et al., 2021; Lange et al., 2022; Gagnon et al., 2023). For the Swedish parts of the Skagerrak, it is estimated that 60 % of eelgrass meadows have been lost since the 1980s (Moksnes et al., 2018; Nyström Sandman et al., 2020). There are many reasons for these decreases such as eutrophication and altered food-web structure due to overfishing, but also boat traffic, moorings and coastal construction of boat infrastructure such as docks and piers and dredged waterways (Baden et al., 2012; Boström et al., 2014; Eriander et al., 2016; de los Santos et al., 2019).

Benefits from restoration. Successful restoration of eelgrass improves ecosystem structure and several ecosystem functions and services such as supporting habitat-formation and biodiversity, acting as fish nursery areas, acting as carbon sinks, providing coastal protection through wave-dampening and sediment stabilisation, and contributing to the sequestration of nutrients and organic matter thus also combating and mitigating the impacts of climate change and eutrophication (Röhr et al., 2016; Howard et al., 2017; Oreska et al., 2020; Krause-Jensen et al., 2022; Lange et al., 2022; Castro-Fernández et al., 2025). Negative responses in connection with restoration have not been reported, although transplantation may potentially damage or thin out donor areas. In case restoration attempts fail, damage to donor sites could then lead to a net loss of eelgrass cover (Lange et al., 2022).

Restoration measures and their effectiveness. Two restoration methods have been evaluated in the Baltic Sea and the Skagerrak area; transplantation of vegetative eelgrass shoots and seeding of eelgrass (Moksnes et al., 2021, 2018; Lange et al., 2022; Kindeberg, 2024). Lange et al. (2022) reported a successful large-scale transplantation of eelgrass shoots in a Danish fjord in the Kattegat. In the northern Baltic Proper (Estonia, Åland Sea), some success has been reported for transplantation using rope substrates and by combining eelgrass and mussel restoration measures (Gagnon et al., 2020, 2021; Meysick et al., 2020; Pajusalu et al., 2023). The estimated time lags for restoration measures using transplantation to be efficient in western Sweden and Denmark are about 1–2 years (Moksnes et al., 2021; Lange et al., 2022). The transplantation method is both expensive and time consuming (van Katwijk et al., 2009, 2016; Infantes et al., 2016; Moksnes et al., 2021, 2018; Lange et al., 2022), and local regime shifts may impede restoration efforts (Moksnes et al., 2018). Seeding of eelgrass has been tested in western Sweden and in Denmark, but has hitherto failed, which could be due to local sediment characteristics and seed consumption by shore crabs (Davis et al., 1998; Moksnes et al., 2021). There are, however, reports of successful seagrass restoration using seeding, both from the USA (for overviews, see Orth et al., 2011, 2020), and from the UK (Unsworth et al., 2019, 2022). It is possible that asexual reproduction (Boström et al., 2014) is predominant at sites were seeding has failed.

Geographical applicability. The measure could be relevant in more or less all areas where eelgrass occurs in the Baltic Sea area, such as along the coasts of the Baltic Proper, in parts of the Åland Sea and in the Finnish and Estonian parts of the Gulf of Finland, and finally the Kattegat and the Skagerrak, where such restoration currently has the

Table 1
Summary of findings regarding the eight evaluated restoration methods in the Baltic Sea and in the Skagerrak.

Restoration target	Main threats	Restoration method	Documented effects	Relevant geographical area	Approximate costs	Gaps and knowledge needs
1 Eelgrass beds	Climate change, Physical loss and disturbance, Eutrophication and organic enrichment, Fishing, Hydromorphological changes, Introduction of non-indigenous species	Active restoration mainly through transplantation of eelgrass shoots, seeding has also been tested	Transplantation has shown both successes and failures, seeding showed mainly failures in this geographical area	Åland Sea, outer parts of the Gulf of Finland, Baltic Proper, Kattegat, Skagerrak	120,000–600,000 euro per restored ha	Success rates are still unknown for many areas; the role of physical regime shifts preventing success need more investigation
2 Macrophyte beds on soft sediments	Climate change, Physical loss and disturbance, Eutrophication and organic enrichment, Fishing, Hydromorphological changes, Introduction of non-indigenous species	Active restoration through transplantation and seeding of macrophyte species or overwintering propagules, harvesting of undesired competing vegetation	Very little information still exists from brackish water areas, but there are examples of both successes and failures	Shallow soft bottoms in low-saline areas along the coasts of the Baltic Proper, in the Åland Sea, Gulf of Finland, Gulf of Riga, and Gulf of Bothnia	120,000–600,000 euro per restored ha (estimated as similar as for eelgrass restoration costs)	The evident lack of hands-on information on restoration of macrophyte species and habitats other than eelgrass in coastal brackish water environments is a deficiency
3 Rocky-shore macroalgal beds	Climate change, Physical loss and disturbance, Eutrophication and organic enrichment, Fishing, Hydromorphological changes, Introduction of non-indigenous species	Active restoration mainly through transplantation of adult seaweeds attached to stones (or free-floating individuals), seeding of kelp on "green gravel"	There are mainly unknown effects and few real success stories for seaweed restoration in the Baltic Sea. Kelp restoration by the use of "green gravel" have shown some promising results in the Skagerrak at a very small scale	For fucoids, the measure may be relevant along the coasts of the Baltic Proper, Åland Sea, western Gulf of Finland and southern Gulf of Bothnia. For kelp, the measure may be relevant in the Skagerrak area	Studies globally present costs in the range of 20,000–2,300,000 euro per ha for macroalgal restoration	The use of free-floating but stationary individuals of bladder-wrack in restoration work in some areas of the Baltic Sea could be a promising way forward
4 Blue mussel reefs	Climate change, Physical loss and disturbance, Eutrophication and organic enrichment, Fishing, Hydromorphological changes, Pollution, Introduction of non-indigenous species	Active restoration through deployment of mussel shells or substrates for mussel colonisation as well as transplantation of adult mussels from nature or mussel farms	There are some success from Denmark, but more limited positive results from the Swedish west coast (the Skagerrak)	Particularly relevant in the Skagerrak and the Kattegat, where salinity is high enough, but also in the Baltic Sea as long as the salinity level is sufficient for blue mussels	International studies report costs to be in the range of 250,000–600,000 euro per ha, although some methods could cost significantly less	Many knowledge gaps exist, such as reasons for declines in mussel distribution in the Skagerrak. These gaps need to be investigated closer in order to improve success rates for any restoration measures
5 Stony reefs in areas where they have been lost	Physical loss and disturbance	Active restoration through deployment of natural or blasted rocks	The restored areas can serve as underwater reefs for colonisation of hard bottom macroalgal and macrofaunal assemblages, including crustaceans, mussels and fish. Examples of success both from Denmark and south-western Sweden	The measure is particularly relevant for the southern and south-western Baltic Sea where stony reefs have been lost historically	Restoration of 7 ha and stabilisation of 6 ha of stony reefs in Denmark costed 4,800,000 euro. The construction and monitoring of seven stony reefs, consisting of 800,000 m^3 of blasted rock in Sweden, costed 1,200,000 euro	Restoration of stony reefs is done to counteract historical losses and is different from artificial reefs that are rather used for modifying the underwater seascape and is therefore not considered as restoration *per se*
6 Coastal wetlands and flads/lagoons (enclosed and semi-enclosed bays)	Climate change, Physical loss and disturbance, Eutrophication and organic enrichment, Fishing, Hydromorphological changes, Pollution, Introduction of non-indigenous species	Active restoration through recreating coastal wetlands by e.g. impoundments to keep more water in the system. Removal of fish migration obstacles allows migratory fish to reach wetlands that are situated further away from the coast. Flads/lagoons may be restored by rebuilding former thresholds to provide benefits both for the underwater vegetation, for macroinvertebrates and for fish recruitment	Many examples of positive effects on fish recruitment, underwater vegetation and the function of these coastal areas as nutrient/carbon traps exist from Sweden and Finland.	The measure may be relevant wherever there are fish that migrate to freshwater for spawning, where underwater vegetation needs to be supported and where nutrient/carbon traps are beneficial for the water quality, such as along the Polish and German north coasts, in many parts of the Baltic Proper, in the Åland Sea, in the	The costs for 1 ha of restored wetland have been estimated to 10,000–20,000 EUR (including both planning and restoration measures, but excluding monitoring costs afterwards). Similar costs have been presented for restored flads and lagoons in the Gulf of Bothnia	In addition to improving fish recruitment, biodiversity and nutrient/carbon trapping, coastal wetlands and flads/lagoons are very popular recreational sites. Compared with many other measures, this restoration is a relatively inexpensive way to achieve many benefits including re-establishment of top-down control by large predatory fish

(*continued on next page*)

Table 1 (*continued*)

Restoration target	Main threats	Restoration method	Documented effects	Relevant geographical area	Approximate costs	Gaps and knowledge needs
				Gulf of Finland and in the Gulf of Bothnia		while combating coastal eutrophication. The measures can thus largely be seen as a quick fix with high added values at comparable low costs
7 Strengthening populations of predatory fish	Climate change, Physical loss and disturbance, Eutrophication and organic enrichment, Fishing, Pollution, Introduction of non-indigenous species	Practical passive restoration measures that can include seasonal or year-round fishing restrictions, fishing gear regulations, catch regulations or controlling predators on piscivorous fish, such as seals and cormorants	Most measures have not been rigorously tested and their effects are poorly known	Potentially relevant everywhere in the Baltic Sea and in the Skagerrak, although different species are concerned in different areas, mainly cod in more saline areas and pike and perch in less saline areas	Costs for protective measures are usually low, but many measures may inflict costs for individual fishers	Precise evaluation of the effects of these measures may be quite difficult as the targeted species for restoration are affected by many pressures and ecological interactions simultaneously
8 Habitat protection	Climate change, Physical loss and disturbance, Eutrophication and organic enrichment, Fishing, Hydromorphological changes, Pollution, Introduction of non-indigenous species	Passive restoration through measures such as establishment of marine protected areas (MPAs), protecting shallow coastal environments and shores, applying fishing and boating regulations, etc., to release or remove ongoing key pressures on the habitat.	Positive effects are mainly local, i.e. seen within the specific protected habitat, but potential larger-scale effects may occur for areas serving as spawning grounds for fish and crustaceans, leading to spillover effects and supporting connectivity between coastal habitats	Potentially relevant everywhere in the Baltic Sea and in the Skagerrak	Costs for creating marine reserves vary, but are relatively low compared to active measures. Compensation costs may be involved to private land and water owners	Although the effects of marine protected areas are quite well studied with numerous positive examples, there is generally a lack of follow-up studies on the effect of habitat protection in the Baltic Sea and the Skagerrak

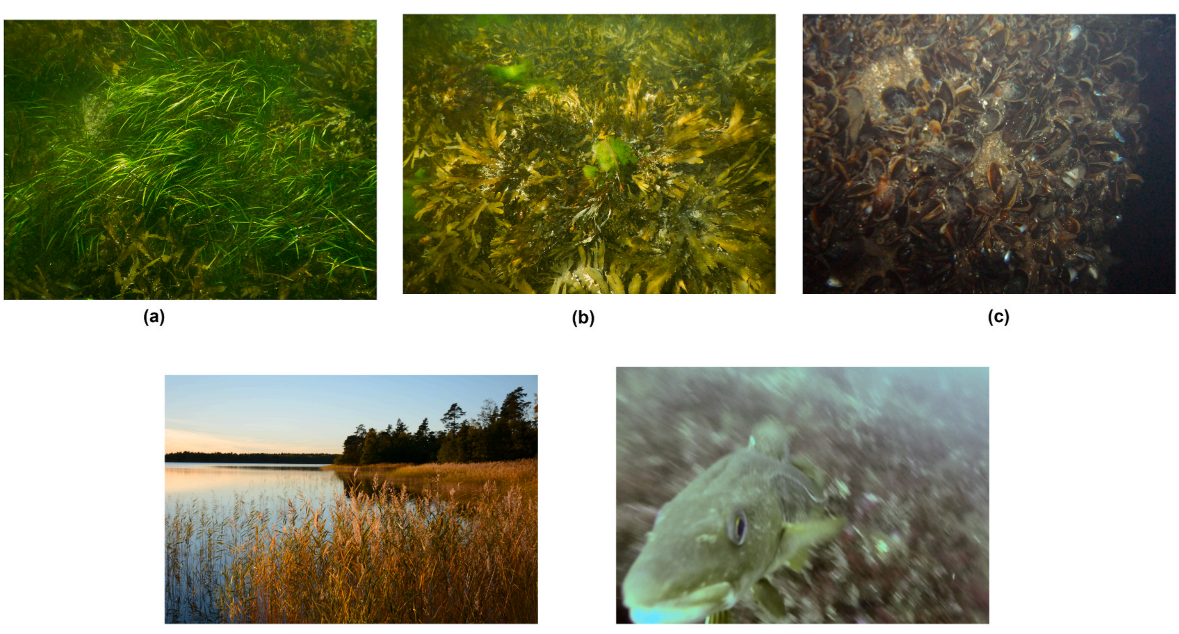

Fig. 2. Pictures of a number of habitats/objects for restoration in the Baltic Sea and the Skagerrak; a) eelgrass bed, b) rocky-shore macroalgal bed, c) blue mussel reef, d) semi-enclosed bay, e) cod. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

highest priority among managers.

Costs. Costs were estimated at 120,000–250,000 euro per hectare restored eelgrass meadow for the transplantation approach used in western Sweden (Moksnes et al., 2021). In comparison, international literature reviews have reported a median cost of almost 400,000 euro per hectare restored seagrass (Bayraktarov et al., 2016) and a range of 250,000–600,000 euro per hectare for coastal systems in general, including seagrasses (de Groot et al., 2012). However, these two studies were literature reviews and did not specify the restoration method. Reynolds et al. (2016) and Oreska et al. (2020) reported a cost corresponding to 1125 euro per hectare in a restoration project reseeding eelgrass in a coastal lagoon in Virginia, USA. Thus, wherever possible, seeding appears to be less expensive than transplantation.

Additional information and key knowledge gaps. Only scant information is still available regarding eelgrass restoration success in many areas where the measure has been applied. The roles of local physical regime shifts involving changes in water transparency and sediment conditions and how and why these background variables prevent eelgrass recovery have been investigated more closely in connection with eelgrass restoration (Maxwell et al., 2017; Moksnes et al., 2018). Thus, measures reducing or removing pressures originally causing eelgrass declines or losses, for example those related to sediment and water quality, need to be developed. Sand-capping of sediments may, for instance, be used to decrease problems with sediment resuspension affecting water transparency and eelgrass survival (Moksnes et al., 2018; Flindt et al., 2022; Steinfurth et al., 2024). In addition, measures to restore populations of large predatory fish and their role in regulating overgrowth of filamentous algae on eelgrass (through trophic cascades; Östman et al., 2016; Chen and He, 2025), has been proposed as a way of improving the success of eelgrass restoration measures (Moksnes et al., 2018).

3.2. Restoration of macrophyte beds on soft sediment

Along a decreasing salinity gradient from south to north and west to east in the Baltic Sea area, as well as along wave exposure and salinity gradients from the open sea towards inner archipelagos, freshwater macrophytes thriving on soft sediment become more abundant (Helcom, 2023). These species largely offer similar ecosystem functions and services as the marine species eelgrass (Kraufvelin et al., 2018; Helcom, 2023). Angiosperms such as *Potamogeton* spp. and *Myriophyllum* spp. are prominent rooted macrophytes in these areas, together with various species of charophytes. These macrophytes serve as a nutrient filter, stabilise the sediment, increase oxygenation to the sediments and constitute important habitats for macroinvertebrates and fish (Degerman et al., 2017; Kraufvelin et al., 2018).

Threats. Losses of macrophytes on soft sediments constitute major changes in ecosystem status occurring in the Baltic Sea. There are many reasons for these decreases such as eutrophication, boating and shipping, as well as construction of infrastructure such as docks and piers and dredged waterways (see Sagerman et al., 2020; Faithfull et al., 2022, 2024 and references therein). According to Helcom (2017), charophytes in the Baltic Sea have decreased by > 25 % during the last 50 years. Here, remote sensing could provide further information on habitat loss and fragmentation (Kutser et al., 2020; Vahtmäe et al., 2025).

Benefits from restoration. Successful restoration of soft bottom macrophytes could improve ecosystem structure and several ecosystem functions. Some of these are supporting habitat-formation and biodiversity, acting as fish nursery areas, acting as carbon sinks and providing coastal protection through wave-dampening and sediment stabilisation. Finally, these macrophytes contribute to the sequestration of nutrients and carbon, thus also combating and mitigating the impacts of eutrophication and climate change. Among possibly negative responses, re-established vegetation may be perceived as obstacles for small boat traffic, swimming and other types of recreational use. The vegetation may also constrain the water flux (van Nes et al., 2002).

Restoration measures and their effectiveness. The practical restoration measures mainly stem from inland freshwater ecosystems and are largely untested in coastal waters, but they may include transplantation and seeding of different macrophyte species, transplantation of overwintering propagules and harvesting of undesired competing vegetation (Degerman et al., 2017; Kraufvelin et al., 2021a; Faithfull et al., 2022, 2024). Some success has been achieved for restoration of macrophytes within lake restoration on the European continent, with technical guides available e.g., in Hilt et al. (2006) and Bakker et al. (2013). Information on freshwaters in Sweden is given by Degerman et al. (2017), while Torn et al. (2010) provided valuable information on brackish-water charophytes in Estonia. In brackish waters of Sweden and Finland, a few projects have been accomplished. Faithfull et al. (2022, 2024), for instance, described restoration of a charophyte meadow in an area of the Gulf of Bothnia in eastern Sweden and found that natural recolonization was just as effective as active transplantation measures. With regard to active restoration in general, it is noteworthy that many methods and working stages used within eelgrass restoration (see section 3.1) might also work for many other species of angiosperms and for charophytes.

Geographical applicability. The measure could be relevant in shallow soft bottom areas in regions with low salinity, such as along the coasts of the Baltic Proper, in the Åland Sea, in the Finnish and Estonian parts of the Gulf of Finland, in the Gulf of Riga, and in the Gulf of Bothnia.

Costs. Faithfull et al. (2022, 2024) found that simple charophyte transplantation using a shovel was the most cost effective method among the restoration methods tested, although it was still less efficient than natural recolonization. The estimated cost for active transplantation using a shovel was about 250,000 euro per hectare (Faithfull et al., 2024).

Additional information and key knowledge gaps. There is an evident lack of empirical information on restoration of freshwater macrophyte species and habitats in coastal brackish water environments. Still, experiences/measures from freshwater systems can to some extent apply also to brackish areas (Shafer and Bergstrom, 2010), although most measures are largely untested outside of the freshwater realm (Kraufvelin et al., 2021a). Estimated time lags for restored systems may be similar to those reported for eelgrass in western Sweden or ca 1–2 years (Moksnes et al., 2021). However, according to Hilt et al. (2006) and Bakker et al. (2013), full re-establishment of plant communities in freshwater systems is generally a very slow process which often comprises 20–40 years and thus similar time scales might also apply for brackish waters.

3.3. Restoration of rocky-shore macroalgal beds

Among the different species of perennial macroalgae that occur on hard bottom areas in the Baltic Sea and the Skagerrak area, two species of brown macroalgae have mainly been considered for restoration, namely bladderwrack (*Fucus vesiculosus*) in the Baltic Sea and sugar kelp (*Laminaria saccharina*) in the Skagerrak. Both species are structurally and functionally important by diversifying bare rock into lush three-dimensional habitats of great importance for many species of associated algae and macrofauna (Christie et al., 2009, 2022; Kraufvelin et al., 2018; Kautsky et al., 2019).

Threats. Decreased distribution of perennial macroalgae on hard bottom areas are primarily attributable to eutrophication, but may also be due to coastal construction, overfishing (through trophic cascades), invasive non-indigenous species and climate change (Kraufvelin et al., 2010, 2021a), In the Baltic Proper, bladderwrack belts are affected by eutrophication, which causes an impaired light climate (Kautsky et al., 1986) and a loss of unoccupied hard surfaces due to competition with fast-growing filamentous algae that may decrease or prevent the establishment of young bladderwrack recruits (Kraufvelin et al., 2007). In the Skagerrak, there has in turn been large-scale losses of sugar kelp, which probably mainly is due to eutrophication and a warming climate (Moy and Christie, 2012).

Benefits from restoration. Successful restoration of brown macroalgae will improve ecosystem structure and support several functions and ecosystem services. Some of these are habitat-formation and biodiversity, acting as fish nursery areas, acting as carbon sinks, providing coastal protection through wave-dampening, contributing to the sequestration of nutrients and carbon-rich organic matter thus also assisting in the combat and mitigation of the impacts of climate change and eutrophication (Ortega et al., 2019).

Restoration measures and their effectiveness. For perennial macroalgae, restoration measures may include seeding of juvenile kelp on "green gravel" (Fredriksen et al., 2020; Alsuwaiyan et al., 2022; Wood et al., 2024), enhancement of *ex situ* recruitment (Verdura et al., 2018), direct seeding (Verdura et al., 2018), transplantation of adult individuals attached to stones/boulders (Carney et al., 2005; Kautsky et al., 2019, 2020), removal of local herbivores (Tracey et al., 2014) and use of artificial reefs (Carney et al., 2005). In the Baltic Sea and the Skagerrak area, only transplantation of adult seaweed individuals (Kautsky et al., 2019, 2020), seeding of juvenile kelp on "green gravel" (Fredriksen et al., 2020) and the use of artificial reefs (Egriell et al., 2007; Dahl et al., 2016; Kraufvelin et al., 2023) have this far been attempted as restoration measures. Restoration through transplantation of bladderwrack seems to be difficult to achieve and still no real success stories exist from the Baltic Proper (Engkvist et al., 2000; Berger et al., 2001; Kautsky et al., 2019, 2020). There has, however, been some limited success with bladderwrack restoration in the Kiel Bight in Germany (see Krost et al., 2018) as well as with bladderwrack and toothed wrack in shallow waters of the Oslofjord in Norway (Christie and Fredriksen, 2011). Additionally, promising new restoration methods could also be discovered in and developed from joint efforts with macroalgal cultivation techniques in the future (Kotta et al., 2022). Negative environmental responses in connection with restoration measures have generally not been reported. For bladderwrack restoration on the Swedish east coast, Kautsky et al. (2019, 2020) have prepared thorough guidelines and they list epiphytic load, light conditions, grazing and type of substratum as factors that need to be taken into consideration in order to achieve a successful outcome.

With regard to sugar kelp in the Norwegian part of the Skagerrak, there are some promising restoration results using the previously mentioned "green gravel" technique (Fredriksen et al., 2020). Gravel was seeded with kelp and reared in the laboratory until the algae reached 2–3 cm when the gravel was transferred to the field. The planted kelp showed high survival and growth over nine months, even when the gravel was dropped from the water surface. The applied technique is quite promising as it infers low costs, is simple and does not require SCUBA diving or highly trained field workers (Fredriksen et al., 2020). The method can also overcome propagule limitation and lack of hard substrate (Gorgula and Connell, 2004; Burek et al., 2018) and it does not include destructive harvest of donor specimens (Fredriksen et al., 2020).

Geographical applicability. Active restoration of bladderwrack, *Fucus vesiculosus*, could be relevant in large areas where this macroalga occurs or has occurred naturally, i.e., in areas of the Baltic Sea with a suitable salinity and substrate type such as along the coasts of the Baltic Proper; in the Åland Sea and in the Finnish and Estonian parts of the Gulf of Finland and in the southern parts of the Gulf of Bothnia. For Denmark, western Sweden and southern Norway, for instance, active restoration of bladderwrack and other seaweed species seems less relevant, unless the measure is linked to reef restoration, because re-establishment of this and related species typically occurs naturally and rapidly, at least during spring and summer (Kraufvelin et al., 2010, 2021a). In the Skagerrak area, restoration of sugar kelp *L. saccharina* has been discussed in previously eutrophicated areas where nutrient levels now have been decreasing (Moy and Christie, 2012; Fredriksen et al., 2020).

Costs. Costs for restoration of bladderwrack in the Baltic Proper have been estimated by Kautsky et al. (2020) and they present the time required for various stages connected with transplantation of a certain number of bladderwrack individuals, including a follow-up program. For restoring 1 m^2 of kelp forest through different measures, the following costs have been reported globally: seeding on "green gravel" 6.23 euro (Fredriksen et al., 2020), enhancement of *ex situ* recruitment 105 euro (Verdura et al., 2018), direct seeding 43 euro (Verdura et al., 2018), transplantation 5–142 euro (Carney et al., 2005), removal of local herbivores 2 euro (Tracey et al., 2014), and artificial reefs 7 euro (Carney et al., 2005). A review by de Groot et al. (2012) presented a range of 250,000–600,000 euro per hectare for coastal systems including perennial macroalgae on rocky shores. The presented costs for macroalgal restoration, depending on species, geographical region and method, thus vary internationally by several orders of magnitudes; from slightly above 20,000 euro per hectare (Tracey et al., 2014; Campbell et al., 2014) to 2,300,000 euro per hectare (Carney et al., 2005).

Additional information and key knowledge gaps. Before attempting bladderwrack restoration in the Baltic Proper, it has to be clarified that the growth conditions for the species are suitable (Schagerström et al., 2025). In areas where bladderwrack has completely disappeared, restoration has proven difficult due to grazers rapidly consuming transplanted specimens, and in other areas, low water transparency may have prevented the photosynthesis of the macroalga (e.g., Engkvist et al., 2000; Berger et al., 2001; Kautsky et al., 2019, 2020). In total, 464 h are estimated to be needed for planning, actual transplantation and monitoring of transplantation success of 350 bladderwrack individuals and at least 4–5 years is calculated to be needed for restoration of bladderwrack forests in the Baltic Proper, since this is the time it takes for the macroalgal individuals to reach reproductive age in the region and thereby to achieve self-sustaining stands (Kautsky et al., 2019, 2020). Recent findings by Schagerström et al. (2025) also demonstrate that bladderwrack can naturally recolonize previously lost areas once eutrophication is reversed. The existence of free-living bladderwrack in the Baltic Sea, reviewed by Preston (2023), may present previously unforeseen possibilities for macroalgal habitat restoration as potentials for this now also could appear in many different kinds of habitats such as also in inner bays with just sediment and bare sand in the absence of hard substrata normally needed for algal attachment. For restoration of kelp by using the "green gravel" technique, the time lags still remain to be established, but there are indications that they may be shorter than for bladderwrack in the Baltic Sea (Fredriksen et al., 2020).

3.4. Restoration of blue mussel reefs

Blue mussels are common and their production is considerable in large parts of the Baltic Sea and the Skagerrak, where the salinity is high enough (above 4.5) and hard surfaces are available. In the Baltic Proper and northwards and eastwards, the dominating species is *Mytilus trossulus*, in the Sound area both *Mytilus trossulus* and *Mytilus edulis* occur in parallel, whereas in the Skagerrak, *Mytilus edulis* dominates (Väinölä and Strelkov, 2011; Knöbel, 2025). Along the shores of the Baltic Proper, blue mussels occur on hard substrates from the surface down to depths of more than 30 m and sometimes in densities above 10,000 individuals per m^2. Here, the blue mussel is considered to constitute 80–95 % of the animal biomass on hard bottom areas and to be of great importance by serving as a foundation species with ecosystem engineering functions for many associated macrofauna species and as food sources for fish and seabirds (Kautsky, 1982; Díaz et al., 2015; Kraufvelin et al., 2018; Westerbom et al., 2019, 2021; Åkermark et al., 2022).

Threats. A larger-scale decline of blue mussels, mainly *Mytilus edulis*, has been reported for western Sweden and southern Norway (the Kattegat and the Skagerrak) by scientists as well as citizens (Andersen et al., 2016; Frigstad et al., 2018; Havs-och vattenmyndigheten 2020; Christie et al., 2020; Jakobsson and Pedersen, 2020; Baden et al., 2021; Laugen et al., 2023; Strand et al., 2023). Thus far, mainly local decreases in blue mussel (*Mytilus trossulus/edulis*) abundance have been reported in the Baltic Sea (Åkermark et al., 2022). A lack of long-term data to quantify changes over time makes it difficult to clearly define the magnitude of the problem and identify possible causes of the decrease. One possible reason is trophic cascading effects from reduced abundance and size of coastal predatory fish due to overfishing or loss of essential fish habitats and subsequent increases in mesopredatory wrasses, roach, round goby, dog whelks and shore crabs that are efficiently consuming juvenile mussels (Christie et al., 2020; Jakobsson and Pedersen, 2020; Åkermark et al., 2022; Meister et al., 2023; Gustafsson et al., 2024). The invasive mud crab is an additional threat in the Baltic Proper (Jormalainen et al., 2016). Baden et al. (2021) suggest the most possible causes to the blue mussel decline to be combined changes in predation from eiders and shore crabs, alterations of natural substrates by eutrophication and climate change. However, as blue mussels in the Skagerrak still thrive on floating structures, explanations involving predators that are unable to reach such sites seem especially likely (Christie et al., 2020; Meister et al., 2023; Banke et al., 2024).

Benefits of restoration. Successful restoration of blue mussel reefs can contribute to many different ecosystem functions and services. Biogenic mussel reefs have several positive effects on the physical environment, including the shoreline, through their wave dampening function, their counteracting of erosion and their stabilisation of the bottom. In addition, the water filtration by the mussels reduces turbidity and makes the waters clearer and lower in nutrient and carbon concentrations by sequestration (Kraufvelin and Díaz, 2015; Kotta et al., 2020) thus contributing to mitigating the effects of climate change and eutrophication (Sea et al., 2022). Successfully applied measures may further support increased fish growth and diversity over time (Kristensen et al., 2015; Kraufvelin et al., 2018). Some negative responses may, however, also be related to the restoration measures such as possible conflicts with boat navigation. There may be risks of damaging donor areas in connection with transplantation of blue mussels and if the restoration attempts fail, there may be net losses in mussel cover. Additional risks are present in connection with all kinds of transplantation such as the risk of spreading diseases and parasites and also causing genetic changes in the local populations (Väinölä and Strelkov, 2011).

Restoration measures and their effectiveness. Some restoration measures to counteract loss of blue mussels have been tested in Denmark as well as on the Swedish west coast (in the Skagerrak). In Denmark, different restoration measures have led to a fast re-establishment of functional (and harvestable) mussel stands within 1–2 years (Dolmer et al., 2009). Restoration can be attempted by deploying mussel shells (for example from mussel farms) or other natural or artificial substrates in areas where there is a natural availability of mussel recruits and possible limitation of hard surfaces suitable for mussel settlement. Alternatively, mussels could be naturally recruited onto deployed substrates in the water column, whereafter the substrate with the mussels are transplanted to the bottom areas to be restored. Such attempts have been tested in the Skagerrak (Strand et al., 2023). Direct transplantation of adult mussels (residual/waste mussels from mussel farms) is another option for the Skagerrak (Strand et al., 2023).

Geographical applicability. This measure may be particularly relevant in the Skagerrak and in the Kattegat, and also in Baltic Sea areas demonstrating losses and decreases as long as the salinity level is beneficial for the occurrence and growth of blue mussels.

Costs. In case there is a lack of suitable substrates and transplantation can be accomplished simply by placing out new recruitment substrates, the costs would be particularly low, but for cases requiring other measures, the costs would be considerably higher. Still, no cost estimates seem to exist for blue mussel restoration in the study area. However, for an indicative global comparison, a median cost around 200,000 euro per hectare of restored oyster reef was given by Bayraktarov et al. (2016), while de Groot et al. (2012) presented a range of 250,000–600,000 euro per hectare for coastal systems including rocky shores. As a comparison, the economic value of oyster reef restoration (focusing on another bivalve) has been estimated to reach something between 5000 and 90,000 euro per hectare and year (Grabowski et al., 2012) and thus those oyster reefs would return their median restoration costs within 2–14 years.

Additional information and key knowledge gaps. As restoration projects focusing on mussel reefs are still rare in the Baltic Sea and the Skagerrak area, not many cases have hitherto been followed up and this may also explain the lack of cost estimates. Time lags for positive effects to be seen could probably be comparably short or around 1–3 years in the western Baltic Sea and in the Skagerrak, but this is very site-dependent (e.g., ambient salinity, abundance of food for the mussels, mussel growth rates, etc.), which is why time lags may be expected to be considerably longer in the Baltic Proper. By using waste mussels, increased circularity and improved resource utilization in aquaculture production can be achieved as a positive spin off effect, with both ecological and economic gains as important natural habitats are recreated, while costs for waste management from mussel production is reduced for the aquaculture companies (Strand et al., 2023). Methods using adult mussels may be especially relevant in areas with a high predation pressure on juvenile blue mussels by eider ducks, mesopredatory fish (e.g., wrasses), dog whelks or shore crabs, which impairs the recruitment to the adult population (Christie et al., 2020; Meister et al., 2023; Banke et al., 2024). The underlying reasons for the observed declines in mussel distribution in the Skagerrak area would, however, need to be investigated closer.

3.5. *Restoration of stony reefs in areas where they have been lost*

Natural hard structures such as stony reefs and boulder fields serve as underwater substrates for habitat-forming macroalgae and blue mussels as well as for their associated diverse assemblages of epiphytic macroalgae, macroinvertebrates and fish (see also sections 3.3-3.4). Historically, these reefs were quite common in the southern parts of the Baltic Sea (Mikkelsen et al., 2013; Johansson et al., 2022), which motivates a restoration need in selected areas, where these reefs have been removed and lost.

Threats. In the southern and western parts of the Baltic Sea, there has been a historical loss of hard surfaces such as natural stony reefs through exploitation, mainly stone fishing, but also through marine extraction and sometimes due to trawling (Støttrup et al., 2014, 2017; Johansson et al., 2022).

Benefits from restoration. Examples of positive responses from such restoration measures are an addition of hard surfaces for marine organisms, increased biodiversity, re-established ecosystem services, improved coastal protection against erosion, and increased sequestration of carbon- and nutrient-rich organic matter as soon as organisms have established on the reefs (see e.g., Flávio et al., 2023). The improved sequestration of carbon and nutrients also serves to combat climate change and eutrophication and mitigate the negative impacts of these processes. Possible negative responses are altered bottom structures, potential changes in water circulation, effects on surrounding soft sediment communities and that introduced hard substrates in areas of predominating soft bottom areas can serve as stepping stones for non-indigenous species (Bulleri and Chapman, 2010; Airoldi and Bulleri, 2011; Airoldi et al., 2015; Dannheim et al., 2020).

Restoration measures and their effectiveness. Dahl et al. (2024) compiled a report about best practices for boulder reef restoration in Danish waters describing a recommended process for designation and implementation of restoration projects and providing an overview of relevant regulations, licences and authorities. As some individual case studies from the Baltic Sea region, a stony reef was restored in Denmark in an area where the original hard substrate historically had been removed by stone fishing, leaving a soft, predominantly sandy substrate that could not support the former natural communities. With the re-introduced stony reefs, the biological community changed as the new structures attracted species with a preference for rocky habitats. Monitoring showed increased biodiversity, increased abundances of fish, including increased abundance of larger specimens of certain species of predatory fish (Støttrup et al., 2014, 2017; Wilms et al., 2021) and also more harbour porpoise (Mikkelsen et al., 2013). Several other projects are going on in Denmark to restore stony reefs to increase bottom areas and reach good environmental status. Around the deployed boulder reefs close to Vinga outside Gothenburg in Sweden, there has been an increase in benthic biota (Salonsaari, 2009; Pålsson, 2009) and also an increase in commercially important fish and shellfish species (Egriell et al., 2007; Bergström et al., 2022b; Kraufvelin et al., 2023). Similar responses as those from restoration of stony reefs can be deduced from species investigation and monitoring close to offshore wind farms in the Sound area between Sweden and Denmark, where boulders are deployed as scour protection around the turbine foundations (Bergström et al., 2013a; Stenberg et al., 2015; Dahl et al., 2025).

Geographical applicability. This measure is relevant for the southern and south-western Baltic Sea where stone reefs have been lost historically.

Costs. The local positive effects of restoring stony reefs are high, but since these kinds of restoration measures may be very expensive, the restored areas are usually small. For instance, restoration of 7 ha and stabilisation of 6 ha of stony reefs at Læsø Trindel in Denmark cost 4,800,000 euro (Støttrup et al., 2014, 2017). The construction and monitoring of seven stony reefs (more of the artificial reef type), consisting of 800,000 m^3 of blasted rock, at Vinga in Sweden cost around 1, 200,000 euro (Egriell et al., 2007; Salonsaari, 2009).

Additional information and key knowledge gaps. There are mainly local positive effects of the measures, but by combining the measure with the establishment of marine protected areas, some wider-scale positive impact may also be achieved (Egriell et al., 2007; Bergström et al., 2022b; Kraufvelin et al., 2023). Combining the deployment of stony reefs with local fishing bans may be important to facilitate rapid re-establishment and to avoid over-harvesting of the populations. It may also be relevant to observe if natural predators such as seals and cormorants gather around the restored stony reefs as fish are expected to become easier to catch in areas where they aggregate. Positive effects on macroalgae and small macroinvertebrates probably occur rapidly on restored stony reefs, within weeks or months (Egriell et al., 2007). However, about 2–3 years are needed in the Skagerrak for significant positive effects to occur on lobster and fish from constructed stony reefs combined with establishment of marine protected areas (Bergström et al., 2022b; Kraufvelin et al., 2023). The possible attraction by fish individuals to reef structures, rather than an increase in production, could lead to overharvesting of certain species or an increased predation pressure from natural predators (Jaquemet et al., 2004; Bortone, 2006; Mikkelsen et al., 2013; Paxton et al., 2022). Whether the observed increases in e.g., fish close to stony reefs are pure attraction effects of the fish, or if increases also reflect effects at the population abundance level, is not yet very well established in marine science due to a lack of long-term follow-up studies (Jaquemet et al., 2004; Brickhill et al., 2005; Bortone, 2006; Becker et al., 2018), but the support for positive production effects seems to be increasing (Smith et al., 2016; Roa-Ureta et al., 2019; Folpp et al., 2020; Flávio et al., 2023).

Intentional deployment of artificial reefs or various types of underwater construction works using hard substrates may have a number of positive and negative effects similar to effects from stony reefs. Such reefs attract e.g., fish and shellfish and supposedly also increase the production of certain species and are thus of interest both for commercial and recreational fisheries and for other types of recreation than fishing (Seaman, 2007; Fabi et al., 2011; Lipcius and Burke, 2018; Paxton et al., 2022; Song et al., 2022; Flávio et al., 2023). Still, deployment of such artificial reefs is not a plain restoration measure and the use of artificial reefs is questionable and may be disputed with both ethical and environmental arguments. Deployment of artificial reefs can be compared to “dumping” and the reefs may affect the benthic environments negatively by e.g., interfering with the natural underwater hydromorphology and by potentially facilitating the introduction and spread of non-indigenous species (Bulleri and Chapman, 2010; Airoldi and Bulleri, 2011; Dafforn et al., 2015; Ruuskanen et al., 2015). Positive synergies may, however, be achieved from reef restoration efforts in combined combination with marine installations (ter Hofstede et al., 2023). Due to the risks associated with deploying artificial reefs, however, the expected ecological improvements need to be carefully weighed against possible negative impacts on existing values already during the planning phase.

3.6. Restoration of coastal wetlands and flads/lagoons (enclosed and semi-enclosed bays)

Nearshore wave-sheltered waters, shallow enclosed and semi-enclosed bays and coastal wetlands have a high biological productivity. This is because they often contain high amounts of aquatic plants and are warmed up early in spring. They are thereby of great importance for many warmwater-adapted coastal fish species in the Baltic Sea whose juvenile development benefits from higher temperatures (see Kraufvelin et al., 2018 and references therein). These water areas are also very important through their high biodiversity, and through their function as nutrient and carbon traps or filters between the land and the sea thus contributing to mitigating the effects of climate change and eutrophication (Hagger et al., 2022).

Threats. As flads and lagoons are biodiversity hotspots in the study area and elsewhere, anthropogenic disturbance of these ecosystems pose a threat to a wide range of flora and fauna (Donadi et al., 2020; Saarinen and Berglund, 2022; Virtanen et al., 2024). Spawning and recruitment habitats in tributaries for coastal fish have undergone substantial deterioration in many regions of the Baltic Sea (Engstedt et al., 2010; Nilsson et al., 2014; Kraufvelin et al., 2018, 2021b; Saarinen, 2019; Hansen et al., 2020; Bergström et al., 2022a; Saarinen and Berglund, 2022; Olsson et al., 2023; Svels et al., 2025). Land drainage, coastal development and eutrophication have led to extensive losses of biodiversity (Saarinen and Berglund, 2022) and of spawning and nursery areas for coastal fish populations (Ljunggren et al., 2011; Nilsson et al., 2014). Flads and lagoons have been affected by dredging of thresholds in their inlets to enable boat traffic. Such activities can seriously affect the water exchange in the flads or lagoons and alter their biodiversity, function and ecosystem services, which calls for restoration of these environments.

Benefits from restoration. Revitalization of enclosed or semi-enclosed coastal waters as biodiversity hotspots, spawning and recruitment habitats for fish and as carbon and nutrient traps are key priorities. Recreating enclosed or semi-enclosed coastal waters, through e.g., impoundments, enables periods with flooding to keep the water longer in the system. Removal of fish migration obstacles is another measure that allows migratory fish to reach wetlands that are situated further away from the coast. More than 100 coastal wetlands have been restored along the Swedish east coast to promote reproduction and recruitment of pike and perch. For the same purpose, fish migration obstacles have been removed in more than 40 coastal streams in Sweden (Hansen et al., 2020). Similar initiatives are also going on in Finland (Arnkil et al., 2024; Trouth and Laingui, 2025). The effectiveness of restoring coastal wetlands and tributaries to support spawning habitats of fish have been under investigation in the Swedish parts of the Baltic Sea (Ljunggren et al., 2011; Fredriksson et al., 2013; Hansen et al., 2020; Flink et al., 2023; Tibblin et al., 2023). Restoration of coastal wetlands as reproduction areas, foremost for pike, has in many cases been shown to result in a strong increase in the production of juvenile pike as a result of optimised spawning conditions, predation refuge and food production (Nilsson et al., 2014; Larsson et al., 2015; Hansen et al., 2020; Tibblin et al., 2023). Tibblin et al. (2023) found that pike abundances were on average 90 % higher in coastal bays with an adjacent wetland, although the effect varied among areas. The same study also revealed that wetland pike constituted a high proportion of the pike found in adjacent coastal habitats. Still, during summer when pike dispersal was greatest, 75 % of sampled female pikes resided within 3 km from the estuary/wetland (Flink et al., 2023).

Restoration measures and their effectiveness. In Sweden, 281 ha of wetland or coastal lakes were restored between 2010 and 2019 and 2610 ha were made accessible for pike by 83 measures or projects by the Swedish Anglers Association and collaborators (Hansen et al., 2020). Coastal wetlands and flads/lagoons may be restored mainly by moderating their inlets by decreasing or increasing waterflow (inlet width/depth) depending on the specific needs for the inlets’ connection to the sea. Restoration measures in these ecosystems are separate categories from those in section 3.2 focusing on macrophytes, because the work that is undertaken here does not concern seeding or transplantation of macrophytes, but is instead mainly targeting the waterways and the positive effects of this on fish and other ecosystem components. A corresponding common restoration measure for flads and lagoons may be to reconstruct thresholds that have been removed by dredging in order to re-open entrances to coastal lagoons blocked by overgrowth to provide benefits both for the underwater vegetation, macroinvertebrates and fish recruitment (Saarinen, 2019; Donadi et al., 2020; Saarinen and Berglund, 2022).

Geographical applicability. This may be a relevant measure wherever there are fish that migrate to freshwater for spawning, where underwater vegetation needs to be supported and where nutrient traps are beneficial for the water quality, such as along the Polish and German north coasts, in many parts of the Baltic Proper, in the Åland Sea, in the Gulf of Finland and in the Gulf of Bothnia.

Costs. In Sweden, the costs for 1 ha of restored wetland have been estimated at 10,000–20,000 euro (including both planning and restoration measures, but excluding monitoring costs afterwards, Hansen et al., 2020). Similar costs have been presented for restored flads and lagoons in the Gulf of Bothnia (Saarinen, 2019). Globally, de Groot et al. (2012) presented a range of 15,000–600,000 euro per restored hectare for coastal wetlands, i.e., on average considerably higher costs.

Additional information and key knowledge gaps. Wetlands and flads/lagoons generally promote aquatic and terrestrial biodiversity (Qu et al., 2022). The effects generally include maintenance of a high biological production and diversity while the wetland and the flads/lagoons may function as carbon, nutrient and sediment traps (buffering zones), support enhanced fish reproduction (supporting pike and perch, but also cyprinids), and provide benefits for bird and amphibian life (Hansen et al., 2020). Increased numbers of predatory fish can also by trophic cascading contribute to decreased eutrophication effects through a higher consumption of smaller fish and other prey species, both in the wetland itself and in the sea outside. The positive effects of single restored areas on fish are mainly local, within the actually restored target area, but with a potential for larger-scale positive effects (see Tibblin et al., 2023). Negative responses of the restoration of coastal wetlands and flads/lagoons include potentially disturbed terrestrial ecosystems, alteration of freshwater or marine habitats and potential harmful effects on certain bird or macrophyte species. Due to these potentially diverging effects, there are evident needs for improved coordination of different management measures within these measures as well as for long-term monitoring of their effects on recruitment, local fish populations and the ecosystem as a whole (Hansen et al., 2020). Each constructed or reconstructed wetland and flad/lagoon has to be carefully designed depending on its main purpose, geology, soil characteristics and hydrology (Feuerbach, 2014).

Generally, it takes at least one year after restoration before significant increases may be registered in juvenile production and juvenile migration of pike in a restored coastal wetland (Nilsson et al., 2014). Effects on the adult population takes considerably longer (Tibblin et al., 2023). Similar time estimates also seem to be valid for fish and biodiversity in restored flads and lagoons (Saarinen, 2019). According to Borja et al. (2010) most of the former ecological functions of coastal wetlands are estimated to become restored within 20 years after the measure has been undertaken.

3.7. Strengthening populations of predatory fish

Many populations of predatory fish are at historical low abundances, with a loss of especially the larger individuals within populations (Myers and Worm, 2003; Hočevar and Kuparinen, 2021; Griffiths et al., 2024). This situation could possible be reversed by passive restoration measures such as fishery regulations and regulation of predators as well as habitat protection (see section 3.8).

Threats. Fishing, and especially commercial fishing that is targeting large predatory species, is a central threat to predatory fish (Worm, 2016; Hočevar and Kuparinen, 2021), as is loss of essential fish habitats by coastal construction (Sundblad and Bergström, 2014; Sundblad et al., 2014; Kraufvelin et al., 2018; Guo et al., 2022) and eutrophication (Bergström et al., 2013b, 2019, 2024). In the Baltic Sea, predation from seals and cormorants has increasing effects on local abundances of many fish species, and mainly on large coastal predatory fish (Hansson et al., 2018; Aarts et al., 2019; Ovegård et al., 2021; Bergström et al., 2022a; Svels et al., 2025). The same applies to predation on eggs and larvae from three-spined stickleback, a species that has increased dramatically during the last two decades (Olin et al., 2022; Makhrov et al., 2025).

Benefits from restoration. The negative situation for predatory fish could possibly be reversed by a number of, mostly passive, restoration measures focusing on re-establishing strong populations of coastal predatory fish and allowing for the recovery of natural systems to follow (Olsson et al., 2023; Bergström et al., 2024; Eriksson et al., 2024). The measures could be undertaken to increase the abundance of large predatory fish, which have declined across the Baltic Sea (mainly cod, pike and perch), as well as in the Skagerrak (mainly cod and other gadoid fishes). Higher abundances and larger body sizes of predatory fish may relieve eutrophication symptoms and serve to strengthen habitats through re-establishment of trophic control and lower abundances of mesopredators (Östman et al., 2016; Donadi et al., 2017; Eklöf et al., 2020; Kraufvelin et al., 2020, 2023; Bergström et al., 2024).

Restoration measures and their effectiveness. Measures targeting populations of predatory fish comprise the application of regulative tools to allow the recovery of target species, rather than restoring their habitat. The practical measures may include regulating fishing gear use and catches, and measures to reduce or keep out predation from seals, cormorants and three-spined stickleback. Also protecting key habitats for fish from physical disturbance can be beneficial (as described in section 3.8). However, knowledge of these measures varies considerable (Bryhn et al., 2022). Fisheries no-take areas, for example, have repeatedly been shown to be efficient for strengthening populations of predatory fish, given that the size and placement of the areas corresponds to the needs of the fish (Moland et al., 2013, 2021; Bergström et al. 2019, 2022b; Knutsen et al., 2022; Eklöf et al., 2023; Kraufvelin et al., 2023). Data from the Vinga marine reserve and other MPA examples indicate that positive responses on harvestable species may be detectable within 1–3 years (Bergström et al., 2019, 2022b; Kraufvelin et al., 2023) and that abundances can be on average four times higher after six years of closure (Bergström et al., 2022b). Still, Bergström et al. (2022a) demonstrated that the positive effects on the fished stock disappeared very rapidly when the total fishing closure ended even though the nursery area still was protected. While the effects of permanent no-take areas are more thouroughly studied, there is not yet much information available from the Baltic Sea and the Skagerrak on the effectiveness of other types of regulations. Eklöf et al. (2023), however, investigated a number of seasonal fish spawning closures in Stockholm archipelago and found that the catch per unit effort of pike was 2.5 times higher in closure zones than in reference areas, while no positive response could be seen in perch, the other frequent predatory fish found in these spawning closures.

Geographical applicability. This may be a relevant measure across the Baltic Sea and the Skagerrak, although it will mainly concern different species with gadoid fish in more saline areas and fish species such as pike and perch in less saline areas.

Costs. Costs for the application of protective measures are uncertain, but usually very low compared to costs for subsidizing commercial fisheries (Balmford et al., 2004; Waldo et al., 2010), although many measures may inflict costs for individual fishers and compensation costs for these from authorities. In their analysis of benefits and costs of two temporary no-take zones, Bostedt et al. (2020) partly reported conflicting results: when fisheries could be relocated in connection with the protection, fisheries benefits outweighed costs, but when no fisheries were relocated, costs outweighed benefits in some scenarios.

Additional information and key knowledge gaps. Evaluating the effects of measures to increase populations of predatory fish may sometimes be difficult as the targeted species for restoration are affected by many simultaneous pressures and ecological interactions. A lot needs to be done within the area of evaluation of effects of the measures. Data from Swedish no-take zones, however, indicate that positive responses on harvestable species may be detectable in only a few years, and a meta-analysis suggests that abundances are on average four times higher after six years of closure (Bergström et al., 2022b).

3.8. Protection of habitats

Habitat protection in the form of establishment of marine protected areas (MPAs) constitutes a passive measure, where protection aims to prevent or decrease concurrent local-scale pressures, such as physical disturbance from coastal construction, dredging or bottom-trawling to allow conservation or possibly natural recovery. It is in this sense complementary to most of the other evaluated measures presented in this paper, particularly the one described in section 3.7. It should be noted that MPAs include various degrees of habitat protection, and this section concerns protection at the stricter part of the range focusing on the protection of the actual physical habitat, rather than of the fish living in the habitat. Habitat protection, together with fishing regulations (see section 3.7), constitutes an even stronger conservation.

Threats. Habitat degradation is continuously increasing in coastal areas today, since the effect of physical modifications of the seabed, development of coastal infrastructure, tourism and boating activities lead to cumulative habitat losses (Sandström et al., 2005; Sundblad and Bergström, 2014; Eriander et al., 2016; Hansen et al., 2019; Moksnes et al., 2019). In addition, fishing may affect benthic habitats through bottom-contacting gear (Kraufvelin et al., 2018).

Restoration measures and their effectiveness. Protection of habitats is not an example of traditional restoration, but comprises measures carried out through establishing MPAs, protecting shallow coastal environments and shores. Such management measures applied in the coastal zone could preferably be done in combination with measures undertaken to protect open sea areas. Substantial indirect evidence of the effectivess of habitat protection is provided from studies showing how habitat deterioration reduces fish productivity (Kraufvelin et al., 2018). For example, Sundblad et al. (2014) showed that habitat limitation for early life stages of perch and pikeperch may restrict the abundance of later stages of adult fish. There is also evidence of long-term negative effects on fish reproduction habitats from physical development, boating and infrastructure related to boating (Sandström et al., 2005; Sundblad and Bergström, 2014; Hansen et al., 2019; Sagerman et al., 2020). However, only a low proportion of the MPAs in the region can be considered fully or highly protected today (www.mpatlas.org). Careful analyses should be conducted to identify areas of specific importance for connectivity and green infrastructure, such as core source and sink areas, stepping stone habitats and key migration routes, and make sure that these are prioritized within restoration and protection efforts (Berkström et al., 2022, 2024; Garbutt et al., 2024; ICES, 2025).

Geographical applicatility. The protection of habitats represents a relevant measure along the entire coastline of the Baltic Sea and the Skagerrak and may thus be a relevant measure everywhere in the focus area of this review. In general, the positive effects of habitat protection are mainly local, within the specific coastal areas, but with potentially positive larger-scale effects (Bergström et al., 2022b; Berkström et al., 2022).

Costs. Costs for protection measures by creating marine reserves and no-take areas are generally lower than other restorative measures. Principally, many areas could be established for quite low costs, unless bought private land and private water areas are included, some compensation fees need to be paid to former users or owners or there will be considerable costs involved with organising legislation or monitoring and guarding the areas.

Additional information and key knowledge gaps. Although the effects of marine protected areas are quite well studied, there is generally a lack of follow-up studies on the effect of habitat protection in the Baltic Sea and the Skagerrak area. As the protective measures are expected to work absolutely best in combination with other restoration measures, it should be recommendable, whenever possible, that the areas that are actively restored also should be automatically protected. The alternative, to undertake active restoration measures inside protected areas, in cases where this is relevant, could also be a feasible way forward. In many MPAs, however, protection is generally weak, allowing most activities with the exception of large-scale development, meaning that the level of protection is low in practice.

4. Discussion

In combination with measures to halt ongoing marine biodiversity loss, there is a recognised need for developing and adapting toolboxes for active and passive restoration measures that can be applied to specific habitat types and situations to strengthen the ecosystem services we depend on (including all relevant socio-economic aspects) and to increase the resilience to climate change and other pressures (Beheshti et al., 2022; EC, 2024). This study provides an overview of eight marine/coastal restoration measures applicable to the Baltic Sea and the Skagerrak, foremostly to reverse negative impacts from physical disturbance or loss of specific habitats. Table 1 summarises the findings of this study for the investigated restoration measures. Among the listed measures, three seem to stand out as entailing especially low cost per hectare, i.e., active restoration of coastal wetlands and flads/lagoons, and passive measures to strengthen populations of predatory fish and to protect habitats. Most measures are understudied in the investigated area, provide limited positive effects in relation to their costs and have geographical limitations or limitations with regard to their sensitivity towards a poor environmental status and continued environmental degradation. In addition, all measures have in common that they seem to need various degrees of continued development and fine tuning in order to be able to offer high levels of success rates and value for money and in order to be efficiently upscaled. This is an obvious area of improvement pointed out by our literature survey. It should also be noted here that high costs for a measure does not automatically imply that it should be avoided; it may still yield more benefits than costs and sometimes there are no other options than restoration to turn negative trends in habitat loss.

In aquatic systems, positive experiences from active restoration measures have hitherto been more apparent in freshwater ecosystems, whereas the focus in coastal systems have more often been on protection and other passive measures to support natural recovery and rehabilitation, rather than active restoration (Geist and Hawkins, 2016; Jones et al., 2018; Kraufvelin et al., 2021a). Nevertheless, as the reliance on passive measures, such as formal protection (see De'ath et al., 2012; Knowlton, 2012; Abelson et al., 2016; Smith et al., 2021) or pressure reduction, often has proven insufficient (Turner and Schaafsma, 2015), various active restorative or rehabilitative measures, through nature-based solutions and eco-engineering, are now increasingly called for to achieve desired conditions (Connell and Slatyer, 1977; Elliott et al., 2016, 2017; Cole et al., 2021; van der Meulen et al., 2022; Oliveira et al., 2024; Danovaro et al., 2025). However, a basic prerequisite for any measure to be successful in the long term, is that the pressures causing the impact are removed or reduced to sustainable levels, and that the physical, chemical and biological changes that have taken place are reversible (Elliott et al., 2016; Danovaro et al., 2025; Schagerström et al., 2025). Indeed, a common reason behind failed restoration efforts is that the external conditions, for example with regard to water quality, were not adequate when the restoration measures were undertaken (Moksnes et al., 2018; Schagerström et al., 2025). Similarly, disturbed food webs lacking the top-down control from large predators may also contribute to failed efforts to restore habitat-forming species such as kelps and seagrasses (Eriksson et al., 2024).

While the specific focus of restoration is to improve biodiversity and safeguard the delivery of ecosystem services, applying measures that can both withstand and also mitigate the effects of climate change is warranted (EC, 2024). As a minimum, it should be assessed if the restored ecosystems will be resilient to changing conditions, to avoid restoring systems that might subsequently be lost due to climate-induced changes. Also, different restoration measures may be advisable in different geographical areas and ecological settings, depending on for example the local community composition, physical habitat characteristics, key environmental pressures as well as the actual environmental status of the habitat in question. For example, Fraschetti et al. (2021), stated that "*Where* is more important than *how* in coastal and marine ecosystem restoration".

An additional strategy to improve the success rates would be to investigate more closely the effects of a combination of different restoration measures – as pressures often are acting on the ecosystem interactively, the application of an interactive simultaneous co-restoration of several habitats at once may be a fruitful way to respond. For example, restoring underwater macrophyte beds in combination with the restoration of mussel reefs that may provide clearer waters for photosynthesis or more stable sediment conditions could, possibly, offer better opportunities for restoration success (Kraufvelin and Díaz, 2015; Kotta et al., 2020; Gagnon et al., 2021; Pajusalu et al., 2023). A combination of blue mussel restoration with the addition of breakwaters and stony structures/substrates including fences (to exclude predatory crabs and promote mussel attachment) may also improve success rates (Schotanus et al., 2020). Another beneficial co-restoration is to strengthen populations of large predatory fish, for example via establishing no-take zones, to improve the success of kelp or seagrass restorations (Eger et al., 2020; Valdez et al., 2020). Many of the measures evaluated in this review could be combined with other measures in the search of positive synergies. Maybe it could even be seen a prerequisite for successful coastal restoration to work at multiple habitats simultaneously (Vozzo et al., 2023). Further, whenever possible, all the measures should preferably be combined with protection to improve the restoration effectiveness and secure the long-term prospects to reach targeted objectives.

The lack of formal experiences on the success of restoration measures highlights a deficiency of follow-up studies in the Baltic Sea and the Skagerrak, which is particularly striking in relation to the amount of investments actually being made to restoration (Kraufvelin et al., 2021a). This is also supported by other observations (e.g., Bayraktarov et al., 2016; Silliman et al., 2024). Evaluations of the effects of restoration efforts is necessary in order to determine if the primary goals of the restoration measures have been achieved and how to improve future restoration work. Documentation and evaluation of all these aspects are keys as we can learn a lot from both successes and failures. In order to be able to more formally assess the success and failure of applied marine restoration measures, it is important to decide which response variables and indicators to examine, to establish reference conditions for these variables in time and space and to follow-up their development during the full course of a restoration process, including long-term studies after the measures have been undertaken (Jones and Schmitz, 2009; Kraufvelin et al., 2021a; Danovaro et al., 2025; ICES, 2025). The results of this paper demonstrate that comprehensive monitoring and follow-up of restoration measures is a future area of improvement, and could even be made conditional by restoration project financers.

To support qualitative and quantitative evaluation of restoration success, a wealth of studies highlight the importance to establish clear restoration aims and objectives, and also the criteria that should be used to assess how well these have been met in relation to reference conditions (Simenstad et al., 2006; Seaman, 2007; Borja et al., 2010; Gann et al., 2019; Danovaro et al., 2025). The reference conditions should preferably describe both habitat structures and functions, and the biological, chemical and physical processes that are creating and maintaining these structures and functions (Kraufvelin et al. 2021a, 2021b). Here, it may be recognised that a lack of information on undisturbed conditions (Hilderbrand et al., 2005; Duarte et al., 2009, 2015; Mehrabi and Naidoo, 2022) can make it difficult to set relevant targets for the measures. Failures may also be due to regime shifts locking ecosystems into new configurations that can be difficult or even impossible to reverse with usual restoration techniques, because of the occurrence of certain threshold levels that cannot easily be surpassed (Scheffer et al., 2001; Duarte et al., 2009; Maxwell et al., 2017; Tomczak et al., 2022; Eriksson et al., 2024). It has been suggested (USEPA, 2000; Beechie et al., 2010) that, as it is quite unlikely that degraded ecosystems can be fully restored, it might be a more relevant aim for restoration and rehabilitation projects to more often focus on restoring sites to their 'remaining natural potential', and that full recovery of biodiversity values is often utopistic.

Available experiences on the success of restoration measures, as supported by the present review, also highlight the importance of applying a mitigation hierarchy in any planned activity that is associated with risks to potentially damage nature values (Cole et al., 2021). Following the mitigation hierarchy implies to first and foremost implement any achievable actions to avoid damage in the first place, second to minimise risks of damage during the activity and finally, to restore and compensate for any unavoidable damage (BBOP, 2018; Jacob et al., 2018). Avoiding and minimising damage before or when the activities are taking place is in most cases much more cost effective than relying on restoration or compensation measures afterwards (Kraufvelin et al., 2021a; Cole et al., 2021), as also supported by the conclusions from the present study regarding feasibility and cost effectiveness of measures.

With regard to cost effectiveness specifically, an evident key issue is that there is a substantial knowledge gap regarding which measures to take and what effects they are expected to provide. In order to be able to apply as relevant and cost effective measures as possible, there are urgent needs to describe and evaluate the potential of currently available restoration options, and their possible development needs. In general terms, ecosystem restoration is expected to be cost effective (e.g., EC, 2024), in meaning that the benefits in general far outweigh the costs, and the view that achieved monetary benefits of restored habitats should be taken into account has been expressed by several authors (Oreska et al., 2020; Gordon et al., 2020; McAfee et al., 2021).

The eight measures evaluated in this paper do by no means make up an exhaustive list. These measures are mainly focusing on restoration after physical disturbance, and have been chosen as they already to some extent have been applied in the Baltic Sea and the Skagerrak. In the future, carefully monitored restoration experiments may reveal new or refined methodologies that are more effective than those listed in this paper. It must also be noted that the compilation of measures of this study is descriptive. No systematic meta-analyses were carried out specifically for this review, for instance to evaluate effect sizes, due to an evident lack of quantitative information for basically all of the examined measures. For a couple of the measures carried out in this region, however, meta-analyses have been run and this is true for restoration of coastal wetlands (Hansen et al., 2020) and for strengthening of predatory fish populations through fishing closures (Bergström et al., 2022b). Further, the success rate of many potential methods for alleviation or reversal of impacts seems to be dependent on both environmental contexts and site-specific features (Kraufvelin et al., 2021a). Hence, broad evaluations of potential restoration measures and solutions over relevant spatial scales and ecological settings will be necessary, preferably applying measures within an overarching seascape perspective (Garbutt et al., 2024; Danovaro et al., 2025). Summarising the results of this study, we believe that it can serve as an initial review documenting what already has been done and stimulating ideas regarding what could be done in the Baltic Sea and the Skagerrak during the second half of the UN's decade of ecosystem restoration. Hopefully, our findings can also be used as support for initiation and further development of national and regional restoration plans as requested for by the EU (EC, 2024).

5. Conclusions

Based on the broad set of studies reviewed in this paper we draw the following conclusions for future restoration efforts and research on the topic in the investigated area.

- It is generally less costly to prevent environmental damage in the first place than to restore habitats once the damage has occurred. However, damage mitigation and protection alone are unlikely sufficient to halt the current losses of biodiversity in coastal areas, and they need to be supplemented by active restoration in many areas. Restoration, if carefully planned and implemented by measures with proven effects and acceptable costs, can contribute to halt and reverse the loss of biodiversity and ecosystem services.
- To support qualitative and quantitative evaluation of restoration success, a wealth of studies highlight the importance to establish clear restoration aims and objectives.
- Different restoration measures are suitable in different geographic areas and ecological settings, depending on, e.g., local community composition, key species, local environmental characteristics, key pressures as well as ecological status.
- Most coastal restoration measures, if successful, show effects at the scale of the actually restored area, or smaller. A possible exception may be measures to enhance mobile predatory fish, which under some conditions could have positive effects also at larger scale.
- Based on this review, active restoration of coastal wetlands and flads/lagoons, and passive protection of populations of predatory fish as well as of habitats appear as the least costly measures with the largest overall positive impact and some positive results also demonstrated outside of the target area. However, more costly measures can still yield higher benefits than costs.
- A combination of several restoration measures may be needed to enhance success rates and reach set objectives. This is partly because many pressures are acting simultaneously, and because different ecological succession processes may need to be supported specifically. For example, a combination of eelgrass restoration with restoration of mussel reefs and habitat protection may be advisable to achieve needed synergies.
- In most situations, alleviation of pressures is a prerequisite for successful recovery and often, successful restoration is dependent on first improving environmental conditions to allow re-establishment of key species.
- Restoration efforts should preferably be planned to support ecological connectivity in marine and coastal landscapes. This may especially concern connectivity among protected areas and restored areas, including restoration of stepping stone habitats and key migration routes.
- Quantitative evaluation of the effectiveness of restoration measures needs to be improved in future efforts to ensure adaptive learning and knowledge sharing with respect to both restoration successes and failures.
- Evaluation of socio-economic aspects of restoration projects are often deficient or lacking. More future effort should be made on establishing cost per hectare estimates, as well as cost-benefit analyses.

CRediT authorship contribution statement

P. Kraufvelin: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **J. Olsson:** Writing – review & editing, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **L. Bergström:** Writing – review & editing, Visualization, Methodology, Investigation, Funding acquisition. **U. Bergström:** Writing – review & editing, Visualization, Methodology, Investigation. **A.C. Bryhn:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

All authors declare that there are no competing interests.

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Data availability

No data was used for the research described in the article.

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