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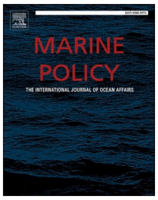

Marine nature-based solutions: Where societal challenges and ecosystem requirements meet the potential of our oceans

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ABSTRACT

Nature-Based Solutions (NbS), a concept introduced in the late 2000s, has developed rapidly during the last years and is now frequently appearing in a broad spectrum of policies developed within the European Union. Its role in marine policies and research programmes is however still limited, but is likely to increase as NbS are adopted as key terminology in both biodiversity strategies and the EU taxonomy for sustainable financing. This will enhance the need for scientific advisory institutions to provide evidence-based advice on potential impacts of various combinations of marine NbS. To facilitate a critical debate about the prospects and pitfalls related to the operationalisation of marine NbS in an EU context, this paper provides an analysis of core definitions, potential categories of marine NBS and a suite of case studies. Coastal waters, shelf and open oceans present multiple options for testing new and scaling up known NbS, which could support both environmental restoration simultaneously with addressing multiple societal challenges, paving the way for a new level of ecosystem-based management. However, as the acceptance of NbS types will depend on ecosystem state and thus history, it will be a significant task to consistently communicate why some solutions may count as a NbS in some areas, while not in others. To conclude, the paper therefore raises a set of research priorities and policy advice aimed at ensuring the successful advice and deployment of marine NBS in support of multiple societal goals.

1. Introduction

According to the ‘new social contract’ between science and society in the 21st century [1], science must increasingly acknowledge its role as the key provider of solutions to address major societal challenges, rather than just generate ‘new knowledge’. Among such major challenges are presently the need to address climate change [2] and provide sustainable social and economic development, while protecting or restoring the planet’s biodiversity and ecosystem services, as proclaimed in e.g., the ‘United Nation’s Decade on Ecosystem Restoration 2021–2030’ [3]. This has led to a call by particularly the European Commission [4] to develop ‘solutions’ which can address societal challenges and ‘nature restoration’ simultaneously, e.g., provide Nature-Based Solutions (NbS) [5] and has appeared centre stage in EU policy [4,6,7] including in specific strategies such as the EC’s Biodiversity Strategy to 2030 [8] and Blue Economy Strategy [4] which both underline the role of NbS in reaching policy targets in relation to climate adaptation.

Similarly have NbS also been integrated in the EU taxonomy for Sustainable Finance, where they are highlighted as an instrument which could help many different types of economic activities meet the ‘technical screening criteria’ to be considered ‘sustainable’ [9]. Finally are NbS also anticipated to be a core instrument in meeting policy targets related to the recent proposal for an EU Nature Restoration Law [10].

Beyond Europe, attention to the concept has also now gained traction following the recent 2022 resolution by the United Nations Environment Assembly [3] which highlighted NbS’ role in addressing sustainable development.

In summary, this provides a new science-policy venue, where

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research institutions are anticipated to not only understand the options and challenges for implementing NbS, but increasingly provide scientific advice on the subject and, where possible, quantitative estimates of impact. The concept of NbS is not new [11–14]. It has surfaced in the past in many shapes and forms [14,15] such as eco-engineering [16] bio-mimicry [16] or building with nature [17].

However popular the concept of NbS, the definition of the notion appears to be in flux. Although quite a common phenomenon when a concept is being developed, and the naming of the concept functions as a boundary object [18] providing interpretation flexibility [19], it also may lead to confusion of what the actual concept entails. While in science developing or changing definitions is a known phenomenon [20] terminology which carries policy implications likely needs a more definitive definition to ensure that the interpretation across stakeholders converges. For example, is it presently highly uncertain to track e.g. financing of NbS [21], underlining the increasing risk that NbS could be too vague a term and on the path to become no more than a buzzword [14,21,22] which could reduce its potential and anticipated impact [23]. Similar concerns are echoed in the resolution by United Nations Environment Assembly [3] which highlights the risk of misuse of the concept.

There are many examples of solutions that are considered to be nature-based[12], yet in the marine/aquatic domain there appears to be few experiences with developing NbS practices, though reviews of national NbS portfolios are starting to emerge e.g. from Malaysia to support more successful future implementations [24]. In order to contribute to the development of the concept, a marine approach to NbS is developed in this article, and operationalisation discussed from a European perspective. The European perspective is maintained, despite the potential global scope to demonstrate its role "*in accordance with local, national and regional circumstances*", whose importance is highlighted in the UNEA resolution [3].

In Section 1 definitions of NbS are explored, including related topics. In Section 2 cases of marine NbS from around the world are analysed, and lessons drawn in Section 3. In Section 4 research gaps emerging from the former sections are presented, while Section 5 addresses policy challenges and options, before concluding in Section 6 how best to enhance operationalisation of the NbS in the marine realm.

1.1. Defining (marine) NbS

The EC [25] defines NbS as "*solutions that are inspired by and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits, and help build resilience*" and further emphasises that "*such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions*" (e.g., in [25] p6). It is additionally a requirement that NbS must "*benefit biodiversity and support the delivery of a range of ecosystem services*". While the EC's definition does not have an official set of principles which should be followed, the EC presents in recent policy communications (e.g., [25]), a set of basic guiding questions which underlines that NbS should support environmental, social and economic benefits.

The International Union for Conservation of Nature (IUCN) [26] defines NbS as "*actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits*". Here the focus is on the system's integrity and the goal is "*to address major societal challenges*" which is explicitly confined to (1) Climate change mitigation and adaptation; (2) Disaster risk reduction; (3) Economic and social development; (4) Human health; (5) Food security; (6) Water security; (7) Environmental degradation and biodiversity loss. Furthermore, IUCN emphasises in its supporting principles and criteria in the global standard [5] that NbS for example, must be understood and applied at the scale of landscapes; and it requires that actions directly respond to evidence-based assessments of the current ecosystem state and pressures; that social, economic and environmental baseline conditions are understood before initiation of interventions; biodiversity conservation and human wellbeing contribution outcomes identified, benchmarked and periodically assessed; and trade-offs and risks addressed beyond the intervention site.

Thus, while apparently aligned, the two definitions differ significantly in some areas, particularly in relation to the overall rationale for NbS and the criteria for actions to be accepted as 'NbS'. Turning to the 'rationale' for NbS, IUCN defines the 'purpose of NbS' as actions to protect, sustainably manage, and restore ecosystems, thus ensuring the *natural state* of ecosystems and their benefits. Contrary to this, using the EC definition, any planned action can be considered an NbS if you add some construction components to the action that will 'benefit' nature to a certain degree. Therefore, the EC definition in some ways aligns closely with the concept of nature-inclusive design, which in a marine context e.g., has been supported as a part of the offshore wind farm development in the Netherlands in recent years [27,28]. In comparison to the EC and IUCN definitions, the recent resolution by the UNEA proposes a third definition, inspired mainly by IUCN's stating that NbS "*are actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits*" [3].

The discussion on the NbS scope is nonetheless not novel. One attempt to provide clarity is presented by Eggermont et al. [11] who proposed a three-level typology to explain the range of NbS based on the degree of ecosystem intervention. These include: Type 1 NbS - focused on the maintaining and enhancing natural ecosystems; Type 2 NbS - focused on approaches to ensure sustainable management of extensively or intensively managed ecosystems to enhance particular ecosystem services; and Type 3 NbS – which include intrusively managed ecosystems and even artificially constructed new ecosystems.

While Eggermont et al.'s [11]typology of NbS certainly advances the scoping discussion, it does not provide a definitive set of practical core features allowing easy operationalisation of the concept, particularly in the marine environment. This is not improved by the fact that both the EC, IUCN or UNEA definitions of NbS also use terminology which, to a large extent, is not defined in detail.

Firstly, among these undefined aspects, is what part of 'biodiversity' is considered, beyond basic suggestions to consider e.g., Shannon index (which e.g., the EC highlights [25]). This is a reoccurring challenge, particularly in marine policies [29] as the term in general is broad, spanning organisational levels ranging from intraspecific genetic diversity to ecosystem functioning and species level conservation units [30]. Furthermore, it is not clear whether degrees of replacement, relocation or compensation of biodiversity is acceptable, which is a fundamental consideration in order to develop scientific advice related to ecosystem restoration actions in general [31]. Similarly, it is not clear from EC, IUCN or UNEA definitions if e.g. protection or restoration of threatened biodiversity should be prioritised over non-threatened biodiversity. Further, it remains an open question if 'biodiversity enhancement' beyond natural or historical levels is within the scope. One example could be a stakeholder group (fishermen, diving operators etc.) interested in the deployment of an artificial reef, in an area where no similar habitat type has ever existed, nor in need of restoration at the scale of the sea basin.

While this line of conceptual inquiry may appear too detailed for the scope of NbS, its clarification is unavoidable, given that e.g. IUCN [5] demands NbS to provide 'net biodiversity gains' which assumes the presence of metrics. IUCN explicitly 'addresses' this paucity in biodiversity metrics in its guidance, by suggesting a case-by-case approach regarding the choice of biodiversity indicators for impact assessments. While recent reports funded by the EC [32] now provide suggestions for performance and impact indicators for terrestrial ecosystems, none has been made for the marine environment. By comparison the UNEA 2022 resolution highlights for both terrestrial and marine NbS that a general assessment and discussions are needed to "*Assess existing and discuss potential new proposals, criteria, standards and guidelines to address divergences, with a view to achieving a common understanding among Member States*" about NbS [3].

Secondly, 'ecosystem services' are integrated in both the EC and IUCN definitions as a key term which provides challenges resembling the case of 'biodiversity'. For example, it is likely going to be challenging for practitioners a priori to determine when to pursue or accept substitutions within single ecosystem service categories, e.g., one type of food for another, or between ecosystem service categories such as between cultural or provisioning services. This is particularly the case in many marine and coastal contexts where the stakeholder landscape often will not be characterised by an intuitive or legally mandated process to identify whose preferences should be given priority. In addition, the distinction between ecosystem services and disservices [33] is not trivial, as the same ecosystem 'output' can count as both depending on temporal context and beneficiary [34].

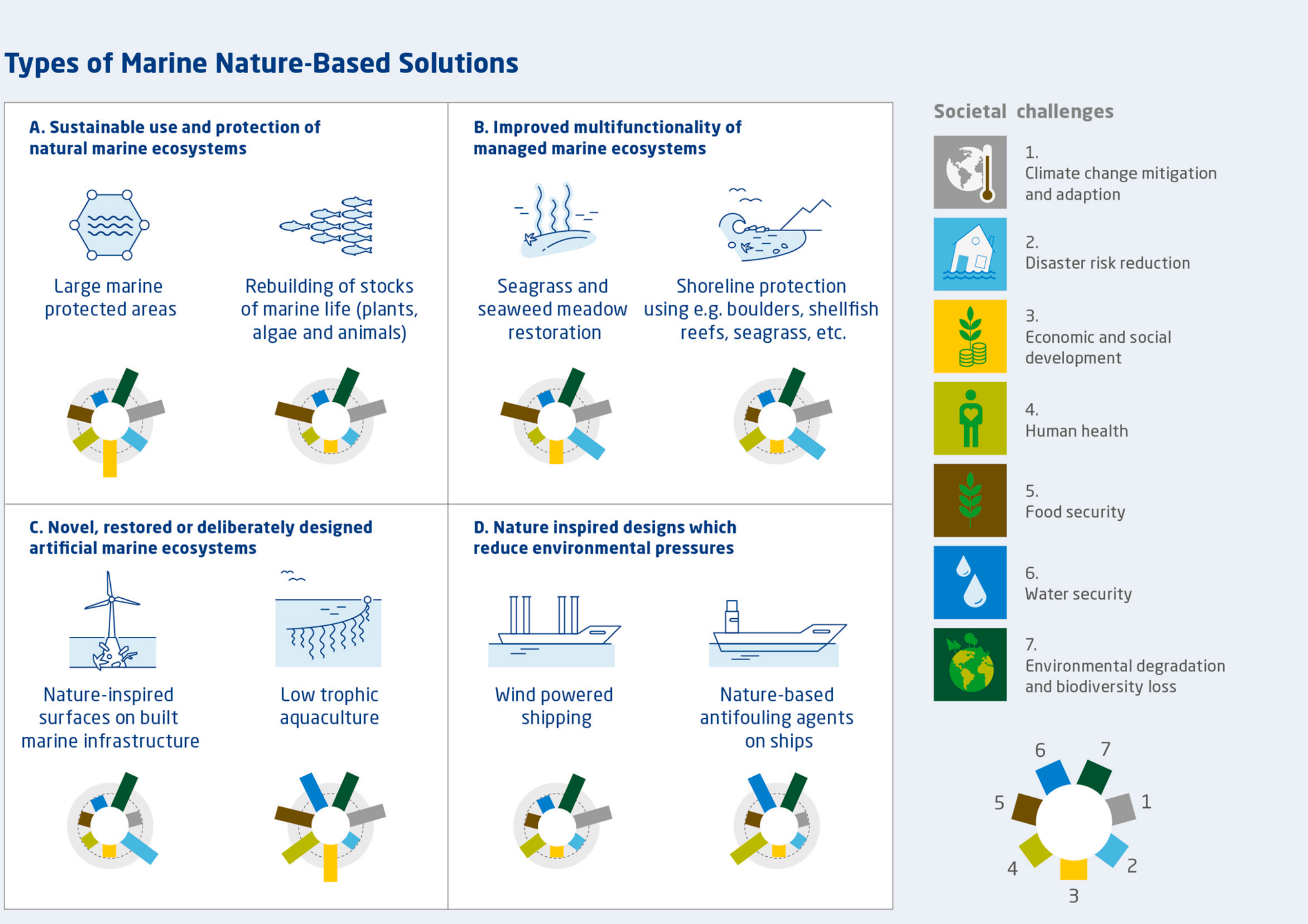
However, most of these considerations are not new, with many already explored in relation to the operationalisation of concepts such as "ecosystem net gain" which aims to combine both biodiversity and ecosystem service attributes in a single assessment to identify relevant environmental offsetting options as a part of a mitigation hierarchy in landscape or infrastructure projects [35], also in marine contexts [36]. Similarly, the ability to determine "marine net gains" has been analysed by Hooper et al. [37], who provided a dedicated set of recommendations regarding its potential implementation.

The example of 'net gains' raises an important question relating to the role of baseline data, as 'gains' imply relative improvements for particular environmental indicators. This suggests that what might constitute a NbS in a marine area with low ecosystem integrity, might not constitute one in a more well conserved area.

Thirdly, an area not covered by all three definitions relates to where and when benefits and negative impacts, including ecosystem disservices [33] are supposed to occur in order to be included in the evaluation of the NbS to understand e.g. environmental burden shifting. As benefits consist of the provision of biodiversity, ecosystem services, social and economic development, it becomes an open question at which temporal and spatial scale to assess these benefits, as some ecosystem services, such as carbon sequestration, are global benefits while others such as nutrient cycling might be very local, or mainly be relevant at a sea basin scale.

2. Examples of marine NbS

In this section a number of marine NbS cases are analysed, and presented using an adapted version of Eggermont et al.'s [11] typology of NbS and recent relevant NbS literature to better align it with a marine context. The proposed categorization of marine NbS mainly focusses on the scope of NbS in terms of the number of ecosystem services provided



Types of nature-based solutions modified from Eggermont et al. (2015) with marine examples. Histograms are not based on quantitative analyses, but only illustrates what categories of IUCN's major societal challenges, each example is likely to address based on the literature review.

Fig. 1. Types of marine nature-based solutions

and the stakeholders involved, but also on the level of engineering required similar to Eggermont et al.'s [11] typology. Furthermore, to provide an extended diversity of examples, we propose a fourth type of NbS-like solutions (Type D) which, unlike the others, are not necessarily place-based, but rather exploit the marine nature in a way which, in relative terms, could be significantly more environmentally sustainable than its present alternatives (Fig. 1). Here we 'stretch' the definition of NbS by suggesting that some solutions, while not directly supporting e.g., biodiversity improvements, may provide significant reductions in environmental pressures if scaled appropriately, which should support passive improvements in ecosystem states and thus the associated ecosystem services. The boundary between each type is rarely distinct, and should only be considered as a mechanism to structure discussions about the level of ambitions of marine NbS. In comparison Type B and C NbS align particularly with the concept of 'nature-inclusive' design and construction suggested by e.g., Hermans et al. [27].

To support the analysis, Annex 1 provides an overview of marine NbS initiatives collected from different policy and literature sources, of which Fig. 2 illustrates a subsample. This does not represent a comprehensive review, but a collection of cases to illustrate the diversity of actions which could be considered as NbS-like by stakeholders. Only marine NbS-like initiatives which have already been implemented and/or appear replicable, or could potentially be transferable to European marine waters, have been considered.

Most of the identified marine NbS-like initiatives address the dual global crises on biodiversity loss and climate change and mainstreaming nature conservation solutions into blue economy sectors to provide ecosystem services and contribute to specific Sustainable Development Goals (e.g., SDG 2, 13, 14). However, as particular ecosystem services and their enhancement are at the centre of multiple societal challenges, we have structured their presentation according to the IUCN's 'major societal challenges' to emphasise the multiple objectives which marine NbS can address (Figs. 1 and 2).

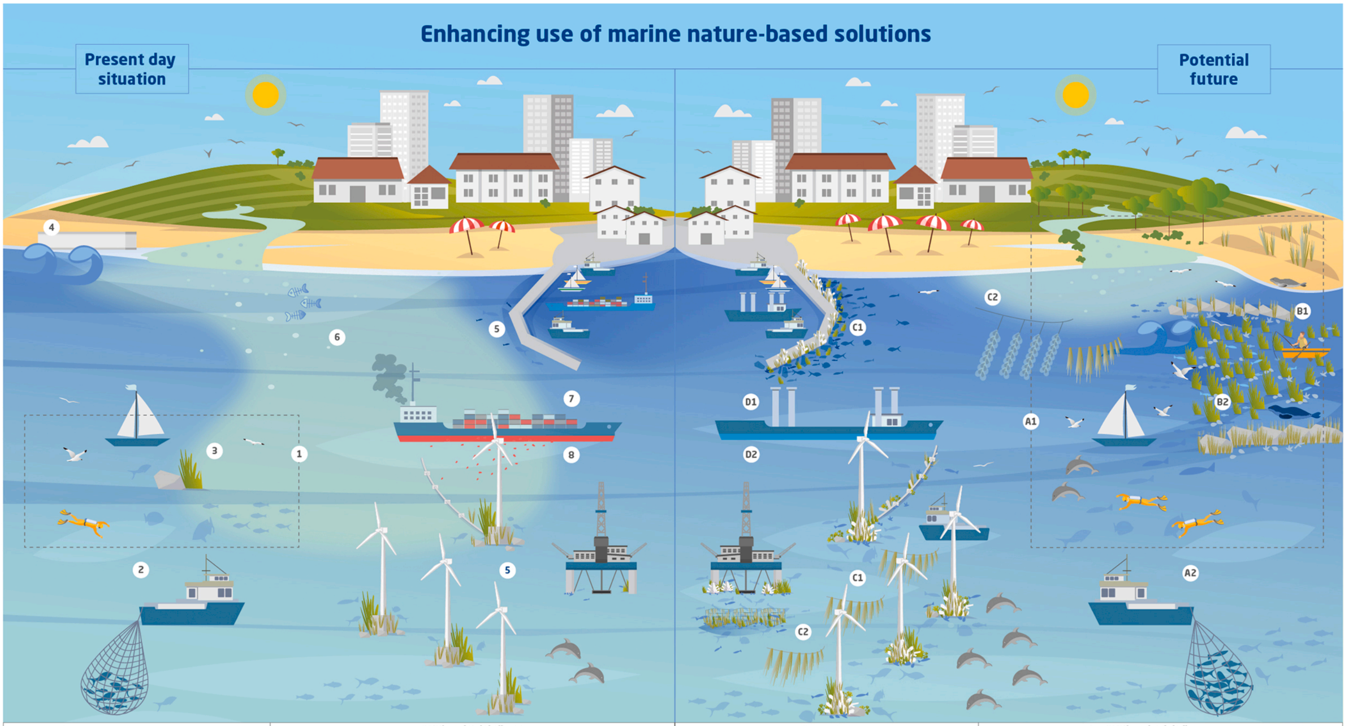
2.1. Type A: NbS that improve the sustainable use and protection of natural marine ecosystems and their services

Type A NbS we define similar to Eggermont et al.'s [11] type 1 NbS as "*consisting of no, or minimal intervention in marine ecosystems, with the objective of maintaining or improving the delivery of ecosystem services both inside and outside these preserved ecosystems, while enhancing nature conservation and sustainable use of biodiversity.*"

2.1.1. NbS supporting climate change mitigation and reversal of environmental degradation and biodiversity loss

Type A solutions make better use of existing natural or protected ecosystems and fully fit with the IUCN's NbS frame. Typically, Marine Protected Areas (MPA) are Type 1 NbS and the establishment of protected marine reserves is a practical, tested and cost-effective strategy to conserve marine biodiversity, to boost the resilience of marine ecosystems and protect their capacity to supply a large diversity of ecosystem services [38–40].

Coastal habitats, such as salt marshes and seagrass meadows (e.g., *Posidonia oceanica*) in Mediterranean MPAs are significant blue carbon ecosystems, in terms of the intensity of sequestration and long-term carbon deposits and may sequester up to 3.1 tCO2/ha and stock up to



Present day situation		IUCN's societal challenges						
		Climate change mitigation and adaption	Disaster risk	Economic and social development	Human health	Food security	Water security	Environmental degradation and biodiversity loss
1	Small marine protected areas	●			●			●
2	Industrial fishing using non-selective gears					●		
3	Small patches of seagrass/seaweed/shellfish beds							●
4	Coastline protection using concrete infrastructure	●	●					
5	Coastal and offshore infrastructures	●	●	●				
6	Eutrophic waters							
7	Cargo ship using bunker oil			●				
8	Loss of toxic antifouling paint from ships							

Anthropogenic activities both on land and at sea impacts the health of marine ecosystems and their capacity for ecosystem service provisioning. Presently some activities resemble known types of nature-based solutions, yet deployment is scarse and at small scale, with many untapped potentials remaining.

Potential marine nature-based solutions		IUCN's societal challenges						
		Climate change mitigation and adaption	Disaster risk	Economic and social development	Human health	Food security	Water security	Environmental degradation and biodiversity loss
A1	Large marine protected areas	●		●	●	●		●
A2	Ecosystem approach to fisheries, using selective gear	●		●		●		●
B1	Seagrass/seaweed meadows and shellfish reef restoration	●	●	●		●		●
B2	Boulder reef/bed restoration to protect shoreline	●	●					●
C1	Greening of hard infrastructure, multipurpose artifical reefs and habitats	●	●	●		●		●
C2	Extractive aquaculture	●		●		●		●
D1	Cargo ships using primarily wind power	●			●		●	●
D2	Nature-based antifouling paint on ships				●		●	●

To deliver on EU and global targets, widespread deployment of nature-based solutions to multiple societal challenges will likely be needed. To support dialogues on the potential and risks of greenwashing, four types of NbS are suggested (modified from Eggermont et al 2015). Type A: NbS that improve the sustainable use and protection of natural marine ecosystems and their services; Type B: NbS that improve multi-functionality of managed marine ecosystems; Type C: NbS which provide novel, restored or deliberately designed artificial marine ecosystems; Type D: Nature inspired designs applied in marine environments which reduce environmental pressures.

Fig. 2. Enhancing use of marine nature-based solutions

4050 tCO2/ha per year [41]. Type A NbS implemented for coastal blue carbon protection also prevent further degradation of ecosystems and CO2 release from seagrasses to the atmosphere [42] mitigating the risks of related-climate change impact while increasing other ecosystem services and adaptation benefits [43]. Similarly, other coastal habitats likely act as donors of macroalgae material, transported to the deep sea or buried in coastal sediment, providing global carbon sequestration amounting to 61–268 TgC yr− 1 of 'blue carbon' [44]. Additional benefit of protecting e.g. seagrass meadows, mudflats and biogenic bivalve reefs is the protection and maintenance of coastlines [45,46], reducing shoreline erosion through the attenuation of water energy, thus providing tangible reductions in disaster risks.

The protection and rebuilding of stocks of marine fauna is another type A NbS. For example, the recovery of some whale stocks could likely provide substantial carbon sequestration benefits [47,48] due to their role in the carbon cycle, just as the same populations would likely contribute to the economic potential for whale watching globally [49]. Similar carbon benefits, due to the deep sea burial of dead animals, could also be achieved from reduced fisheries pressure in high seas [50]. In other places it would however likely be more relevant to rebuild fish stocks to increase the potential for sustainable future biomass harvest to enhance food security [51].

A further motivation for rebuilding particular fish stocks, is attributed to their role in the marine inorganic carbon cycle which in some areas likely buffer the acidification effects in the surface layers of the ocean [39]. This process stems from fish regulation of their osmotic pressure by drinking seawater and precipitating calcium and magnesium in the gut, forming carbonates that are dissolved in near-surface marine waters, which increases alkalinity [52]. In case of mesopelagic fish species, their large vertical migration from deep sea to surface waters have thus been suggested to operate as a sort of 'alkalinity pump' [39]. Hence, the management of fish stocks must balance and prioritize food security versus acidification mitigation, and possibly other utilities.

2.2. Type B: NbS that improve multifunctionality of managed marine ecosystems

Type B NbS differs from Eggermont et al.'s [11] type 2, and refers to the targeted use of 'challenge specific' actions which aim to restore or enhance selected types of naturally occurring biodiversity and ecosystem services in managed areas where they need to coexist with other marine activities.

2.2.1. NbS supporting climate change mitigation and reversal of environmental degradation and biodiversity loss

The use of active ocean fertilization is based on the hypothesis that adding limiting nutrients will stimulate phytoplankton blooms causing plankton cells or assemblages to sink from the surface to the deep ocean, thus sequestering carbon as a part of the biological pump. This hypothesis has been confirmed through experimental trials in the Southern Ocean, where iron is a limiting factor for phytoplankton growth, though more experiments are still needed to explore the actual potential in areas with different environmental features [53]. Further gains from increased primary production would be the potential for enhanced overall ecosystem productivity in terms of secondary and tertiary production, providing greater fisheries opportunities as well. However, marine primary production is declining [54], and acidification can be responsible due to its negative impact on phytoplankton iron uptake [55].

Other NbS to mitigate climate change encompass the ecosystem restoration and the carbon sink capacity of seaweeds and seagrasses in coastal ecosystems. This solution has been tested in the Fishing Reserve of Cape Roux (Western Mediterranean Sea) where artificial reefs, optimized for the growth of algae (*Cystoseira*), were deployed to restore depleted natural meadows. Despite early predation from sea urchins, which initially fed on the small, transplanted seaweeds, after a few months the upper surface of the artificial substrates supported a well-developed *Cystoseira* coverage, and the structures were colonised by fish with juveniles in those areas with an algal cover [56].

A large seagrass restoration project, which involves planting seagrass seeds over two hectares, has been launched in the Dale Bay, Pembrokeshire (UK). Once fully established, the restored seagrass meadow is expected to sequester up to half a ton of carbon dioxide per hectare each year. Moreover, the seagrass meadow is expected to become a nursery for a variety of marine organisms supporting an estimated 160,000 fish and 200 million invertebrates [57].

Restoration of *P. oceanica* seagrass in 15 transplant sites along the Italian coasts, which together represent about 30,000 m^2 of transplanted meadows, has positive effects on degraded *Posidonia* habitat [58,59]. Transplantation strategies, including age of seed, shape and materials of substrates [60] local environmental conditions and water dynamics influenced the transplant success [59]. Preservation of meadow substrate (i.e., dead matter) was confirmed to be a critical element to enable future recovery of *P. oceanica* meadows[61], after pipeline placement in the bay of Majorca (Balearic Sea). It is recognised that these active restoration projects need to consider the time for the succession of ecosystems to develop all trophic levels and biodiversity in order to deliver their full range of ecosystem services [62].

2.2.2. NbS supporting reversal of environmental degradation and biodiversity loss

Restoration of subtidal boulder structures, or shellfish or coral reefs is primarily aimed at the recovery of essential threatened habitats with associated spatial heterogeneity and biodiversity. These interventions, successfully implemented worldwide [24,63–65], provide multiple benefits related to other challenges i.e., food provisioning, maintenance and development of local coastal communities, improvement of water quality and carbon sequestration.

An example is the Laeso Trindel reef project (Kattegat Sea, Denmark) aimed at recovering the local cavernous boulder reef habitat which had been destroyed by extraction of boulders for land constructions. After restoration, economically important fish species spent more time within the habitat than outside, and had greater abundances compared to the same area before the intervention [66,67].

Shellfish restoration is growing in geographic extent and scale globally, motivated by evidence of the widespread decline of these bivalve species [68], and the capacity of restored systems to support the delivery of multiple ecosystem services [69,70]. Around 600 projects were developed in the last decades in North America, Europe, Asia, Oceania and South America [71] targeted at different shellfish species, including 34 bivalves and 15 gastropods, using different strategies, e.g. habitat restoration providing substrata for settlement, supplementation or redistributing of natural recruitment and/or hatchery seed for population/species recovery.

An example of bivalve shellfish restoration at a substrate and recruitment-limited site is the large-scale project realized in Port Phillip Bay, southern Australia, to restore the subtidal oyster and mussel reefs which had collapsed due to overfishing, poor water quality and increased sedimentation [64]. In the US, where a total of 5199 ha of degraded *C. virginica* beds has been restored from 1987 to 2017 [72] mean oyster recruitment was ~12 times higher in restored reefs than in natural reefs, and potential larval output from restored and protected reefs may be six folds larger than natural reefs [73,74].

Shells of bivalve molluscs (*Aequipecten* spp) in the northern Adriatic Sea were tested as biogenic material to reduce heavy metals contamination and improve quality of marine waters and sediments [75]. Various laboratory tests have also shown that the shells of these molluscs, even when crushed, are capable of binding heavy metals (e.g., cadmium), and that, consequently, they can be used for the purification of numerous aqueous matrices, containing metal pollutants, such as for example natural waters contaminated by industrial wastewater [76]. In many countries around the Mediterranean Sea [77], where desalination of seawater is used to produce drinking, irrigation or industrial water, such NbS may also be relevant in relation to long term water security.

These cases suggest that with the use of biomaterials and compounds common in nature the number of ecosystem services can increase, whereas the risk of unforeseen ecosystem hazards can decrease.

2.2.3. NbS supporting disaster risk reduction

The increasing need to protect coastal urban settlements and infrastructures has led to the construction of seawalls and other coastal defences, with detrimental effects on the natural shoreline habitats and consequent loss of species diversity [78] as well as of valuable ecological services [79–81]. Despite the difficulty of restoring original conditions to extremely modified shorelines, the adoption of purposely designed NbS within wider coastal risk reduction strategies could offer coastal protection while enhancing or rehabilitating natural ecosystems[82], e.g., intertidal coral reefs and boulder habitats, and associated ecosystem services e.g., mitigation of climate change, economic and social development, human wellness and food provision [83–85]. This solution was undertaken in the northern part of Grenville Bay, Grenada Isle (Caribbean Sea), where coastal erosion had occurred as consequence of degradation of the natural coral reef. A pilot artificial reef was deployed to provide a stable substrate for coral colonization and facilitate the re-establishment of coral growth and associated ecological functions as an alternative to coastal armouring and conventional breakwaters [86].

The accumulation of *P. oceanica* dead leaves on the beaches of the Mediterranean shores is a natural phenomenon and the so called “banquettes” represent a valuable resource, with important ecosystem functions, including coastal protection against erosion [87] The mechanical removal of the banquette, in Majorca (Balearic Islands), showed a severe impact on the beach profiles, resulting in the erosion of both the “cleaned” beach and the foredune [88]. In Sardinia (Italy), it has been estimated that the removal of the banquette, which can retain an average of 93 kg/m^3 of sediment, can lead to a loss of sediment between 0.5 and 1725 m^3 [89]. Beached leaves of *Posidonia* in the Southern Adriatic Sea have therefore been used as biomaterial to reconstitute and protect degraded dune cords [15]. As an example, approximately 35,000 m^3 of leaf biomass are estimated to accumulate annually in the mouths of the Ugento channels (Puglia, Ugento) and are reused to reconstitute and protect dunes. Finally, *Posidonia* leaves also provide habitat for a variety of organisms (gastropods, crustaceans, annelids and insects) and represent an important input of nitrogen and carbon, contributing to the formation of the dune and its colonization by vegetation [90].

2.3. Type C: NbS which provide novel, restored or deliberately designed artificial marine ecosystems

Type C NbS is generally aligned with Eggermont et al.’s [11] type 3 as it encompasses the introduction of new habitats in the marine environment in order to replace destroyed essential habitats, enhance sustainable food provisioning, reduce risk disasters and mitigate climate change. This type of solution typically addresses multiple issues and provides a range of ecological and societal services.

2.3.1. NbS supporting reversal of environmental degradation and biodiversity loss

One example from the Black Sea relates to the dual challenge of reducing contaminant load and eutrophication both in the water and in the sediments, while recovering the abundance of marine life depleted by illegal trawling. Recognizing the role of filtering organisms (e.g., bivalves) to reduce the contaminant load in the marine environment, the strategy was to deploy artificial subtidal bottom reefs and floating structures for the settlement and development of wild mussel populations, the reefs simultaneously protecting the coastal areas against illegal fishing [91]. The results indicated a substantial improvement of environmental conditions, increase of fish abundance at the reefs and in the coastal areas, and re-establishment of economic and societal services [91,92].

Illegal trawling is widespread in the Mediterranean Sea where it causes loss of essential coastal habitats, increased sedimentation on neighbouring rocky habitats and consequent loss of biodiversity [93]. In addition, it generates inter- and intra-sectorial social and economic conflicts [94]. Purposely designed artificial reefs have been deployed by several countries to prohibit illegal trawling while increasing habitat heterogeneity in flat bottom areas. Next to allowing the re-establishment of the natural soft bottom benthic and fish communities, the artificial structures provided hard surfaces for sessile organisms (e.g., algae, shellfish), while reef-dwelling finfish and macroinvertebrates benefited from enhanced access to food and refuge in the new habitat where some of them established resident populations (e.g., [95–97]).

Another line of interventions has recently been coined ‘greening of grey hard infrastructure’ [98] where e.g., concrete or steel pillars and walls used in harbours, break waters, pipelines, wind farm foundations, are shaped to accommodate better attachment of particular types of organisms and to offer shelter from predation to juvenile fish [82]. For marine wind farms this could include the engineering of scour protection [99], to provide particular complex habitats which e.g., Atlantic cod (*Gadus morhua*) have been found to benefit from in terms of energy conservation, which enhances growth potential [100].

In Mayotte (France, West Indian Ocean), the construction of a 2600 m underwater pipeline in a shallow coral lagoon (MPA), with an extremely sensitive coral reef ecosystem, was permitted according to a set of greening actions to create or restore habitats and biodiversity in the lagoon [101]. Based on the diversity of habitats occurring in the area, two types of modules were used as “green” pipeline weights: the first one was designed to mimic shallow biotopes and create effective habitats for juvenile fish; the second one was planned to mimic deeper biotopes and introduce habitat for adult fish. It is particularly noteworthy that juveniles and adult fish colonized modules just after the end of placement and by incorporating green techniques increased construction costs by less than 1 %.

2.3.2. NbS supporting food security and reversal of environmental degradation and biodiversity loss

Aquaculture, in the different spectrum of aquaculture activities, ranging from extractive to fed aquaculture [102] can be designed as an NbS, in line with the typology 3 of Eggermont et al. [11].

A key example is the cultivation of low trophic species, such as photoautotrophs and filter feeding animals, which could offer NbS to societal challenges such as climate change mitigation [103], adaptation [104], economic and social development [105], mitigation of environmental pressures [106,107] and meet the eight criteria for IUCN global standards [108]. Low trophic aquaculture extracts inorganic nutrients (seaweed aquaculture) and organic nutrients (bivalve aquaculture) and is linked to the enhancement of marine ecosystem services [109,110] including regulating nutrient cycling and carbon storage [70,109]. Recent results include e.g. estimates where a single hectare of bivalve shellfish and seaweed aquaculture where found to remove up to 1 ton of nitrogen, filter up to 25 M gallons of water per day, capture CO_2 in coastal water and increase the abundance of wild fish up to 5 tons per year and provide new habitat value for mobile fish and invertebrates [111]. In eutrophic coastal waters in China, seaweed farming has been estimated to remove large amounts of both nitrogen (75,000 ton in 2014) and phosphorus (9500 ton in 2014), thus abating impacts of inland nutrient pollution at regional scales[107], for the nation who is the largest global producer of seaweed [105]. Similarly nutrient removal provided by line farmed blue mussels (*Mytilus edulis*) in the Danish Limfjord, has been suggested as a relatively cost-effective nutrient mitigation tool [112] to meet environmental policy targets in the EU [106]. Depending on the scale this type of production alters the structural diversity of the habitats, due to the long lines of mussels in the water column, but also provides further ecosystem services, including improving water transparency [113,114].

Integrated multitrophic aquaculture (IMTA), which incorporates marine species from different trophic levels into a single system, has been considered as a mitigation approach to mitigate the excessive quantities of nutrients and organic matter generated by intensive aquaculture [115], providing food biomass. IMTA practices have been developed and are close to being commercially mature in marine temperate waters [115], in China [116], and in Canada [115]. Similarly, innovative IMTA systems are under investigation along the Mediterranean coasts [117], to improve the dual benefits of reduced pollution and increased productivity [118]. As an example, in Italy around 400 t of nitrogen and 30 t phosphorus are extracted by 90.000 ton of farmed mussels (*Mytilus galloprovincialis*), and the N/P budget is integrated with the N/P input from sea bass and sea bream cage farming [119], to provide a net-balance of nutrients input from aquaculture into the coastal environment [120].

Deployment of purposely designed artificial reefs to provide new habitats to reef-dwelling target species and/or manage their life-cycle is widely spread throughout the world. For example, concrete cages to develop wild mussel populations are deployed in the coastal areas of the central and northern Adriatic Sea characterised by eutrophic waters and high abundance of larvae which spontaneously settle on the substrates providing a production of 20–50 kg/m^2 per year [121].

Another example of NbS aimed to provide new habitats for reef-dwelling species is the sea ranching of greenlip abalone (*Haliotis laevigata*) occurring at Flinders Bay, Western Australia (Indian ocean). As marine algae are the primary food source of abalone, the intervention consists of (a) deploying suitable artificial (concrete) habitats that provide shelter for juvenile abalone and surface area for colonisation by macroalgae, (b) seeding the artificial habitats with juvenile abalone from onshore hatcheries once the algal coverage has been developed, and (c) harvesting the shellfish when grown [122].

The construction of artificial habitats to manage and support the entire life-cycle of fish is another example of NbS realized in the Iki Islands (Sea of Japan), where schools of snapper were observed to follow a migratory route coinciding with the propagation of waves inside a bay [123]. The strategy adopted was to place an induction reef at the entrance of the bay to attract adults, a spawning reef where the waves converged, and a nursery reef to improve the survival of juveniles.

Increased growth efficiency for greater food availability and energy saving at the artificial habitats has also been demonstrated for a few commercial fish species, suggesting a contribution to biomass production (e.g., [124–127]) Although these solutions primarily aim to increase food production and sustain the local coastal communities (e.g., [128–130]), they also contribute to provide further services e.g., reduced contamination and organic pollution and mitigation of ocean acidification depending on the environmental features of the site.

2.3.3. NbS supporting climate change mitigation and food security

Marine eco-engineering solutions have been proposed and/or developed to enhance food production and reduce atmospheric CO_2 [131], by providing artificial nutrient rich deep water upwelling in waters where primary production is nutrient limited [132]. Purposely designed artificial reefs (so called “sea mountains”) have been deployed in the open sea to enhance primary production by pressing the lower water masses and nutrients deposited on the seabed up into the euphotic zone [133,134]. This artificial upwelling can enhance overall productivity and create foraging areas for pelagic organisms. Side effects are sustenance of local fishing communities and mitigation of ocean acidification and global warming through the carbon sequestration by phytoplankton.

As a potential greenhouse gas removal technology, wave-powered pumps have in recent decades been tested to induce artificial upwelling [135]. The effect of translocating nutrient-rich deep ocean waters to the surface waters on the growth of phytoplankton and removal of CO2 have been tested in various locations (UK, Japan, Norway, EU and China) and at different scale, but it has remained unproven with a very limited CO2 sequestration potential [136]. Side-effects are still unproven, but studies suggests that this technology could pose threats to fisheries, ecological cycles, and the climate [137,138].

2.3.4. NbS supporting disaster risk reduction

The construction of coastal protection through the introduction of new habitats formed by boulders or oyster shells, used alone or associated with artificial reefs, can represent an alternative approach to the conventional armoured structures. This solution was adopted to restore the seawall along the Seattle’s waterfront which needed to be replaced [139]. A pocket beach replaced riprap armouring, and a habitat bench was added as a shelf to the base of the seawall transforming the site in a public area extensively used for recreational purposes. In addition, incorporation of the new habitats provided refuge for larval and juveniles fish and increased feeding opportunities for juvenile Chinook salmon providing small-scale enhancement for this species [139]. Other examples include the construction of intertidal reefs in the Northern part of the Gulf of Mexico, where artificial modules and oyster shell bags have been used extensively, and with considerable success to restore and stabilise eroding shorelines [140].

2.4. Type D: Nature inspired designs applied in marine environments which reduce environmental pressures

Type D NbS includes technical solutions which adopt a design inspired by nature (sensu Benyus 1997 [141]) to exploit marine nature in ways which are relatively more sustainable than its present alternatives, and supports the reduction of environmental pressures. These solutions are likely easily transferable across environmental contexts or global in impact, and thus not necessarily place-based to the same degree as the other NbS types.

2.4.1. NbS supporting climate change mitigation

Decarbonisation of the transport sector is a climate mitigation goal, both globally and in the EU, where it is highlighted in e.g., the EC’s Green Deal [142]. Benefits are however also expected in terms of reduced pollution beyond greenhouse gasses, such as emissions from diesel engines including NO_x, SO_x and particulate matter [143], which should benefit societal goals related to both human health and reversal of environmental degradation [144]. Here the use of wind, to provide propulsion for cargo ships equipped with sails or flettner rotors [145], could be considered a NbS-like solution. Presently evidence is emerging for substantial fuel savings with a payback period of six years, with 2021 fuel prices [146].

Such solutions may also in the future help periodically reduce the demand for in-water propulsion, which should reduce the pressure on marine life from anthropogenic underwater noise [147].

2.4.2. NbS supporting reversal of environmental degradation and biodiversity loss

Submerged artificial surfaces in marine environments generally experience fouling, which can impact operational performance due to frictional resistance. To reduce negative impacts, such as loss of propulsion on ships, anti-fouling agents are applied, of which some have later been found to have significant negative environmental impacts, such as in the case of tributyltin (TBT) in gastropods [148]. Emerging new types of antifouling agents, based on naturally occurring marine compounds [149] can provide a comparatively reduced environmental pressure on marine biodiversity, while also ensuring energy efficient propulsion [150] and hence averted carbon-based fuel emissions.

Hence, in summary, based on theory and the examples presented in Annex 1 and above, NbS can be classified according to the ecosystem services provided, the stakeholders involved and the level of engineering required. Also, NbS could range from primarily targeting nature conservation with additional societal benefits to addressing societal challenges in a nature inclusive fashion and what constitutes a NbS will be context specific, both in temporal and spatial aspects. The impact of NbS can range from local (coastal defence, building with nature), to regional (restoration of habitats) to global (carbon sequestration, fertilization of oceans). In addition, the (societal) costs and benefits may be distributed between stakeholders in different ways. From the perspective of the fisheries community, the Japanese example of the construction of artificial habitats at the Iki Islands is a case where the fisheries community directly benefits from ecosystem engineering. In many ecosystem restoration examples the benefits are more indirect, with an increase of fish stock levels over time such as for the British example of seagrass restoration in Dale Bay.

From a global perspective, it is also relevant to consider that increased utilisation of marine ecosystems for e.g., renewable energy production, sustainable food production and nature conservation, likely impacts the number of stakes and stakeholders in the marine realm. This enlarged stakeholder community presents a wide range of perceptions of the costs and benefits of NbS. Hence the need to clearly define the concept of NbS and their role, becomes even more important, when considering the demand for structuring e.g., co-creation processes with stakeholders interested in the distribution of societal costs and benefits of various NbS. This aspect should not be underestimated as lack of stakeholder alignment and supporting incentives likely present some of the core risks for long term success of NbS, as highlighted by e.g., [24].

3. Key lessons

Based on the analysis of cases of marine NbS some key lessons are presented here, including their particular relevance from a European perspective.

3.1. Alignment with environmental policies

- While many NbS are likely relevant for reaching specific environmental policy targets, such as ‘Good Environmental Status’ in EU coastal and marine waters, few cases have yet been developed specifically for this purpose. The use of strategic environmental assessments [151] of NbS projects focusing on impacts on descriptors in e.g., the EU Marine Strategy Framework Directive [152] could assist in overcoming this challenge.
- Improvements or changes in the class, quantity or value of both ecosystem services and disservices are often not evaluated. For marine interventions this would be relevant at both sea basin and the local scale where the intervention happens, to align with e.g., sea basin specific plans and conventions, which are often relevant in a European context. This could further help quantify how a specific NbS could support progress towards specific policy targets.

3.2. Prioritization of ecosystem targets

- As NbS can support many types of marine biodiversity and ecosystem services, prioritization appears relevant particularly where trade-offs between ecosystem targets exist. A hierarchy of basic environmental priorities is likely needed to ensure that e.g., threatened or overexploited habitats or species are not sacrificed to support others less urgent biodiversity or ecosystem service priorities.
- Direct improvements in ecosystem conditions can be conceptualised as both short and long term measurable marine ecosystem net gains, understood as restoration of both ecosystem service provisioning and biodiversity (i.e. [37]). However, when marine ecosystem net gains are not feasible, direct reductions in pressures could likely provide equally relevant short term targets for marine NbS.

3.3. Ensuring environmental sustainability of NbS

- To avoid significant burden shifting in terms of where, when, who and how severely people and ecosystems are impacted by interventions, a ‘life cycle’ perspective on impact assessments is likely warranted. For example, impact and performance assessments of the NbS can be assessed through methodologies inspired by classic life cycle assessments (e.g., [153]).
- The NbS’ resilience according to future climate and ecosystem trajectories would here be an embedded feature in the ‘life cycle’ perspective on the NbS.
- NbS which aim to exploit specific ecosystem services (e.g., fisheries, wildlife for nature-based tourism), are not necessarily supported by adequate management plans, which can ensure the sustainability of the NbS. A policy review is therefore advised in the evaluation of proposed NbS, just as the inclusion of relevant stakeholders to understand long term project risks. This should minimise the risks of greenwashing coastal development projects [98].

3.4. Performance of NbS

- While NbS is a relatively new concept, many NbS-like actions have been tested in different forms (e.g., [24]), with some providing long data series [154]. Yet many environmental, social and economic impact categories appear not to have been monitored or at least reported in some cases, making quantitative assessments of performance difficult, for example in relation to the resilience to both environmental and anthropogenic perturbations.

- Future NbS aiming at piloting new or relatively unexplored or undocumented concepts, should be accompanied by consistent monitoring programmes to document short- and long term impacts, to enable evidence-based decision making about where to deploy and how to scale solutions most effectively. This is especially important in those cases where ecosystems are expected to develop by succession to an anticipated climax state. For example, it is highly unfortunate how little monitoring has been prioritised in e.g., North European waters to document broader impacts of wind farms given the recent EU strategy for significant upscaling of offshore wind energy production in the North Sea [155].
- While actions aiming at actively restoring degraded habitats, e.g. type A NbS, are likely an intuitive way of conserving nature, this should not be used a priori to dismiss alternative types of NbS in all situations. For example, in certain contexts, it could potentially be more cost-effective to apply a type C or D NbS to reduce a specific environmental pressure, rather than e.g., restocking a naturally occurring population of animals, seaweed or similar, i.e. a type A or B NbS. However, large scale impacts could likely demand simultaneous deployment of many NbS to reach environmental policy targets at sea basin scale (Fig. 2).

4. Key research questions for marine NbS in Europe

Based on the above analysis of possible lessons, this section provides high level research questions relevant for the development of consistent scientific advice about the potential of marine NbS in different contexts to relevant stakeholders. Similar to terrestrial NbS, marine NbS will likely be motivated by a demand to address large societal challenges, in line with IUCNs scope and several of the targets in the recent EC Blue Economy Strategy. Thus, within the EU increasing demand for costal protection and renewable energy production in light of climate change and aquatic food provision [156,157]is likely going to drive the development and deployment of co-located NbS, and to optimise progress towards multiple policy goals, within confined areas. Examples could include farming of marine species NbSwith low environmental impacts [158], within offshore wind farms with foundations build to restore lost habitat features to conserve threatened species inhabiting such habitats (e.g. Fig. 2).

- *Harvesting present knowledge:* Which present marine NbS-like actions have been monitored sufficiently to allow performance to be evaluated quantitatively and recommendations about efficient application and scaling in support of EU policy targets, and social challenges including in particular climate change mitigation, food security and reversal of environmental degradation which are key priorities in the EU Blue Economy strategy?
- *Choice of NbS*: What type of instrument is needed to evaluate which alternative marine NbS are most desirable from an environmental, social and economic perspective in an EU context, considering the overall demand for alignment with marine policies and the ecosystem approach?

- *Deployment and risk management of NbS*: What type of environmental data collection, policy alignment and degree of stakeholder involvement should be minimum requirements for each type of NBS in EU waters, considering the diversity among ecosystems and stakeholder communities?
- *Impact evaluation*: How should the overall environmental, social and economic sustainability of a marine NbS be monitored, evaluated and communicated both in relative and absolute terms?
- *Investor's perception of marine NbS*: How do investors perceive the potential role of marine NbS in relation to e.g. the new EU taxonomy on sustainable finance, and global focus on science-based nature targets? And what are the major knowledge gaps to cover from an investor perspective?

5. Policy recommendations

In this section the present EU policy approach is addressed through a number of recommended actions, which we necessary to match the EC's ambitions in a marine context.

1) Develop and adopt a more stringent and consistent approach to the implementation of NbS in the Union, which clearly prioritises threatened biodiversity. The approach and target do not need to be identical across terrestrial or marine areas, nor the approach similar for all types of NBS to allow more stakeholders to take an active role.
2) Performance and impact indicators for NbS are relevant to understand the degree of success, but do not replace the need for strict criteria in terms of what the Union accepts (and funds) as NBS, considering the significant variety of potential actions presented for example in this paper. Performance and impact should be aligned with policy targets.
3) Implementation of the EC's approach to NbS should be a core feature of its research and innovation programme Horizon Europe throughout its innovation parts, and not just a subpart of its climate or biodiversity focused programme.
4) Develop and adopt components of NbS where possible in litigation requirements for new marine constructions or decommissioning of present ones. Request member states to report on progress towards this to facilitate learning.
5) Use the annual 'EU Blue Economy Report' by the EC [159] to assess the specific marine and maritime sectors' potential for adopting NbS, and deliver guidance for implementation supported by the recent EU Knowledge Centre for Biodiversity and the European Environmental Agency.

6. Conclusions

The European Union has a unique opportunity to spearhead deployment of NbS worldwide, enabled by the conceptual development provided by the IUCN in particular. Yet, the EU's own approach to date could presently endanger the effectiveness of actions under the NbS umbrella due to the vagueness of requirements to actions labelled as such. This is not only a concern for marine scientific advisory institutions, but should also be for the wider EU financial community as NbS have been given a central role e.g., in implementation of the EU Taxonomy on sustainable finance, and are likely to be among the key instruments to reach 'net positive biodiversity impacts' which are now a proclaimed target among some of the largest global renewable energy developers [160].

Nonetheless, it is not suggested to adopt the IUCN's strict requirements for NbS as it will likely exclude many key stakeholders, who will be needed to deliver the transformational change which e.g., IPBES [161] emphasises is needed to halt present loss of biodiversity. Following the launch the Blue Economy Strategy, which also emphasises the deployment of NbS and the upcoming legally binding EU nature restoration law, the EU is encouraged to develop its own criteria, in accordance with other ecosystem specific policies such as the Marine Strategy Framework; Marine Spatial Planning; and Habitat Directives which should provide multiple relevant environmental targets to embed in a marine NbS frame, advancing a new level of ecosystem-based management.

Coastal waters, shelf and open oceans present multiple options for testing new and scaling up known NbS, which could support both environmental restoration simultaneously with supporting climate adaptation/mitigation benefits and the Blue Economy. However, as the acceptance of NbS types will depend on ecosystem state and thus history, it will be a significant task to consistently communicate why some solutions may count as a NbS in some areas, while not in others.

Finally, in order to succeed with its ambitions, the EC is encouraged to embed NbS in research areas beyond classic biodiversity topics in its research and innovation programmes, to ensure awareness, understanding and uptake across the large and diverse stakeholder landscape necessary for such broad societal agendas.

Author statement

The authors declare they have no competing interests to declare.

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Appendix A. Supporting information

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