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DAPSI(W)R(M) put into practice for a nature-based solution: Framework applied to the coastbusters approach

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ABSTRACT

Nature-based Solutions (NbS) can be applied to alleviate negative human impacts on ecosystems and promote the general health or well-being of the environment. Human-induced activities, including installation of NbS, are governed by legislative requirements (e.g. Environmental Impact Assessments (EIA)), especially when such activities occur in Marine Protected Areas (MPA's). A correct and thorough description of the legislative framework governing the application and development of NbS is therefore essential. The Drivers-Activities-Pressures-State change-Impacts (on human Welfare)-Responses (using Measures) or DAPSI(W)R(M) framework is valuable when environmental assessment procedures include a NbS, as well as when policy and industry require guidance for the practical application of a NbS concept. In this study, we applied the DAPSI(W)R(M) framework to the *Coastbusters* approach, in which mussel beds (*Mytilus edulis*) and tubeworm aggregations (*Lanice conchilega*) are installed in the Belgian part of the North Sea with the aim of improving coastal resilience and maritime infrastructure works. Within the context of the *Coastbusters* approach, the various elements of the DAPSI(W)R(M) framework were elucidated. Coastal defense is a driver, with activities including the integration of coastal infrastructure and aquaculture practices. Pressures related to these activities on benthic habitats were described using the MarESA sensitivity approach. State change assessments were performed based on the various marine regulations (e.g. Marine Strategy Framework Directive, Habitat Directive, Water Framework Directive) which together outline a precise set of criteria and indicators designed to assess the sustainability and health of ecosystems. The present study provides a detailed framework for the environmental evaluation of seaward NbS, from state changes to impacts on human welfare. Three quantitative estimations of ecosystem service indicators (coastal protection, carbon retention and water quality (N) regulation) were used, with the indicators quantified by in-situ measurements and data from literature. Subsequently, the 10-tenets approach for taking measures (e.g. use of biodegradable material, local species, etc.) was used to develop responses that facilitate the optimal implementation of NbS. The approach outlined in this study can be used as a guide for stakeholders as they move through the environmental evaluation processes that are required for successful development of a seaward NbS. Our results underscore the importance of a favorable institutional environment for NbS and suggest that public acceptance and stakeholder involvement play a crucial role in successful implementation. This study contributes to the understanding and operationalization of Nature-based Solutions in coastal management.

1. Introduction

Soft-sediment coastal ecosystems are vulnerable to a diversity of pressures [1]. Coastal resilience measures are increasingly required as sandy coastal zones are under threat due to climate change (sea level rise, intensification of storms, increasing beach erosion) [2,3] as well as increasing anthropogenic pressures (demographic evolution, loss of habitats, economic expansion) [4]. The combination of threats to these ecosystems significantly reduces the resilience of coastal areas. Current engineering approaches to coastal protections, which include both hard and soft measures, fall short in terms of efficiency as well as cost-effectiveness [5,6]. A recent IPCC report [1] shows that adaptation

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to climate change largely depends on society's ability and willingness to anticipate the change, recognize its effects, plan to accommodate its consequences [7,8] and implement a coordinated portfolio of informed solutions. New sustainable approaches for a resilient coastline, that is a coastline capable of withstanding and recovering from disturbances, must be developed to safeguard the economic, ecological and societal assets of these soft-sediment coastal ecosystems.

An emerging approach [9] offers an alternative to the traditional "grey infrastructure" approach [10] by adopting measures that mimic the complex features and processes of natural ecosystems: "Nature-based Solutions" (NbS) [11,12]. The strength of NbS is the integrated approach to addressing societal challenges. By definition, ecosystem services (ES) are the contributions that ecosystems (in combination with other inputs) deliver to support human well-being [13]. NbS operationalizes the concept of ES in real-world situations, generating an explicit way of promoting sustainability [12,14]. The concept of NbS has gained ground across diverse stakeholder communities, including science, practitioners, civil society, and the business sector. The United Nations Environmental Programme (UNEP) defines NbS as "*actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits*" [15]. Other concepts and practices under the NbS umbrella include concepts such as Ecosystem-based Approach (EbA), Ecosystem-based Disaster Risk Reduction (Eco-DRR), Green-Blue Infrastructure (GBI) and others [16,17].

1.1. Embedding a NbS into the legislative framework

To ensure the successful deployment of NbS and their integration into existing national policy frameworks, the European Commission is aligning the R & I agenda on NbS with several European Union (EU) policies and actions that support the implementation of an Ecosystem-based Approach (EbA) [18,12]. Davies [19] found that NbS are currently not well integrated into existing policy frameworks. This is mainly because policies at different levels do not always match between municipal, regional, national and transnational policies and regulations [20,21]. Furthermore, [22] reports that the use of seaward NbS for coastal resilience is relatively unexplored in terms of practice and planning, notwithstanding extensive documentation [27] of the ecosystem services delivered by coastal ecosystems such as kelp forests [23], seagrass meadows [24], offshore reefs [25] and mussel beds [26]. As stated in The United Nations Environment Assembly (UNEA) Resolution 5/5, the intergovernmental consultation should "*further support the implementation of Nature-based Solutions*" [15]. Future implementation of NbS in agreement with the multilaterally agreed definition of NbS will require intergovernmental consultations (EU and non-EU) to agree on international standards and operational principles/guidelines for NbS implementation, as well as an assessment framework with criteria and indicators to support effective evaluation of a NbS [28]. The legislative framework in which NbS will need to operate is also important, as human-induced activities are mostly subjected to legislative requirements (e.g. Environmental Impact Assessments (EIA)), especially when those activities occur within Marine Protected Areas (MPA).

The conceptual framework(s) required depend on the issue to be addressed, the stakeholders involved and available knowledge. Due to the diversity and complexity of coastal zone situations, there is no "one size fit all" framework to improve coastal resilience [22,29] using a NbS. Many frameworks have been extensively analyzed and utilized, e.g. Social-Ecological Systems (SES), Ecosystem Services Assessment (ESA), Driver-Pressure-State-Impact-Response (DPSIR) framework. Certain key frameworks having varying degrees of operational implementation within the EU and each framework is applied only in specific contexts. This variety furnishes policymakers with a range of potential options, allowing them to choose the most suitable framework for a given situation. In practice, these frameworks are all part of systems theory and can be used together. For example, the ESA framework is often considered necessary for understanding SES, and the DPSIR approach includes some processes that explain SES dynamics [22].

The DPSIR conceptual framework [30,31] is an environmental management concept, with its broadest form being the DAPSI(W)R(M) or Drivers-Activities-Pressures-State change-Impacts (on human Welfare)-Responses (using Measures) [32]. The strength of this framework is how it can reveal the fundamental relationships between societal and environmental factors. This makes it valuable for communication purposes, such as discussion among researchers across diverse disciplines, between researchers and policymakers, and communication with stakeholders (science, policy and industry). It can be combined with other frameworks, methods or models [33,34] and is thus useful in an operational decision context, even when scientific evidence is lacking [32,35,22]. The DAPSI(W)R(M) framework is used in this study to encapsulate the complex EU legislative landscape and visualize the background of activity-pressure-state evaluation requirements and societal benefits of NbS for a variety of stakeholders. Several main EU legal instruments are relevant to the coast, such as the 2030 Biodiversity Strategy (COM/2020/380 final, 2020) [36], the EU Habitats (1992/43/EC) [37] and Birds Directive (2009/147/EC) (Natura 2000 network) [38], the Environmental Impact Assessment (EIA; 2011/92/EU) [39] as amended by 2014/52/EU), the Water Framework Directive (WFD; 2000/60/EC) [40] and the overarching EU Marine Strategy Framework Directive (MSFD; 2008/56/EC) [41] and the Marine Spatial Planning Directive (MSPD, 2014/89/EU, 2014) [42]. They all have the goal of ensuring sustainable use of the environment promotion of healthy ecosystems. The EU Natura 2000 network, a MPA network, aims to conserve biodiversity by creating protected areas across Europe designated to safeguard habitats and protect the species listed in the EU Habitats and Birds Directives. Each EU Directive encompasses a tailored set of criteria and indicators that serve primarily to evaluate the sustainability and overall health of the ecosystem. This offers and thorough and accurate assessment of the ecological well-being and long-term viability of the environment. These assessments are coordinated via the Integrated Maritime Policy (IMP, COM/2007/575 final, 2007) [43]. In addition, the European Green Deal (COM/2019/640 final, 2019) [44], European Climate Law (EU 2021/1119, 2021) [45] and 2030 Biodiversity Strategy (COM/2020/380 final, 2020) [36] are all relevant for coastal resilience and also provide a link to international legislation [22].

1.2. The research case: the coastbusters approach

The *Coastbusters* approach is to introduce Nature-based Solutions (NbS) in relation to Ecosystem-based Approaches (EbA) to coastal resilience and infrastructure works in the marine environment. Specifically mussel beds (*Mytilus edulis*) and Tubeworm aggregations (*Lanice conchilega*) are installed in the Belgian Part of the North sea (BPNS) (Fig. 1). These solutions are appropriate for temperate regions characterized by turbid waters and sandy beach coastlines. The *Coastbusters* (2020–2023) public-private innovation partnership is comprised of three private partners (Dredging International (DI), Jan De Nul (JDN) and Sioen Industries (SIOEN) and two scientific research institutions (Flanders Research Institute for Agriculture, Fisheries and Food (ILVO) and Flanders Marine Institute (VLIZ)). In 2021 they deployed several reef-facilitating systems meant to induce biogenic mussel bed formation, including a novel design named the mussel shaker (Fig. 2). This methodology was tested in different dynamic nearshore coastal environments (sheltered and exposed sites; red dot in Fig. 4) as a basis for the development of a full-fledged, nature-inspired coastal protection measure [46,47,48]. The *Coastbusters* site is located in the *Abra alba* community (benthic habitat), according to the habitat suitability map; L. *conchilega* aggregations are a specific habitat feature within the *Abra alba* community [49]. The *Coastbusters* project resulted in the successful creation

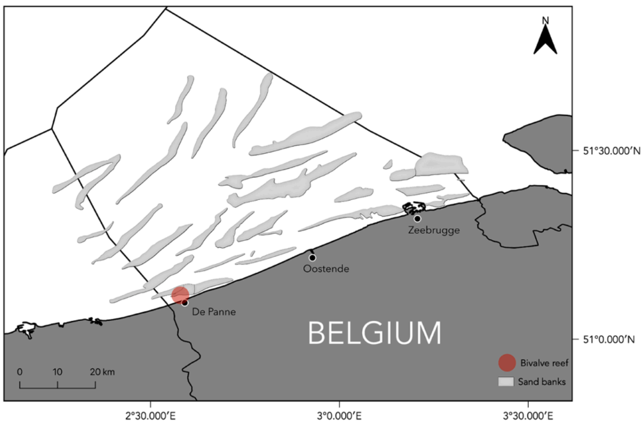

Fig. 1. Location of the *Coastbusters* site in the BPNS (© Goedefroo Nanou) (red dot) located in the benthic habitat of *Abra alba* with aggregations of *Lanice conchilega* [49].

of mussel bed patches in the sandy environment, using several reef-facilitating systems such as an aquaculture longline system and a mussel shaker (Fig. 2).

2. Dapsi(W)R(M) conceptual framework

Determination and assessment of the link between human pressures and state changes in marine and coastal ecosystems is challenging. Several existing conceptual frameworks have been developed to describe these links, the DAPSI(W)R(M) provides the most accurate and complete information [50,51] (Fig. 3). The essence of DAPSI(W)R(M) is to link the natural and social systems required for the EbA. In other words, the aim is to protect and maintain the natural system so it can provide ES, which then help to deliver societal goods and benefits [35].

The term ‘driver’ refers to the basic human needs such as food, shelter, security, and material goods. To obtain these, society performs activities which in turn create pressures (defined as mechanisms that result in a positive or a negative effect). When the natural system (the physico-chemical and ecological system) is subject to one of these effects, the term ‘state change’ (e.g. change in functioning of the system) is used to separate these effect from ‘state’ (a description of the characteristics at any given time). State changes in marine environments encompass alterations to the substratum, the water column and their constituent biota. Such effects on the natural system may result in a change on human welfare and on the ES that ultimately produce societal benefits [53]. Such changes require a response in the form of a measure such as economic and legal instruments, technological devices, remediation agents, and societal desires [54]. In the present study the DAPSI (W)R(M) framework was applied to evaluate which criteria and indicators were applicable to the Belgian implementation of the various EU environmental regulations, and were thus useful to evaluate the added value of the *Coastbusters* approach (Fig. 4). The *Coastbusters* activity is to install an aquaculture based coastal infrastructure and introduce NbS for coastal defense purposes. Here, coastal defense is the primary driver. Pressures resulting from this activity are hydrological changes (inshore/local), physical loss (permanent change), physical damage (reversible change), physical pressure (other), pollution, and other chemical changes (see Table 1). For each of those pressures, the sensitivity of the main benthic habitats present around the *Coastbusters* site was listed and summarized (see Annex Table 6, 7 and 8).

The link between the relevant EU legal instruments implemented in Belgium was established in order to assess the state change of the marine habitats. This was accomplished by using the criteria of the Directives and indicators (e.g. the BEQI tool-Benthic Ecosystem Quality Index to assess the ecological quality of benthic ecosystems) (Table 2) as well as evaluating changes to the natural environment resulting from the multiple pressures described. We expanded the assessment by including social concerns as well, owing to the lack of recent and specific information on societal attitudes about NbS [55,76]. A practical set of ecosystem service indicators is suggested as a proxy of the impact on human welfare. To safeguard the ecosystem features, functioning, and ES, a response may be needed in the form of management measures. Measures are indicated to prevent or mitigate possible changes and/or impacts resulting from deployment of the *Coastbusters* approach. Each component of the framework is outlined in more detail below and summarized in Fig. 4.

2.1. Driving forces (D)

The driving forces behind the *Coastbusters* approach are rooted in fundamental basic human needs, namely physiological necessities like food, water, and shelter, followed by safety needs such as security and protection [56]. The DAPSI(W)R(M) framework accounts for both economic welfare and psychological well-being ([35] adapted from [56]).

The *Coastbusters* NbS concept addresses a range of human needs. First, it fulfills the primary need of coastal defense and protection by introducing key species (mussels and Tubeworms) that can help to stabilize coastal sediments and prevent sand loss. Better coastal resilience also may safeguard the safety of the human inhabitants of coastal communities. Furthermore, seaward NbS offer potential to realize the ambitious targets related to conservation, biodiversity and climate mitigation by contributing to the active restoration and protection of Marine Protected Areas (MPA’s) while simultaneously enhancing coastal resilience [57,58]. Additionally, the *Coastbusters* approach caters to secondary needs by facilitating resource utilization, for example harvesting mussels from the aquaculture installation for food. On a larger scale, the *Coastbusters* approach can address macro-economic needs by promoting multiple uses of marine/coastal space. Moreover,

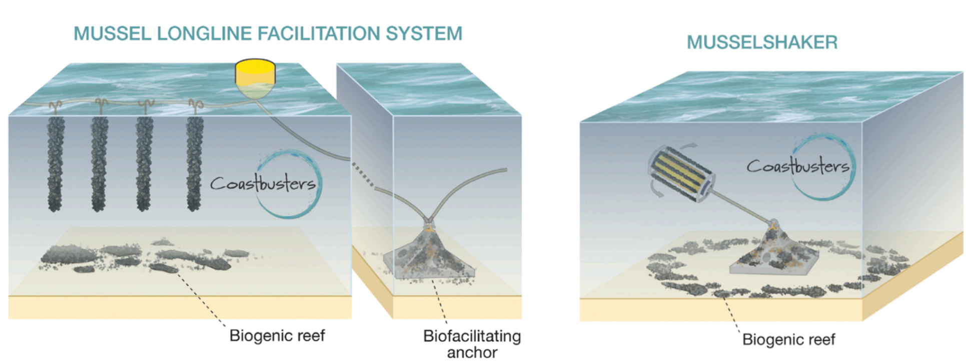

Fig. 2. Graphical original representation of an aquaculture longline system with vertical hanging dropper lines meant to induce a biogenic reef on the seafloor (left) with bio-facilitating anchor to anchor the installation on the seabed (middle) and original design of the mussel shaker used during the *Coastbusters* project (right) [48]. The mussel shaker combines a bio-facilitating anchor with a vertical buoy surrounded by dropper lines (© Coastbusters).

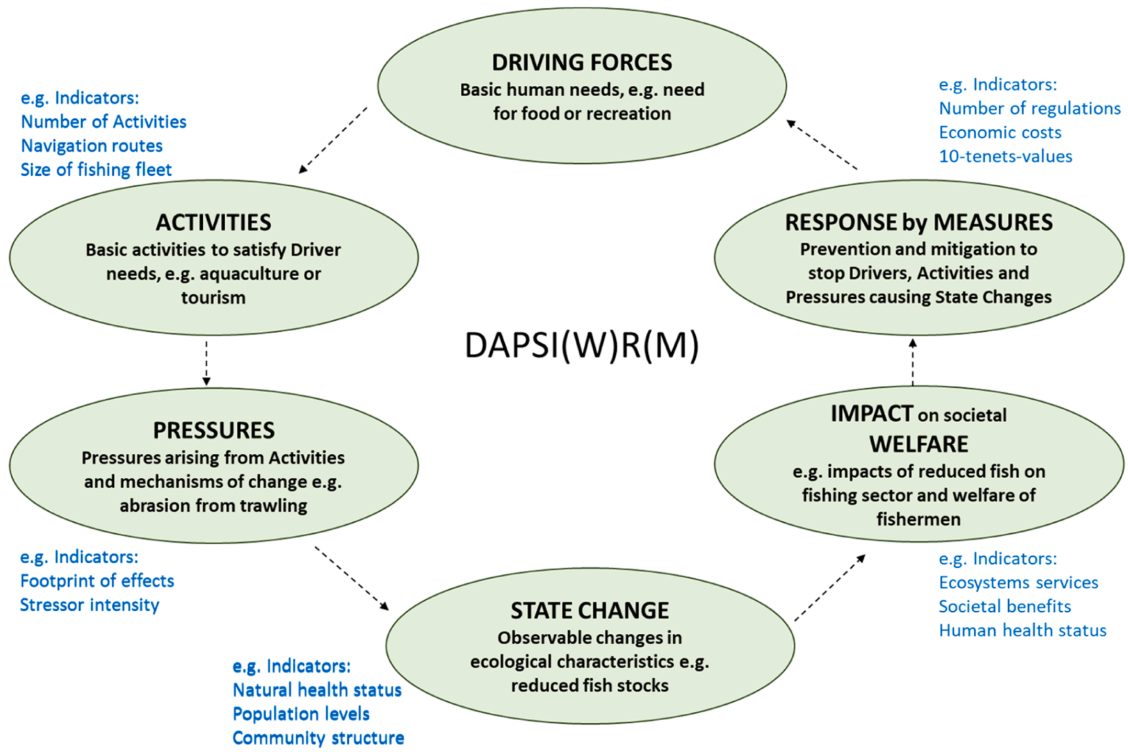

Fig. 3. DAPSI(W)R(M), the most evolved version of DPSIR (as defined in [51] by [32]). Examples of indicators for each element of the DAPSI(W)R(M) framework were added (as shown in [52]). For a more detailed visualisation of the interactions, we refer to the more comprehensive scheme in [99].

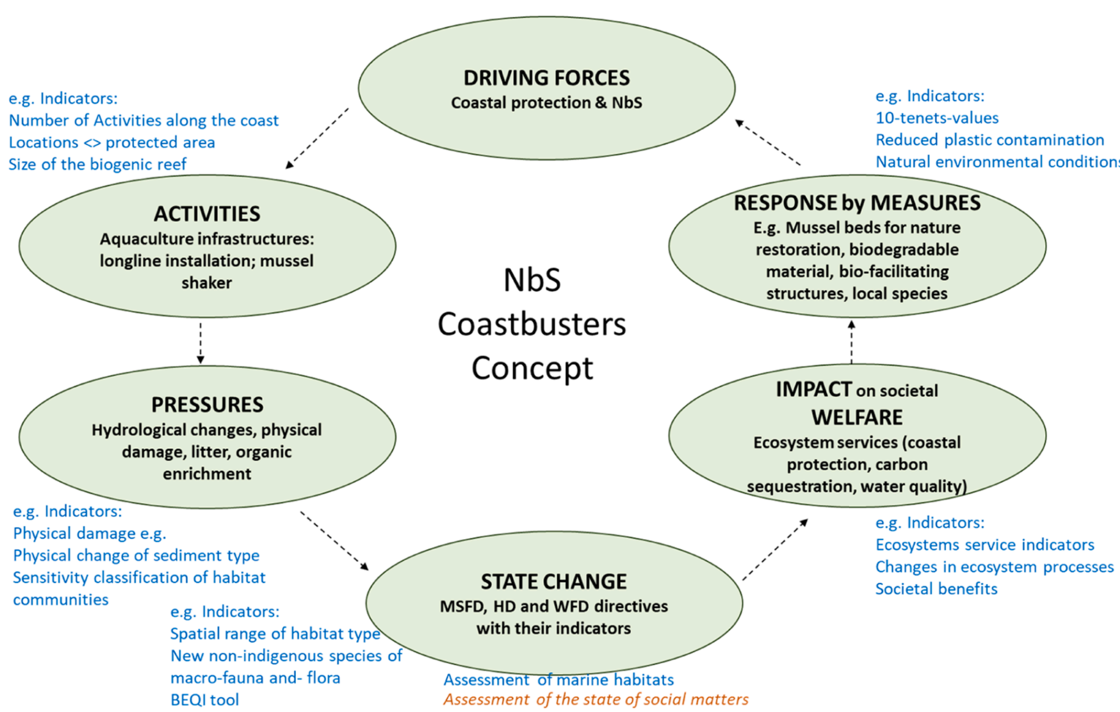

Fig. 4. DAPSI(W)R(M) applied to the NbS of enhancing a biogenic reef using the *Coastbusters* approach; indicators are added for each element (as shown in [52]). The activity involves using aquaculture-based coastal infrastructure, with coastal defense as a driver. Resulting pressures include physical damage and other pressures. The sensitivity of benthic habitats to these pressures is addressed. Links to relevant EU legal instruments (MSFD - Marine Strategy Framework Directive, HD - Habitat Directive and WFD - Water Framework Directive) are made to assess the state change of marine habitats as well as that of social matters [55]. A set of ecosystem service indicators is suggested to assess the impact on human welfare. Management measures are recommended to prevent or mitigate impacts or to safeguard ecosystem features and functions.

it could foster tourism by offering opportunities for water-based recreational activities like diving, which would stimulate local economies. In the industrial sector, the *Coastbusters* approach supports innovation and growth by installing new aquaculture installations, developing new techniques, and introducing advanced materials. This not only reinforces existing industries but also opens perspectives for emerging

Table 1

Summary table of pressures and their benchmarks for the *Coastbusters* approach: The marine pressures used in the MarESA approach are based on the pressure definitions developed by the OSPAR Intersessional Correspondence Group on Cumulative Effects (ICG-C) – Amended 25th March 2011, the MarESA guidance document [61] and climate change related pressures [65]. (https://www.marlin.ac.uk/sensitivity/SNCB-benchmarks) *Pressure Benchmark: The standard descriptor of the pressure defined in terms of the magnitude, extent, duration and frequency of the effect. Benchmarks may be quantitative or qualitative [70]. Comment in table, is taken from MarLIN website to highlight shortcomings or thoughts of the developers, which we also find relevant to mention here.

Pressure Theme	ICG-C Pressure	Benchmark	Pressure description
Hydrological changes (inshore/ local)	Wave exposure changes- local	A change in nearshore significant wave height >3% but <5% for one year	Local changes in wavelength, height and frequency. Exposure on an open shore is dependent upon the distance of open sea water over which wind may blow to generate waves (the fetch) and the strength and incidence of winds. Anthropogenic sources of this pressure include **artificial reefs** that can directly influence wave action or activities that may locally affect the incidence of winds. *Comment*: Further research is required on the correlation between significant wave height and wave exposure scales.
	Water flow (tidal current) changes – local (including sediment transport considerations)	A change in peak mean spring bed flow velocity of between 0.1m/s to 0.2m/s for more than 1 year	Changes in water movement associated with tidal streams prevailing winds and ocean currents. The pressure is therefore associated with activities that have the potential to modify hydrological energy flows. The pressure extremes are a shift from a high to a low energy environment (or vice versa). The biota associated with these extremes will be markedly different as will the substratum, sediment supply/transport and **associated seabed/ ground elevation changes**. The potential exists for profound changes (coastal erosion/deposition) to occur at long distances from the construction itself if an important sediment transport pathway was disrupted. As such these pressures could have multiple and complex impacts associated with them. The pressure will be spatially delineated.
Physical loss (permanent change)	Physical change (to another seabed/ sediment type)	**Benthic species/habitat** Change from sedimentary or soft rock substrata to hard rock or artificial substrata or vice-versa	**The permanent change of one marine habitat type to another marine habitat type, through the change in the substratum, including to artificial** (e.g. concrete). This, therefore, involves the permanent loss of one marine habitat type but has an equal creation of a different marine habitat type. Associated activities include the installation of infrastructure (**coastal defenses**), **creation of artificial reefs, mariculture, i.e. mussel beds**. Comment: This pressure assumes a permanent change, while short-term smothering of substrata with sediment is addressed under **smothering** (siltation).
Physical damage (reversible change)	Changes in suspended solids (water clarity)	A change in one rank on the WFD (Water Framework Directive) scale e.g. from clear to intermediate for one year	**Changes water clarity (or turbidity) due to changes in sediment & organic particulate matter and chemical concentrations**. It is related to activities disturbing sediment and/or organic particulate matter and mobilizing it into the water column. Particle size, hydrological energy (current speed and direction) and tidal excursion are all influencing factors on the spatial extent and temporal duration. Salinity, turbulence, pH and temperature may result in flocculation of suspended organic matter. *Comment*: **from <u>turbid</u> to intermediate (suspended solids) for one year or more.**
	Abrasion/disturbance of the substratum on the surface of the seabed	**Benthic species/habitat** Damage to seabed surface features (species and habitats)	Physical disturbance or abrasion at the surface of the substratum in sedimentary or rocky habitats. The **effects are relevant to epiflora and epifauna living on the surface of the substratum**. In the sublittoral, surface abrasion is likely to result from chains associated with fixed gears and **moorings, anchoring** of recreational vessels, **objects placed on the seabed** or of epifaunal species (e.g. oysters) **epifaunal biogenic reef communities**. Activities associated with surface abrasion can be relatively localized activities e.g. seaweed harvesting, recreation, potting, and **aquaculture**.
	Penetration and/or disturbance of the substratum below the surface	**Benthic species/habitats** Damage to sub-surface features (e.g. species and physical structures within the habitat)	**Physical disturbance of sediments where there is limited or no loss of substratum from the system**. This pressure is associated with activities such as **anchoring, taking of sediment/geological cores**, propeller wash from vessels and certain fishing activities. Activities associated with abrasion can cover relatively large spatial areas and include fishing with towed demersal trawls (fish and shellfish); bio-prospecting such as harvesting of biogenic features. After extraction, conditions for recolonization remain suitable for relatively localised activities including seaweed harvesting, recreation, potting and aquaculture.
	Smothering and siltation rate changes (depth of vertical sediment overburden)	**Benthic species/habitat** “Light” deposition of up to 5 cm of fine material added to the habitat in a single, discrete event	**When the natural rates of siltation are altered (increased or decreased).** Siltation (or sedimentation) is the settling out of silt/ sediments suspended in the water column. Activities associated with this pressure type include **mariculture** and various construction activities. It can result in short-lived sediment concentration gradients and the accumulation of sediments on the seafloor. This accumulation of sediments synonymous to **“Light” smothering relates to the deposition of layers of sediment on the seabed. Most benthic biota may be able to adapt, i.e. vertically migrate through the deposited sediment.**

(*continued on next page*)

Table 1 (*continued*)

Pressure Theme	ICG-C Pressure	Benchmark	Pressure description
Physical pressure (other)	Litter	**Benthic species/habitat** Introduction of man-made objects able to cause physical harm (surface, water column, sea floor and/or strandline)	Marine litter is any manufactured or processed solid material from anthropogenic activities discarded, disposed or abandoned (excluding legitimate disposal) once it enters the marine and coastal environment including plastics, metals, timber, rope, fishing gear, and their degraded components, microplastic particles. Ecological effects can be physical (smothering), biological (ingestion, including uptake of microplastics; entangling; physical damage; accumulation of chemicals), and/or chemical (leaching, contamination). Comment: **We are not aware of any evidence on the effects of "litter" on benthic marine species.** While there is documented evidence of the accumulation of microplastics in some species, no ecological effects have been shown to date. The only exception is the effect of ghost fishing on large crustaceans (crabs, etc.). Therefore, the sensitivity to litter is not assessed for habitats and was scored "No evidence" by [63] [64]. Clearly, it is relevant for large macrofauna such as fish, birds and mammals.
Pollution and other chemical changes	Organic enrichment	A deposit of 100gC/m2/year	Resulting from the degraded remains of dead biota and microbiota (land and sea); **faecal matter** from marine animals; flocculated colloidal organic matter and the degraded remains. **Organic matter** can enter marine waters from **aquaculture**. Organic enrichment may lead to eutrophication (see also **nutrient enrichment**). Adverse environmental effects include deoxygenation, algal blooms, changes in community structure of benthos and macrophytes. Comment: Direct evidence on the effect of organic enrichment was used to make sensitivity assessments by [63] [64]. In the absence of direct evidence, reference was made to the AMBI index, supplemented by any other relevant evidence on the effects of organic enrichment on habitats.
	Nutrient enrichment	Compliance with WFD criteria for good status	Increased levels of the elements nitrogen, phosphorus, silicon (and iron) in the marine environment compared to background concentrations. **Nutrients can enter marine waters by natural processes** (e.g. decomposition of detritus, riverine, direct and atmospheric inputs) or anthropogenic sources (e.g. **aquaculture**, atmospheric deposition). Nutrient enrichment may lead to eutrophication (see also organic enrichment).

technologies. This approach can also greatly aid food security by combining aquaculture facilities with passive fishery practices (e.g. pots for crabs and/or *Sepia* spp. fishery). By generating additional employment opportunities, *Coastbusters* would contribute to economic vitality and social well-being. Lastly, the *Coastbusters* approach is committed to ensuring the environmental sustainable management and preservation of coastal ecosystems through the application of NbS. As this approach addresses a wide range of societal and economic needs, *Coastbusters* holds great potential as a comprehensive and adaptive solution for sandy coastal areas.

2.2. Activities (A)

The activities related to the *Coastbusters* approach, coastal infrastructure and aquaculture activities were selected from the list of activities presented previously [35], that paper contains a wider set of activities related to the coastal and marine environment (adapted from [59]). This development of coastal infrastructure involves a range of operations including the creation of biogenic reefs, building barrages, constructing groynes, and implementing measures such as removal of space and substrata such as the construction of sea walls or breakwaters. Additional operations related to aquaculture practices are tasks such as management of shellfish harvest.

The basic activities required to implement the *Coastbusters* NbS approach (creation of biogenic reefs) are implemented by the installation of an adapted aquaculture installation (in 2018), and through implementation of an innovative design, the mussel shaker (in 2021) (Fig. 2). The principle behind both installations is the same: they both use drifting structures with dropper lines to facilitate the growth of mussels, which drop at certain times and establish biogenic reefs on the seafloor. The longline structure consists of anchoring the aquaculture installation on both sides by preferable bio-facilitating anchors, linked by a main horizontal backbone with vertically hanging dropper lines [46,47,48]. The mussel shaker is a vertical buoy surrounded by dropper lines anchored to a single bio-facilitating anchor. The bio-facilitating anchors used in the *Coastbusters* project were pyramid-shaped concrete blocks with holes.

2.3. Pressures (P)

2.3.1. Pressure classification

Pressures have been defined as "the mechanism through which an activity has an effect on any part of the ecosystem" [32,60]. Pressures can be physical, chemical, or biological. The nature of the pressure is determined by activity type, intensity, and distribution. Pressures that result from one or more of the abovementioned activities reflect the mechanisms of change and can result in changes to the natural environmental system (state changes) and subsequently the social system (impacts (on human welfare)) [35]. To link the pressures with the possible impact on the environmental system, a sensitivity classification can be used that reflects the resistance/resilience of the ecosystem to any given pressure. The MarLIN network (Marine Life Information network) (*www.marlin.ac.uk*) represents the largest review of the potential effects of human induced pressures and natural events on marine and coastal habitats. It is the most comprehensive sensitivity classification for assessing a wide range of pressures in the EU. This makes it a relevant source for determining the sensitivity of our habitat features to these pressures. The sensitivity of selected habitats in the MarLIN network is based on the MarESA approach (Marine Evidence based Sensitivity Assessment) (*https://www.marlin.ac.uk/sensitivity/sensitivity_rationale* [61]). The MarESA sensitivity assessment involves a systematic process to examine the biology or ecology of a feature, compile the evidence of the effect of a given pressure on the feature (species or habitat), assess the likely sensitivity of the feature to the pressure against standard scales, document the evidence used, and justify assessments made. The applicability of this MarESA approach has been proven by selecting the major pressures caused by the *Coastbusters* approach and determining the sensitivity of the selected habitats to these pressures at the Belgian study site.

The major pressures and their descriptions (hydrological changes (inshore/local), physical loss (permanent change), physical damage (reversible change), physical pressure (other), pollution and other chemical changes) defined as relevant for the *Coastbusters* approach are summarized in Table 1. The pressure benchmarks are designed to provide a "standard" level of pressure, against which resistance and resilience, and hence sensitivity, can be assessed. The pressure benchmarks were based on [62] and were subsequently revised by [63,64] in liaison with the SNCBs (Statutory Nature Conservation Bodies), Defra and Marine Scotland with additional climate change-related pressures developed in 2019 [65]. The pressure and benchmark list are subject to change but full details of their interpretation and application to MarESA sensitivity assessments are given in the MarESA guidance document [61]. Furthermore, the "pollution" or "contaminant" pressure definitions were revised in 2022 [66]. This exercise illustrated that the MarESA sensitivity assessments are a good source to summarize the pressures related to the *Coastbusters* activities and estimate the species/habitat sensitivity to those pressures.

2.3.2. Sensitivity classification of the main benthic habitat features

The MarESA sensitivity approach for the sensitivity classification has been applied to benthic species and habitats in the near vicinity of the *Coastbusters* site. The approach defines "sensitivity" as a product of: the resistance (likelihood of damage due to a pressure) and resilience (recoverability once the pressure has abated or been removed). These scores are combined to give an overall sensitivity score [61]. In other words "*a species (population) is defined as very sensitive when it is easily adversely affected by human activity (low resistance) and recovery is only achieved after a prolonged period, if at all (low resilience or recoverability)*" [67,68].

The *Coastbusters* site is located in the *Abra alba* community according to the habitat suitability map; L. *conchilega* aggregations are a specific habitat feature within the *Abra alba* community [49]. The *Coastbusters* approach also contains the ambition to create a *M. edulis* habitat.

Those habitats and species are therefore assessed for their sensitivity (see annex Table 6 for *M. edulis*, Table 7 for L. *conchilega* and Table 8 for *A. Alba* community) to the defined pressures (Table 1). The sensitivity classification evaluation of the three main benthic habitat features located in the *Coastbusters* site reveals that all three communities have a high sensitivity for the pressure of physical loss (permanent change) due to physical change to another seabed or physical change of sediment type. *M. edulis,* in contrast, is not sensitive in general, nor is it sensitive to the physical change of sediment type. It can colonize a wide range of hard and sedimentary habitats, thus a change in substratum type would therefore not necessarily reduce its habitat quality. For the other benthic habitat types (L. *conchilega and A. Alba*), which do not occur on artificial substrata or rock habitats, any substratum other than the sediments (medium to very fine sands) could lead to a reduction in habitat suitability and population loss. Furthermore, except L. *conchilega*, all communities have a medium sensitivity for the pressure of physical damage (reversible change) by abrasion/disturbance of the substratum on the surface of the seabed, by penetration and/or disturbance of the substratum below the surface and by smothering and siltation rate changes (depth of vertical sediment overburden). Several features make L. *conchilega* more resilient: it has robust, flexible tubes and may retract below the surface. The individuals are also able to rapidly rebuild or repair tubes [69]. These characteristics reduce exposure to these pressures and enhance recovery.

Moreover, attention should be given to the materials used for the aquaculture installation. Components of longline systems, such as ropes and buoys, are often made from plastic or synthetic materials. These can break down over time or be lost during storms. Lost or degraded materials can contribute to marine litter, entangle wildlife, and release microplastics into the marine environment. A sensitivity evaluation of litter for the 3 benthic habitats by the MarESA approach was lacking due to the absence of tangible effects of litter to benthic habitats. For the other evaluated pressures, a low to medium level of sensitivity was observed.

2.4. State change (S)

2.4.1. Environmental concerns

Within the DAPSI(W)R(M) framework, state changes relate to changes in the natural environmental system as a result of a single or multiple pressures (Table 1), especially changes in physico-chemical variables (i.e. dissolved oxygen, organic matter) and changes to the health of all levels of biological organization (i.e. nursery areas, density frequencies) – the individuals, populations, communities and ecosystems. The state assessment of marine habitats is defined in the EU under three main legal instruments: the EU Marine Strategy Framework Directive (EC, 2008; MSFD, 2018a, 2018c) [41,71,73], the EU Habitat Directive (HD, 2018b, revised in 2022) [72,74] and the Water Framework Directive (WFD; EC, 2000) [40].

The MSFD [41,75] is the environmental pillar of the Integrated Maritime Policy (IMP) [91]. Its aim is to achieve the full economic potential of the seas, integrating environmental protection and sustainable use. The ultimate goal is Good Environmental Status (GES) of EU marine waters and to sustain the resource upon which marine-related economic and social activities depend. It is formulated as: "*Marine strategies shall apply an ecosystem-based approach to the management of human activities, ensuring that the collective pressure of such activities is kept within levels compatible with the achievement of GES and that the capacity of marine ecosystems to respond to human-induced changes is not compromised, while enabling the sustainable use of marine goods and services by present and future generations*" (Article 1, paragraph 3). This anticipates a link between GES, structure and functioning of the ecosystem and the sustainable use of ecosystem goods and services. GES is based on 11 descriptors, in line with the Drivers-Pressures-State-Impact-Response approach (DPSIR) [32,35], relating anthropogenic impacts and pressures (non-indigenous species, fisheries, eutrophication, hydrographical alterations, contaminants, marine litter, and introduction of energy) to the state of the marine environment (biodiversity (D1), ecosystem functioning including food webs, and finally sea bottom integrity (D6)). The MSFD goals and related indicators for Belgium are defined in *Belgische Staat*, 2018a and 2018c [71,73].

The HD [72] obliges Member States to strive for the conservation and protection of important or threatened species and habitat types via the Natura 2000 network of MPA's. In Belgium, the south-western area "Vlaamse Banken" was designated as a marine protected area, with two habitat types to be protected. The first habitat type 1110 "Sandbanks continuously covered by sea water" represents the most important habitat type of the BPNS and includes the entire area with a geologically unique sandbank system. Gravel beds and biogenic aggregations of the sand mason worm L. *conchilega*, found within these sandbank systems, are classified as habitat type 1170 "Reefs". This is the second habitat type to be protected. For Belgium the Conservation Objectives (IHDs) and related indicators are revised and defined in [74]. For both habitat types, the IHD's are in line with the environmental targets set out in the MSFD. Belgium's implementation of both Directives, HD and MSFD, is therefore following an integrated approach.

The oldest Directive, the Water Framework Directive (WFD) [40], dating to 2000, has the aim of establishing a framework for the protection of inland surface waters, transitional waters, groundwater and coastal waters (within 1 nautical mile) by enhancing the protection and improvement of the aquatic environment through specific measures and

Table 2
Overview of the conservation objectives as defined under the Habitat Directive (HD) for the Vlaamse Banken (Belgische staat, 2018b; 2022) [72,74] and linked to the environmental targets of the Marine Strategy Framework Directive (MSFD) in the BPNS (Belgische staat, 2018a) [71]. *IHD= Conservation Objective, *D*= MSFD Descriptor criteria numbers. Elements of the Water Framework Directive (WFD) (Directive 2000/60/EC) [40,93] also added. Overall linking to the ICG-C pressures can be viewed by objective.

Objectives	HD	MSFD	WFD	ICG-C Pressure
The spatial range of habitat type 1110 "Sandbanks continuously covered by sea water" does not change meaningfully: Hydromorphological elements supporting the biological elements: structure and substrate of the coastal bed, depth variation.	IHD 1	D6.1	ANNEX V; 1.1.4	Wave exposure changes- local Water flow changes – local Physical change (to another seabed/sediment type)
The spatial range and distribution of Level 2 (−3) EUNIS physical habitats (sandy mud to mud, muddy sand to sand and gravel containing sediment) fluctuates - in relation to the reference status as described in the "Initial Assessment" (MSFD) - within a margin limited to the accuracy of the current distribution folders.	IHD 1.1	D6.2		Wave exposure changes- local Water flow changes – local Physical change (to another seabed/sediment type)
The spatial range and distribution of the *Abra alba* community fluctuates - in relation to the reference status as described in the "Initial Assessment" (MSFD) - within a margin limited to the accuracy of the current distribution folders.	IHD 1.2			Wave exposure changes- local Water flow changes – local Physical change (to another seabed/sediment type) Abrasion/disturbance and penetration of the substratum on the surface of the seabed / below the surface
Function of shallow sandbanks as spawning and nursery areas is maintained or enhanced.	IHD 2			Abrasion/disturbance and penetration of the substratum on the surface of the seabed / below the surface
The occurrence and densities of juvenile flatfish such as Plaice (*Pleuronectes platessa*) and Sole (*Solea solea*) in the coastal zone are maintained or increased.	IHD 2.1			Abrasion/disturbance and penetration of the substratum on the surface of the seabed / below the surface
Non-native species introduced by human activities exist at a level where the ecosystem does not change.	IHD 3	D2		Genetic modification & translocation of indigenous species Introduction or spread of invasive non-indigenous species
Introduction of new non-indigenous species of macrofauna and macroflora (>1 mm) introduced by humans that alter an ecosystem is avoided. Biological elements: Composition and abundance of other aquatic flora.	IHD 3.1	D2.1	ANNEX V; 1.1.4	Genetic modification & translocation of indigenous species Introduction or spread of invasive non-indigenous species
The frequency of occurrence of vulnerable and benthic key-species increases.	IHD 4	D6		Abrasion/disturbance and penetration of the substratum on the surface of the seabed / below the surface
The ratio of benthic R-strategists to K-strategists (at species level) is decreasing.	IHD 4.1			
The number of K-strategists (at species level) is increasing.	IHD 4.2			
There is a positive trend in the mean density of adult specimens (or frequency of occurrence) of a selection of long-lived and/or slow reproducing species and the major structuring benthic species groups in mud to muddy sands and pure fine to gravelly sands.	IHD 4.3	D6.5		Physical change (to another seabed/sediment type) Abrasion/disturbance and penetration of the substratum on the surface of the seabed / below the surface
The benthic ecosystem provides sufficient food for higher trophic levels.	IHD 5			
The ecological quality of the benthic habitat of the *Abra alba* biotope is preserved.	IHD 6			Smothering and siltation rate changes (depth of vertical sediment overburden) Abrasion/disturbance and penetration of the substratum on the surface of the seabed / below the surface
The Benthic Ecosystem Quality Indicator as determined by BEQI tool is a minimum value of 0.60 for each occurring Community. Biological elements: Composition and abundance of benthic invertebrate fauna.	IHD 6.1	D6.4	ANNEX V; 1.1.4	Physical change (to another seabed/sediment type) Abrasion/disturbance and penetration of the substratum on the surface of the seabed / below the surface
The bioturbation potential (BPc), an indicator for evaluating the functioning of the ecosystem has a minimum value of 331 for the *Abra alba* community (or a minimum value of 0.60 (as determined by BEQI procedure)).	IHD 6.2	D6.6		Physical change (to another seabed/sediment type)
The autonomous development of *Lanice conchilega* aggregations is not prevented.	IHD 7			Physical change (to another seabed/sediment type) Abrasion/disturbance and penetration of the substratum on the surface of the seabed / below the surface
The 3D structures formed by *Lanice conchilega* are preserved.	IHD 7.1			Smothering and siltation rate changes (depth of vertical sediment overburden) Abrasion/disturbance and penetration of the substratum on the surface of the seabed / below the surface
The densities of the Lanice reef-associated species (e.g. *Eumida sanguinea, Pariambus typicus, Microprotopus maculatus* and *Phyllodoce* spp.) do not show a downward trend.	IHD 7.2			Smothering and siltation rate changes (depth of vertical sediment overburden)
There has been an increase in species richness within taxa typically associated with hard substrates (specifically Porifera, Cnidaria, Bryozoa, Polychaeta, Malacostraca, Maxillopoda, Gastropoda, Bivalvia, Echinodermata and Ascidiacea).	IHD 9.1	D6.9		Physical change (to another seabed/sediment type)

(*continued on next page*)

Table 2 (*continued*)

Objectives	HD	MSFD	WFD	ICG-C Pressure
There is an increase in the frequency of occurrence or median density of adult or mature colonies of at least half of the most important and long-lived species within gravel beds: native Flat oyster (*Ostrea edulis*), Mussel (*Mytilus edulis*), Whelk (*Buccinum undatum*), Dead man's thumb (*Alcyonium digitatum*), erected sponges (such as Geweis sponge (*Haliclona oculata*)) and erected Bryozoa (such as Sea fingerlings (*Alcyonidium* spp.) and Leafy hornwort (*Flustra foliacea*).	IHD 9.2	D6.8		Smothering and siltation rate changes (depth of vertical sediment overburden)
There is an increase in the median body size of the larger benthic species: Whelk (*Buccinum undatum*) and Spider Crabs (*Majidae* spp.).	IHD 9.3	D6.7		Abrasion/disturbance and penetration of the substratum on the surface of the seabed / below the surface
There is an increase in the number and size of sand tubeworm (*Sabellaria spinulosa*) reefs and the number of clusters of triangular tubeworms (*Pomatoceros (Spirobranchus) triqueter*).	IHD 9.4	D6.10		Smothering and siltation rate changes (depth of vertical sediment overburden) Abrasion/disturbance and penetration of the substratum on the surface of the seabed / below the surface
The quality of the habitat in terms of food availability, contaminants, underwater noise and amount of waste is such that it is suitable for supporting the different phases of the life cycle of marine mammals.	IHD 11	D10.1 D10.2 D10.3 D10.4		Litter Noise changes Pollution and other chemical changes
Satellite observations provide a synoptic picture of the amount of matter in suspension and of the turbidity in the Belgian zone as a whole. The concentration of matter in suspension and consequently also the turbidity appear to be high in the Belgian coastal zone. It should be noted that the shallow photic depth in the coastal zone is mainly due to sediment suspended by tidal currents. Eutrophication and the chlorophyll a concentration play only a marginal role in light attenuation compared to the tidal processes that suspend sediment, except in the open sea zone where the matter in suspension is mainly organic. Biological elements: Composition, abundance and biomass of phytoplankton.		D5 Crit.4	ANNEX V; 1.1.4	Changes in suspended solids (water clarity) Organic enrichment Nutrient enrichment
The species composition and relative abundance of the macrofauna communities reach values that indicate the absence of negative effects due to enrichment with nutrients and organic matter. Chemical and physico-chemical elements supporting the biological elements: Nutrient conditions.		D5 Crit.8	ANNEX V; 1.1.4	Organic enrichment Nutrient enrichment
Other approaches: Assessing functioning of a community structure or ecosystem using secondary production estimates; for example functional diversity indices [90]. Unpublished master thesis, UGent). Predators (The disturbance of biota not by anthropogenic activities) - number of species demonstrate predation on biogenic reefs.	IHD 6.1 IHD 6.2	D6.4 D6.6	ANNEX V; 1.1.4	Physical change (to another seabed/sediment type) Abrasion/ disturbance and penetration of the substratum on the surface of the seabed / below the surface Biological pressure towards specific Removal of target species.

quality elements (benthos, fish, phytoplankton and algae) for classification of ecological status.

The implementation of the *Coastbusters* approach in Belgium necessitates a comprehensive consideration of a multitude of criteria and indicators, as defined under the three Directives summarized in Table 2. Of those directives, the MSFD and HD are the most relevant. This complexity underscores the intricate web of factors that must be taken into account by policy and industry for the successful deployment of the *Coastbusters* approach in an area. It is illustrated for Belgium waters, but this complexity of legislation and indicators is similar to other EU countries [100]. Nevertheless, this approach of using the criteria/indicators from the EU Directives in assessing state changes should be used when transferring the concept to other EU countries.

2.4.2. State changes at coastbusters site

Regarding the description of state changes, the *Coastbusters* approach undertook a comprehensive monitoring program [94,95], to assess the ecological and morphological evolution of biogenic reefs and benthic communities at two sites near De Panne, Belgium. These sites were chosen for their different hydrodynamic conditions, with one site sheltered behind the Trapegeer sandbank and the other exposed to the open sea with strong waves and currents. In terms of seabed morphology and sediment characteristics, the exposed site experienced significantly higher erosion than the sheltered site. Sediment analysis revealed that the sheltered site had higher organic carbon, mud, and fine sand content, while the exposed site had coarser sediment due to its more energetic conditions. The impact of mussels on seabed dynamics was notable, particularly in the sheltered site, where mussel beds contributed to sediment stabilization. However, this effect was not statistically significant.

The benthic community structure also differed between the sites. The sheltered site exhibited higher density, biomass, richness, and diversity of benthic communities compared to the exposed site. The differences in community composition were influenced by the varying hydrodynamic conditions, with species like Oligochaete and L. *conchilega* more prevalent in the sheltered site. Temporal patterns in macrobenthic community characteristics showed changes over time, with species diversity increasing in the sheltered site and decreasing in the exposed site.

Mussel occurrence and dynamics were a crucial focus of the *Coastbusters* approach. Mussel patches, essential for reef formation, showed seasonal variability, peaking in winter but often disappearing in spring. The mussel beds were more persistent in the sheltered site, with predation by starfish and crabs being significant limiting factors. To establish effective mussel beds in dynamic environments, it is essential to address external pressures and ensure sufficient mussel abundance. Integrating mussel beds with other ecosystems could enhance overall ecological resilience. However, effectively implementing initiatives in high-energy environments necessitates a thorough monitoring program, alongside evaluating changes in the environmental conditions.

2.4.3. Social concerns

When testing the *Coastbusters* approach in Belgian waters, various challenges arose, including social concerns (e.g. installation was vandalized by third parties where parts of the structures and buoys were removed, among others). This highlights the need to consider not only the state of the environment, but also the state of social matters [55]. Getting stakeholders actively involved not only makes initiatives work better but also creates buy-in by the local community. The implementation of the *Coastbusters* approach reveals a knowledge gap as there is a notable scarcity of research surrounding the social acceptance of NbS in Belgium and worldwide [76]. This critical aspect remains unclear and largely un-investigated, representing a lacuna in the current understanding of viability of the *Coastbusters* approach. Planning and implementation of a NbS also involves collaboration among multiple stakeholders with diverse backgrounds and perspectives on how to approach solutions. For seaward NbS such as the *Coastbusters NbS*, this is even more difficult for a number of reasons [98]: (1) the physical distance of seaward NbS from the coast hinders people's ability to observe and appreciate the benefits and impacts of these solutions; (2) marine ecosystems are complex and inherently less understood by the general public; (3) indirect benefits, such as coastal protection and biodiversity enhancement, are often indirect and long-term, which make it challenging for society to recognize and value them; (4) NbS are technical and scientific, involving specialized scientific knowledge and technical expertise thus leading to a disconnect between scientific findings and public perception; (5) engaging the public in marine and management activities is more challenging due to logistical barriers; (6) coastal communities and stakeholders often prioritize immediate economic and social needs, such as fishing and tourism, which can lead to a lack of support or interest in seaward NbS. Therefore, if industry or policy wish to implement this approach in practice, a sociological study (of social, economic and cultural issues) is advised before starting a NbS project [92]. This was not possible in the current study due to limited funding. A possible solution is [77] where a comprehensive, dynamic, and adaptable framework was developed for developing questionnaires to collect primary data about the social acceptance of different NbS. The intention is that the collected data could be integrated as inputs into sustainability assessments. This will ultimately lead to solutions that last longer and have a bigger impact on society as a whole [76]. The importance of believing in and supporting NbS needs to be emphasized. When results align with societal values and preferences, initiatives become more relevant and are more likely to be adopted.

2.5. Impacts (I) (on human welfare)

Impacts (on human welfare) within the context of DAPSI(W)R(M) refer to changes (positive or negative) in the natural system that have consequences for societal welfare [35,78,79]. This term of welfare includes human well-being and happiness [52]. To assess changes in the marine ecosystem, a practical set of ecosystem service indicators can be used to track the state, behavior, and direction of marine ecosystem components and processes, as well as intermediate and final ES [52,79]. Clear objectives and indicators are essential to apply the ES approach effectively for marine managers, especially in the context of coastal protection (such as sediment stabilization, marine fisheries, aquaculture, water quality, and carbon sequestration) [80,81]. The link between ES and human well-being must not be forgotten; communication of results and social literacy are key [82].

A knowledge gap and an underdevelopment of tools to assess coastal and marine ES is evident in literature [82]. There are also critical knowledge gaps on the environmental and socio-economic co-benefits, site-specific feasibility and impacts of various combinations of nature-based and hybrid solutions to build coastal resilience [22]. Research on ecosystem service indicators for the *Coastbusters* approach, i.e., NbS using biogenic reefs, has increased in recent years [83]. The *Coastbusters* approach has been noted as a regulating ES in the top-10 of the stakeholder ranking of important ES, indicating its societal relevance [84]. However, further ES studies on NbS for the BPNS are nearly non-existent. A quantitative estimate of the ES provided by the biogenic reef located in the western part of the BPNS was made. To achieve this, the ES expected to be affected by the development of the biogenic reef were identified using the qualitative assessment tool (EVK-tool) developed in the "Ecosystem Vision for the Flemish coastal zone" project [85]. The tool provides information on which processes driving the ES supply are affected, providing insight into their production mechanism. Based on the process changes identified by the tool (Table 3), the tool identified seven ES, five of which were considered applicable to the *Coastbusters* approach (i.e. fisheries production, carbon retention, water quality regulation, coastal protection and recreation), that are expected to be affected by the development of the biogenic reef. The selection of ES was based on local conditions (e.g. distance from the coast, height of the water column above the biogenic reef, etc.) and the demand for ES in the area under consideration. In total, three of the five ES identified could be quantified within the *Coastbusters* approach. More specifically, the regulating ES of coastal protection, carbon retention and water quality (N) regulation were quantified. The other ES could also potentially be quantified if measurements and monitoring are carried out according to specific indicators (see Table 4). The quantification was carried out using the SUstainable Marine Ecosystem Services (SUMES) model [96]. The SUMES model is a suite of models used to calculate the impact of human activities at sea (e.g. aquaculture) on marine ecosystems. The input data consisted mainly of in-situ measurements (bathymetric, sedimentological and biological parameters) and, where missing, parameters derived from research conducted under environmental and social conditions similar to the area under consideration.

The quantification of three regulating ES (coastal protection, carbon retention and water quality (N) regulation) showed that the *Coastbusters* approach made the greatest contribution to human welfare through coastal protection. The new mussel beds contributed to a sand accumulation of 1 485 $m^3\ y^{-1}$. In addition to coastal protection through sediment stabilization, mussel beds contribute to water quality (N) regulation through denitrification. The mussel beds and associated benthic community were responsible for 3.452 kg N y^{-1} of denitrification. As the benthic community is included in the calculation, it is recommended that future studies assess nitrogen fluxes using incubation techniques. This would allow mussels to be isolated from the benthic community, enabling direct measurement of fluxes. In terms of carbon retention, bivalves are net generators of CO_2. When the carbon budget of a mussel is calculated, including respiration, biocalcification, food ingestion and egestion of unabsorbed food (faeces), more CO_2 is released than is retained. Between 554 kg $CO_2\ y^{-1}$ and 572 kg CO2 y^{-1} (from a total of 126 104 mussels) were generated by the mussels in the *Coastbusters* project. As the mussels are not harvested, no carbon is removed from the marine environment. If the mussels were to be harvested in the future, the shell has the potential to act as a net carbon sink [97]. Therefore, harvesting only a minor part of the mussels could both provide food and promote carbon retention, cf. Nature-Inclusive Harvesting (NIH) [14]. However, the aquatic environment, due to its three-dimensionality and the multifaceted use of space, is complicated as an ES approach [84,82]. Moreover, [14] has presented a robust evidence-based framework of indicators particularly applied to NbS cases (e.g. shellfish reefs as climate rescuers) and Nature-Inclusive Harvesting (NIH). Furthermore, the applicability of multifaceted use of space has been taken up by [13], in which a conceptual framework and tool set have been developed for location-specific assessments of changes in ES supply across various ES due to cumulative impacts. During further implementation of the *Coastbusters* approach, such frameworks could offer insights into effects on both the ecosystem's state (its components and functioning) and human well-being through changes in the supply of multiple ES. This balance between state of the ecosystem (nature conservation purpose) and multi-use (harvesting, passive fishing) needs to be discussed with the stakeholders, especially when applied in Natura 2000 network sites. Additionally, the increased biodiversity and productivity of the area is not always the goal of each stakeholder, as for example nature conservation bodies, which may argue that the system is changed from the natural environment.

Table 3
Expected changes in ecosystem processes due to the development of a biogenic reef (new habitat) and the loss of foreshore (original habitat) (output from EVK-tool) [86]. The symbols describe the expected trend in the rate/intensity of the process: ++ strong positive effect, + positive effect, o no effect, - negative effect and - - strong negative effect.

		TREND IN RATE/INTENSITY OF PROCESS	
		ORGINAL HABITAT (FORESHORE)	**NEW HABITAT (BIOGENIC REEF)**
ECOLOGICAL PROCESSES	Hydrodynamics	–	–
	Morphodynamics	- -	+
	Ecological engineering	+	O
	Benthic production	o	+ +
	Pelagic production	–	+
	Transfer	–	+ +
	Primary dune formation	+ +	O
	GHG emissions	o	–
	Denitrification	o	+ +
	Population dynamics	- -	+ +

Table 4
List of ecosystem service indicators – suggestions for monitoring at the *Coastbusters* site. * Parameters for carbon retention and water quality regulation to be complemented with literature values on losses through decomposition and denitrification. ** Oxygen concentration at sediment-water interface to be used for selecting relevant literature for deriving losses through decomposition and denitrification [87].

Category	Ecosystem service	Indicator	Temporal or spatial requirements
Provisioning services	Fisheries production	Abundance by size/age class of commercial species	Temporal: around peak density (species dependent)
Regulating services	Water quality regulation (N) (P)	Particulate Organic Carbon concentration * Particle Number Concentration concentration * Photoprotective pigments concentration * Bulk density * Sedimentation rate * Oxygen concentration **	Spatial: sediment between mussels
		Length mussels Density mussels Weight mussels Population growth/recruitment Growth rate mussels Follow-up of mussels year to year Elevation of reef and zone of influence surrounding the reef in all directions (surface map)	Spatial: sediment-water interface Temporal: all seasons
Regulating services	Coastal protection	Species diversity (fish and macrofauna)	Spatial: zone of influence (ex. from Oosterschelde NL: 2 à 75 m from reef) Temporal: time 0, after 1y, 2y, …
Cultural services	Recreation e.g. Diving	Occurrence of rare or emblematic fish/macrofauna species Turbidity	

Therefore, a thorough debate among stakeholders is needed to decide on which ES are kept in mind when applying a NbS in an area.

2.6. Responses (R) (using measures)

In order to prevent or mitigate the changes and impacts (or impacts on human welfare) as a consequence of the activity performed, responses are required. The expansion of management responses to include "as measures" enables the DAPSI(W)R(M) approach to become more harmonized with the terminology used within EU Directives such as the MSFD and the WFD [88]. The measures could be added to the respective Programmes of Measures (PoMs) of the EU Directives. Note that the success of management responses (as measures) depends on the extent to which they follow the 10-tenets approach for adaptive management and sustainability (expanded from [89,54], where the measures should be ecologically sustainable, technologically feasible, economically viable, socially desirable (education), legally permissible, administratively feasible, politically expedient, ethically defensible, culturally inclusive and effectively communicable (information boards on site)). As an example, Table 5 illustrates measures required to address the "ecologically sustainable" tenet, by creating the physical, chemical and biological conditions for restoring the natural system by NbS. Management measures should ensure that ecosystem features and functioning, and both fundamental and final ES, are safeguarded. Those measures were linked with the *Coastbusters* approach as an example. Those measures could be relevant for executing the NbS, or improving the ecological sustainability of the NbS or restoring the area after exploitation. For example, important measures that were already a goal of the *Coastbusters* NbS, are the development of biodegradable material for the installation (dropper lines) and the testing of bio-facilitating anchoring. This will further help to define if certain environmental measurements are needed and what it means in terms of monitoring requirements (integrated in the *Coastbusters* approach monitoring road map).

3. Conclusion

The present study applies the DAPSI(W)R(M) framework to the *Coastbusters* approach. The various elements of the framework were identified; the project comprises a multifaceted approach by addressing primary, secondary, and macro-economic needs as drivers. The implementation of activities integrates coastal infrastructure and aquaculture practices. Pressures on the benthic habitat features were evaluated using the MarESA sensitivity assessment approach (Table 1, 6, 7 and 8). Furthermore, the state change assessment of the environment was assessed by a multitude of criteria and indicators as defined under three EU Directives (HD, MSFD, WFD) (Table 2), followed by a quantitative estimation of three ecosystem service indicators that were identified as

Table 5
Based on the 10-tenets approach, examples of measures to address the ecologically sustainable tenet, applied to the *Coastbusters* approach (mussel bed development by longline/buoy system). A full measure category list is available in [35].

Objective/class	Measure category	*Coastbusters* linkages
Biology/Ecology/ Other	To develop and/or protect specific habitats	Mussel beds in relation to nature restoration
	To develop and/or protect specific species	Mussel beds in relation to nature restoration
	Prevent introduction of or to control/eradicate invasive species	Working in NbS with local species (no introductions)
	To develop natural gradients and processes, transitions and connections	Taking into account natural environmental conditions
Hydrology/ morphology	Restore morphological quality (structure and substratum)	Avoid installation of artificial structures on sea-bottom (e.g. bags with stones)
	Restore morphological diversity (structure and depth variation)	Minimize scouring around installation (structure of anchoring), bio-facilitating structures
Physical/chemical quality	Reduce pollutant loading (point and diffuse sources)	Reduced plastic contamination (marine biodegradable material)
	Reduce nutrient loading (point and diffuse sources)	Use of organisms in NbS that have a filtering function
	Improving oxygen conditions	Action needed if NbS should lead to anoxic conditions below installation

affected by the development of the biogenic reef (Table 3). The quantification is based on the in-situ measurements and monitoring data of the project. Suggestions for further monitoring parameters and ecosystem service indicators were made (Table 4). Finally, a number of measures and responses for the ecologically sustainable tenet are recommended (based on the 10-tenets approach) (Table 5). Consequently, this study represents an initial effort to make seaward NbS implementation ready for the EU environmental legislation procedures. The aim is to ensure that the plans, programs and projects that are likely to affect the environment as well as society, are subjected to a profound assessment prior to their approval or authorization.

4. Recommendations

Based on the findings and conclusions of this study, the following recommendations are proposed to facilitate the successful integration of Nature-based Solutions (NbS) within European Union (EU) environmental legislation and coastal management practices:

1) Create a Favorable Institutional Environment [19]:
   - Establish clear regulatory frameworks and policies that support the implementation of NbS. This includes aligning NbS initiatives with existing environmental directives, such as the EU Habitats, Birds, and Marine Strategy Framework Directives.
   - Promote interagency collaboration to streamline the approval and authorization processes for NbS projects to ensure that they meet environmental, social, and economic criteria.
2) Enhance Public Acceptance and Stakeholder Engagement [77]:
   - Develop and implement communication strategies to raise awareness and understanding of NbS among stakeholders, including local communities, industry partners, and policymakers.
   - Facilitate stakeholder involvement throughout the project life cycle, from planning and design to monitoring and evaluation, to ensure that the perspectives and needs of all parties are considered. Also examine social acceptance through a sociological study prior to starting a NbS project.
3) Adopt a Detailed Methodology for NbS Implementation:
   - Use the DAPSI(W)R(M) framework as a structured approach to assess and manage NbS projects. This involves defining drivers, activities, pressures, state changes, impacts on human welfare, and responses using measures.
   - Incorporate the MarESA sensitivity assessment approach to evaluate the pressures on benthic habitat features, to ensure that the environmental impacts of NbS projects are thoroughly assessed.
   - Rely on existing criteria and indicators, for example from the EU Directives that are in force within the area, for assessing the state changes associated with the activity and related pressures.
4) Quantify and Monitor Ecosystem Services (ES):
   - Conduct comprehensive quantitative assessments of ecosystem service indicators affected by NbS projects using in-situ measurements and monitoring data. This provides a robust basis for evaluating the environmental benefits and trade-offs of NbS.
   - Develop and implement monitoring programs to track the long-term performance and impacts of NbS projects to ensure that adaptive management practices can be applied.
5) Apply the Six-Step Approach for Resilience Management [22]:
   - Follow the six-step approach proposed [22] to guide the resilience management process for NbS projects. This includes: (1) Viewing the management process as adjustable over time, (2) Engaging stakeholders throughout the entire process, (3) Selecting appropriate frameworks, such as DAPSI(W)R(M), for guiding assessments, (4) Reinforcing adaptive capacity within the management framework, (5) Providing training and capacity-building for stakeholders and practitioners, (6) Continuously evaluating and refining NbS solutions based on feedback and monitoring data. This study on the *Coastbusters* approach presents a detailed report of step 3, the selection of an appropriate framework, in this case the DAPSI(W)R(M).
6) Integrate NbS into Multi-Level Policies and Practices:
   - Ensure that NbS are embedded within local, regional, and national policies and planning processes. This integration helps to create a cohesive approach to coastal management that leverages the benefits of NbS.
   - Promote the alignment of NbS initiatives with broader sustainability and climate resilience goals, contributing to the overall well-being of ecosystems and communities.

5. NbS impacts and implications

The applied DAPSI(W)R(M) framework towards the *Coasbusters* approach embodies Nature-based Solutions (NbS), leveraging natural processes to address environmental, economic, and social challenges. This approach carries substantial implications for the marine ecosystem.

Environmentally, the reef enhances biodiversity, stabilizes the seabed, offering possible resistance against coastal erosion. A link is made between the relevant EU legal instruments, implemented in Belgium, to assess the state of the marine habitats (criteria and indicators) and possible changes to the natural environment as a result of the multiple pressures described. Socially, the mussel beds sparks scientific curiosity, community engagement, and awareness regarding marine conservation, nurturing a profound connection between individuals and their coastal surroundings. Elaborating further by taking into account the need to incorporate social acceptance studies is important. Economically, it creates opportunities for aquaculture, tourism, research and reducing the need for costly artificial defenses. In essence, the *Coastbusters* concept emerges as a comprehensive and sustainable seaward NbS remedy for both coastal safeguarding and ecosystem enrichment.

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CRediT authorship contribution statement

Alexia Semeraro: Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Rémi Dupont:** Validation, Writing – review & editing. **Vicky Stratigaki:** Funding acquisition, Writing – review & editing. **Tomas Sterckx:** Funding acquisition, Writing – review & editing. **Gert Van Hoey:** Conceptualization, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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ANNEX

A sensitivity classification evaluation has been summarized for the main benthic habitat features represented in the near vicinity of the *Coastbusters* site. These are outlined in the following tables: table 6, 7 and 8.

Table 6
Marine Evidence based Sensitivity Assessment (MarESA). Whereby linking sensitivities of the community(s) to the pressures are shown. Guidance on the application of the MarESA approach is provided in [61]. (**Colors**: None & Very Low= Brown, Low=red, Medium=orange, High=Light Blue or red, Not Sensitive=Dark Blue, Not Relevant/Not assessed=grey) A5.625 - Mytilus edulis beds on sublittoral sediment. https://www.marlin.ac.uk/habitats/habitat/6/blue_mussel_beds_on_subtidal_sediment.

Pressure Theme	ICG-C Pressure	Resistance	Resilience	Sensitivity
		A5.625 - Mytilus edulis beds on sublittoral sediment		
Hydrological changes (inshore/local)	Wave exposure changes- local	Low	Medium	Medium
	Water flow (tidal current) changes – local (including sediment transport considerations)	Medium	Medium	Medium
Physical loss (permanent Change)	Physical change **to another seabed**	None	Very Low	High
	Physical change of **sediment type**	High	High	Not sensitive
Physical damage (Reversible Change)	Changes in suspended solids (water clarity)	High	High	Not sensitive
	Abrasion/disturbance of the substratum on the surface of the seabed	Low	Medium	Medium
	Penetration and/or disturbance of the substratum below the surface	Low	Medium	Medium
	Smothering and siltation rate changes (depth of vertical sediment overburden)	Medium	Medium	Medium
Physical pressure (other)	Litter	Not Assessed (NA)	Not assessed (NA)	Not assessed (NA)
Pollution and other chemical changes	Organic enrichment	High	High	Not sensitive
	Nutrient enrichment	High	High	Not sensitive

Table 7
Marine Evidence based Sensitivity Assessment (MarESA). Whereby linking sensitivities of the community(s) to the pressures are shown. Guidance on the application of the MarESA approach is provided in [61]. (**Colors**: None & Very Low= Brown, Low=red, Medium=orange, High=Light Blue or red, Not Sensitive=Dark Blue, Not Relevant/Not assessed=grey) A5.137 Dense Lanice conchilega and other polychaetes in tide-swept infralittoral sand and mixed gravelly sand. https://www.marlin.ac.uk/habitats/detail/116/dense_lanice_conchilega_and_other_polychaetes_in_tide-swept_infralittoral_sand_and_mixed_gravelly_sand.

Pressure Theme	ICG-C Pressure	Resistance	Resilience	Sensitivity
		A5.137 Dense *Lanice conchilega* and other polychaetes in tide-swept infralittoral sand and mixed gravelly sand		
Hydrological changes (inshore/local)	Wave exposure changes- local	High	High	Not sensitive
	Water flow (tidal current) changes – local (including sediment transport considerations)	High	High	Not sensitive
Physical loss (permanent Change)	Physical change **to another seabed**	None	Very Low	High
	Physical change of **sediment type**	None	Very Low	High
Physical damage (Reversible Change)	Changes in suspended solids (water clarity)	High	High	Not sensitive
	Abrasion/disturbance of the substratum on the surface of the seabed	High	High	Not sensitive
	Penetration and/or disturbance of the substratum below the surface	High	High	Not sensitive
	Smothering and siltation rate changes (depth of vertical sediment overburden)	High	High	Not sensitive
Physical pressure (other)	Litter	Not Assessed (NA)	Not assessed (NA)	Not assessed (NA)
Pollution and other chemical changes	Organic enrichment	High	High	Not sensitive
	Nutrient enrichment	Not relevant (NR)	Not relevant (NR)	Not sensitive

Table 8
Marine Evidence based Sensitivity Assessment (MarESA). Whereby linking sensitivities of the community(s) to the pressures are shown. Guidance on the application of the MarESA approach is provided in [61]. (**Colors**: None & Very Low= Brown, Low=red, Medium=orange, High=Light Blue or red, Not Sensitive=Dark Blue, Not Relevant/Not assessed=grey) Abra alba Community, A5.261, A5.241, A5.351.

Pressure Theme	ICG-C Pressure	Resistance	Resilience	Sensitivity
		Abra alba Community, A5.261, A5.241, A5.351		
Hydrological changes (inshore/local)	Wave exposure changes- local	High	High	Not sensitive
	Water flow (tidal current) changes – local (including sediment transport considerations)	High	High	Not sensitive
Physical loss (permanent Change)	Physical change **to another seabed**	None	Very Low	High
	Physical change of **sediment type**	Low	Very Low	High
Physical damage (Reversible Change)	Changes in suspended solids (water clarity)	High	High	Not sensitive
	Abrasion/disturbance of the substratum on the surface of the seabed	Low	Medium	Medium
	Penetration and/or disturbance of the substratum below the surface	Low	Medium	Medium
	Smothering and siltation rate changes (depth of vertical sediment overburden)	High	High	Low
Physical pressure (other)	Litter	Not Assessed (NA)	Not assessed (NA)	Not assessed (NA)
Pollution and other chemical changes	Organic enrichment	High	High	Medium
	Nutrient enrichment	High	High	Not sensitive

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