COASTBUSTERS

A NATURE-BASED SOLUTIONS COASTAL MANAGEMENT ALTERNATIVE

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Today's challenges of erosion, flooding and storm surges are primary concerns for coastal communities around the world. Traditional coastal engineering solutions, such as concrete seawalls or rock breakwaters however, will become unsustainable due to their limited resilience, higher costs, societal impacts and unwanted ecological side effects. In response to these challenges, Coastbusters developed a nature-based solutions approach to sustainable coastal management. These solutions will create new habitats based on known 'biobuilder species' in the form of biogenic coastal reefs. The purpose of the reefs is to induce natural accretion of sand, attenuate storm waves and reinforce the foreshore against coastal erosion, thus adding to coastal protection.

Three key biobuilding concepts were identified and tested to develop ecosystem-based coastal engineering.

Coastal zones are under duress of climate change (e.g. sea level rise, intensification of storms, increasing beach erosion) and enhanced anthropogenic pressure (e.g. demographic evolution, loss of habitats, economic expansion). Both hard and soft conventional coastal protection measures, such as sea walls, dykes, embankments and beach reclamations, are increasingly required to combat flood risks (Malherbe et al., 2013).

Conventional coastal protection measures however, are currently challenged by stakeholders because they are seen as unsustainable and carry high installation and structural maintenance costs. Hard structures are designed for current sea levels and are incapable of adapting to increasing flood risks. Soft measures will suffer from storm events and require additional maintenance afterwards. As a consequence, current civil engineering approaches can fall short in efficiently and cost effectively protecting the coast (Syvitski et al. 2009). This often results in negative or unforeseen impacts on local ecology and surrounding ecosystems on larger scales, reducing the resilience of the coast.

Resilient coastal protection

Innovative, sustainable and perennial approaches for a resilient coastal protection are therefore crucial to safeguard economic, environmental and societal assets of the coast. In recent decades, sustainable coastal management approaches have emerged within the nature-based solutions (NBS) philosophy (European Commission, 2015; IUCN, 2016; Nesshöver et al., 2017). In this context, the application of ecosystem engineering species for achieving civil engineering objectives is not new. From a coastal protection point of view, these species need to have the ability to modify the local physical environment by their structures or activities to trap sediments and attenuate waves (Borsje et al., 2011; Emmerman et al., 2013). Examples of coastal ecosystem engineers are numerous, with the most tangible being dune vegetation, seagrasses, corals and mangroves.

An ecosystem-based coastal flood protection can only be brought into large-scale practice as a regional solution, on condition that:

1. sufficient space is present to accommodate the creation and development of (additional) ecosystems;
2. key engineering species and its habitat naturally occur; and
3. local stakeholders support development of ecosystem services.

Once these conditions are met, solutions can be designed to translate the desired ecosystem engineering functionality into coastal management measures. On the one hand, such development requires a generic framework to select the appropriate measures based on the spatial and temporal scale of coastal protection. On the other, it requires knowledge (and broad dissemination thereof) on the ecology, engineering and ecosystem services delivered by the reef-forming ecosystem.

The core of Coastbusters is to understand and validate the underlying processes that drives this natural biostabilisation. To translate the optimal conditions for the development of biogenic reefs into an engineered design will generate a new business model for coastal

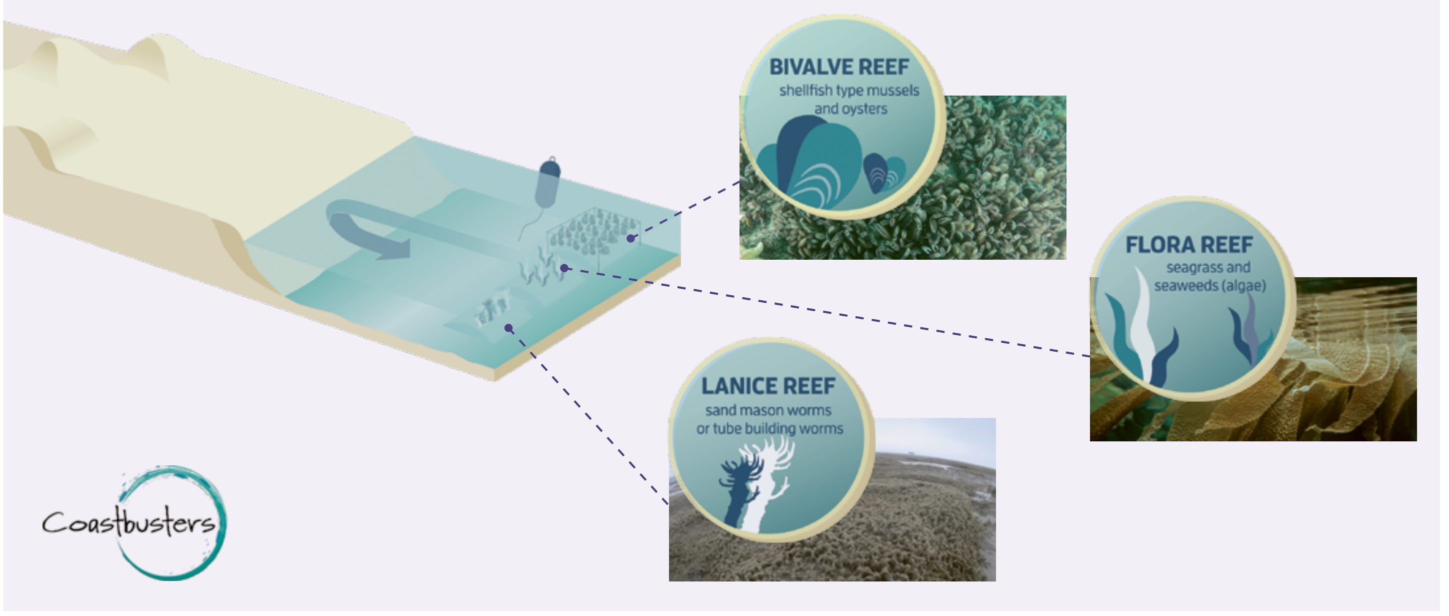

FIGURE 1

Illustration of the three different reef types at the test site off the Belgian coast of De Panne.

management (Sterckx et al., 2019). To unravel this dynamic interaction between traditional technical and ecological engineering requires diverse expertise and multidisciplinary collaboration. Therefore, an exceptional public-private partnership was created. The Coastbusters consortium is currently composed of three companies, Dredging International (part of the DEME group), Jan de Nul and Sioen industries, together with two research institutes, the Institute for Agricultural, Fisheries and Food Research (ILVO) and the Flanders Marine Institute (VLIZ). The Coastbusters research projects are facilitated by the Blue Cluster (DBC) and supported by the Flemish agency for Innovation and Entrepreneurship (VLAIO).

Ecosystem engineers

The implementation of nature-based solutions (NBS) in the marine environment necessitates in-depth knowledge and insights on the driving parameters and natural processes. Moreover, integrating this fundamental expertise of the natural processes into the traditional technical engineering of coastal management tools (i.e. design, installation, operational management and maintenance) is key. To acquire the required knowledge and skills, a chain of dedicated research and innovation lines are introduced.

The original Coastbusters research and innovation lines focus on three ecosystem engineers present in Belgian coastal waters: seaweed (*Saccharina latissima*); tube-building sand mason worms (*Lanice conchilega*); and blue mussels (*Mytilus edulis*). Respectively referred to here as flora reef, lanice reef and bivalve reef.

An ecosystem engineer is defined as an organism that directly or indirectly modulates the availability of resources to other species, by causing physical state changes in biotic or abiotic materials. In doing so, it modifies, maintains and creates habitats. The reef-building capacity of ecosystem engineers is important for marine management as the recognition as reef builder is key for both regulators and offshore industry. To classify as reefs however, ecosystem engineering activities need to significantly alter several habitat characteristics (i.e. elevation, sediment consolidation, spatial extent, patchiness, reef-builder density, biodiversity, community structure, longevity and stability) as defined in EU habitat directive guidelines (Hendrick and Foster-Smith, 2006). This foundation is the rationale for selection behind the original three coastal Coastbusters reefs.

Owing to their functional characteristics, these biobuilders can exert a strong influence on the surrounding system properties that exceeds what may be expected based on their relative abundances alone. Therefore, following the cascading effects on the wider ecosystem, it is crucial to consider this group of common, but functionally important, species beyond a mere conservation point of view. They are the natural tools for a resilient coastline and our best allies to cope with sea level rise.

Flora reef

Seaweed beds are critical for the recruitment and protection of many commercially important fish species. Seaweeds that attach to the substrate by means of a holdfast are structurally important components of the marine environment and support high biodiversity by providing habitat, shelter and food, as well as affecting wave flow and energy. The French Atlantic coast and Californian coast are famous examples where kelp forests thrive in the coastal ecosystem. Additionally, seaweed beds play a significant role in the removal of nutrients and organic materials, especially from eutrophicated water, serving as buffers of coastal water quality.

For the flora-reef field setup, the consortium installed bags and frames with innovative spore impregnated (geo)textiles. Such techniques are commonly used on land applications such as grass seeds in cellulose fabrics. For the purpose of Coastbusters, the substrates have been re-engineered to advanced textile seaweed cultivation substrates. A second flora-reef research line investigated the use of biodegradable material as potential impregnation substrate. Unfortunately, the seaweed tests proved unsuccessful due to the aggressive local hydro- and morphodynamics, and competition with other organisms for a settling substrate. As a response, Coastbusters developed a third flora-reef research line for another ecosystem engineering species that traps sediments and dampens wave action: seagrasses. As currently no seagrass meadows naturally occur at the Belgian coast test site, a Coastbusters spin-off project called 'PLANT ME' has been initiated (see reference box).

FIGURE 2
The advanced textiles for seaweed cultivation (AlgaeTex©) being impregnated with seaweed spores before being lowered into the sea.

Lanice reef

Aggregations of tube-building polychaetes, here *Lanice conchilega* (commonly known as the sand mason worm or tube worm) stabilise the intertidal sediment bed of sandy shorelines. The bay of Mont Saint-Michel in France is a famous example of such a natural biogenic reef. The harder aggregations within soft sandy sediments provide refuge from predation, competition and physical as well as chemical stresses. The formed reef also represents an important food resource and critical nursery or spawning habitats

PLANT ME project

Plant a million seagrasses is an ambitious Coastbusters spin-off project focussing on the further development of the flora reef, more specifically for seagrasses. The project aims to restore these important ecosystems. A large-scale restoration planting technique, which will stabilise the seabed and reduce coastal erosion, will be developed. Based on natural biodegradable substrates overgrown with seagrass plants, this new method is relatively low cost to produce. Thus, allowing the quick and easy planting of seagrass beds in shallow coastal ecosystems.

Coordinated by DEME (Belgium) and co-promoted by Jan de Nul (Belgium), a public-private partnership has been established combining scientific expertise and hydraulic engineering, comprising Ghent University (Belgium) and Centro de Ciências do Mar (Portugal).

FIGURE 3

Sand mason worms (Lanice conchilega) on an intertidal sandy beach.

for a diversity of organisms. Therefore, this filter-feeding polychaete is considered an interesting target species in the search for nature-based solutions for coastal management.

In contrast with tidal marsh plants and mangroves, *L. conchilega* aggregations cannot be planted. Tube worms undergo a pelagic larval phase prior to settling. This settlement process is facilitated by the presence of small hard structures on the sandy seabed (e.g. shells or tubes of adult conspecifics). The presence of other sand mason worms in the area indicate favourable conditions. Thus, to induce and enhance adult aggregation, larval settling needs to be facilitated.

Coastbusters investigated two lanice-reef research lines:

1. The cultivation of larvae and settlement process on different substrates through laboratory trials; and
2. The facilitation of natural larval settlement using artificial substrates in small-scale field pilots.

During the laboratory trials, different designs of substrates (geo-textile and bio-based) were investigated. The biological and mechanical properties of the different substrates to attract larvae were tested under controlled conditions. These revealed a number of potentially interesting engineered substrates to attract larvae (Wyns et al., 2020).

Following the laboratory trial results, small-scale field pilots were conducted to optimise the design and installation of the chosen substrates in natural conditions. Prior to the start of the field tests and in the control reference site, no sand mason worms were found in large numbers, nor in aggregations. The field pilot and the associated scientifically underpinned monitoring revealed a positive effect on the settlement (i.e. presence of *L. conchilega* and slight sand elevation) of certain substrates. A significantly higher number of sand mason worms were observed in and under substrates having a stiffer but open three-dimensional matrix structure.

In conclusion, the substrate 3D matrix generated favourable local stable conditions to facilitate larvae settlement. The physical structure (thickness and density of the 3D matrix) seems likely to determine the effectiveness of the holdfast structure during the settlement process. The open structure allowed growth of the larvae to adult specimens without hampering exchange with the environment (e.g. food, water and oxygen). In turn, the settled worms seemed to slow down the passing water flow, which locally causes sand to pile up and the sediment bed to stabilise. Additionally, the newly formed biogenic reef is oxygenated due to tube irrigation activity of the worms, which benefits creation of distinct microhabitats in an otherwise uniform landscape.

In other words, the Coastbusters engineered reef-facilitation textiles successfully attracted larvae of the sand mason worm and enhanced its settlement. Over time, the induced natural reef will further stabilise the sandy shore and generate a local biodiversity hotspot. Whilst promising, this low-cost deployment of stabilising textile mats in the intertidal sandy shoreline has several upscaling shortcomings. The three main hurdles encompass:

1. The anchoring of the substrates in a dynamic intertidal environment;
2. Coping with the temporary (biodegradable) function of the facilitation substrates; and

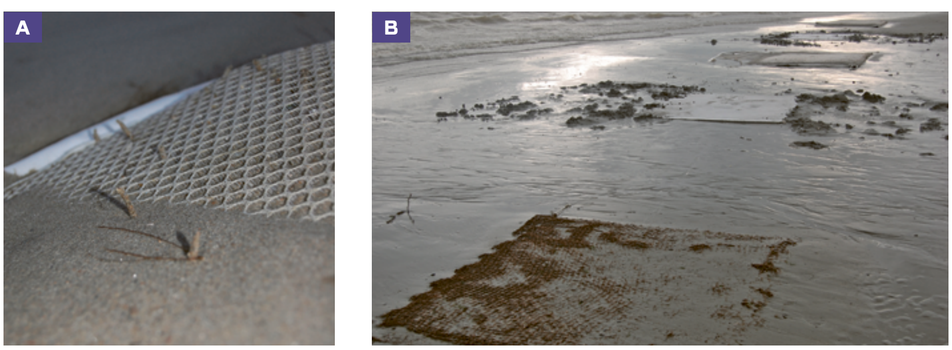

FIGURE 4

(A) A sand mason worm colonised substrate after a few weeks of deployment. (B) Small-scale field pilot installation of different biofacilitating substrates.

A

B

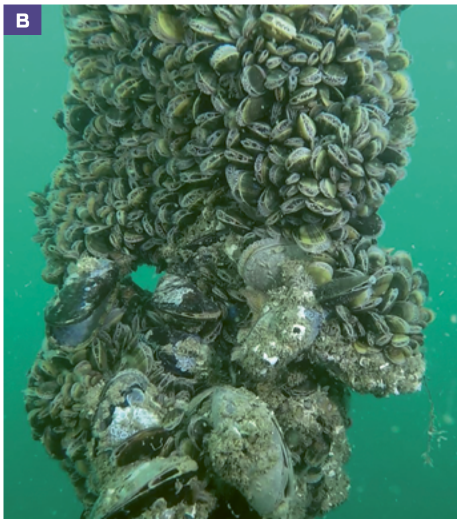

FIGURE 5

(A) Floating linear longline with mussel-grown droppers during maintenance survey. (B) Underwater picture of a dropper colonised by blue mussels and associated fouling community. Photo © Sven Van Haelst, VLIZ.

3. The interface with other users and stakeholders of the shoreline.

To conclude, the aggregation-inducing process of the lanice reef works but needs to be refined and requires further research steps before it is operational for large-scale and industrial use.

Bivalve reef

Mussel beds are biogenic reefs that can serve for bio-stabilisation of the sediment in a high-energy environment (e.g. high turbidity, high current velocity, strong wave action). Coastbusters investigated the use of a mussel bed as a third possible nature-based solution for coastal protection and biodiversity enhancement. In order to initiate such a mussel bed, Coastbusters relied on aquaculture techniques to capture mussel spat (*Mytilus edulis*). By using a modified mussel longline system and dropper lines, the setup enabled an efficient attachment of mussels' larvae. When the mussels have grown large and dense enough, they detach in clumps and fall to the seabed beneath the lines. These mussel clumps then form a mussel bed on the seabed under the facilitating structure.

A proof-of-concept test in sheltered conditions provided a first solid knowledge base on the technical requirements of a longline system in a high-energy coastal environment. This gave an initial insight into the efficiency of different (non-) biodegradable materials (e.g. dropper lines). The project also generated knowledge on the safe deployment and decommissioning for such an installation. In addition, light was shed on the biological diversity development of the newly formed mussel biogenic reef as new habitat. In conclusion, Coastbusters was able to build a dense mussel bed under the mussel longline facilitation system for two consecutive seasons.

Over time, the induced natural reef will further stabilise the sandy shore and generate a local biodiversity hotspot.

This very successful proof-of-concept test obviously yielded more dedicated questions and challenges than direct operational answers. For instance, what is the impact on the underlying sediment in terms of compaction and composition? Is the Coastbusters biogenic reef producing a more cohesive and less erodible sediment? Does the evolution of a soft sand surface to a protruding 3D mussel carpet structure significantly alter the hydrodynamics and enhance sediment stabilisation? Are the partial disappearance of reef patches in winter related to the presence of predators like common starfishes (*Asterias rubens*) and netted dogwhelks (*Tritia reticulata*) or are the physical forces of winter storms overcoming the reef's cohesive forces? Does the increase in local biodiversity influence the adjacent sand banks biodiversity? Which factors influence the density distribution of the reef? How can Coastbusters configure the facilitating infrastructure to be more modular and better fitting the mussel distribution? From which (bio)material should each element of the facilitating structure be? Etcetera.

To answer these questions and to prepare to scale up the proof-of-concept, fine-tuning through advanced research and innovative adaptation was needed. Moreover, the Coastbusters bivalve reef is adapting a commercial aquaculture system to a completely different objective than seafood harvesting, which it was originally designed for. It should be clear, that the commercial value at hand is the biogenic reef that contributes to coastal protection and boosts ecosystem services. It is not the adapted aquaculture system, which is merely a tool to facilitate the reef formation.
The current approach has not been attempted before and therefore a significant amount of novel research still has to be conducted to make this tool fit for the purpose at hand (i.e. installation of a biogenic reef). Subsequently, a Coastbusters bivalve reef 2.0 project to implement significant improvements to the complex offshore facilitation system was started.

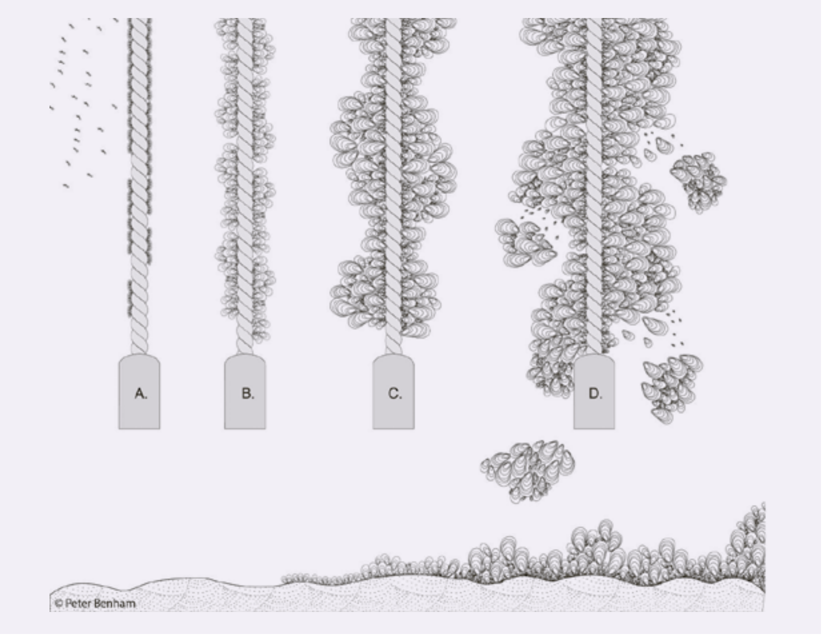

FIGURE 6

Bivalve reef formation sequence: (A) Mussel larvae attach to the suspended substrate. (B) Mussels begin to grow in size. (C) Competition for space forces some mussels away from the surface of the substrate, forming clumps. (D) Clumps of mussels break off from the dropper line and fall to the seabed to form a mussel reef.

Bivalve reef 2.0

The sequel installation was planned with various scientifically underpinned research trajectories. By bringing together expertise and experience on both technical and ecological engineering, Coastbusters coordinated to achieve a further elaboration of the bivalve concept first developed. More specifically, trying to get an answer to the following elementary research questions:

- Can tuneable (controlled over time) bio-based/biodegradable materials be used to replace conventional off-the-shelf materials as building components of an offshore reef-facilitating setup?;
- What is the most appropriate technical, spatial and temporal design of the offshore setup stimulating efficient biogenic-reef forming and survival under different hydrodynamic conditions?;
- Which advanced environmental observation techniques are necessary to scientifically underpin the development, the evolution and overall resilience of the newly formed reef?; and
- What are the boundary conditions (e.g. biology, safety and survivability) and added ecosystem values and services of such a mussel reef?

Tuneable bio-based materials

The mussel biogenic-reef facilitation structures are based on modified aquaculture techniques and materials. The current Coastbusters off-the-shelf engineered textiles and materials withstood the offshore harsh conditions perfectly and fulfilled their purpose in the formation of the biogenic reef. However, improving the material type (of the floating and the seabed-based elements) would enable Coastbusters to achieve an innovative tuneable design and improve the reef in two ways: (1) to increase the resilience of the formed reef and (2) enhance the biodiversity associated to it. Moreover, judicious material selection could reduce the carbon footprint and general impact of the production. Therefore, under the lead of the industrial Coastbusters partners, innovative bio-based, biodegradable materials will replace some key elements within the reef-facilitating structure. In addition to the composition, the selected materials will have to attract a specific assemblage of organisms.

Evidently, only materials that do not adversely affect the adjacent environment as a result of weathering or leaching processes should be used. Biodegradable materials are often presented as the least impacting solution because they 'biodegrade'. However, the certification of the biodegradation process is often achieved in environments that are far from the natural conditions of coastal waters (e.g. high temperatures, non-saline and low oxygen). Hence, some biodegradable materials tend to first break down into potentially harmful pieces, such as microplastics, before truly biodegrading, if ever completely (Fojt et al., 2020). Coastbusters will thus create and monitor colonisable materials taking into account the timescale of degradation and composition

FIGURE 7

Underwater picture of a successfully newly formed bivalve reef and its associated benthic community. Photo © Sven Van Haelst, VLIZ.

Deployment of the mussel shaker and biofacilitating anchor prototypes.

Mussel Shaker and Biofacilitating Anchor

As part of the optimised modular configuration of the facilitating structures and in search of environmentally friendly alternative materials (compared to classical linear aquaculture longline setup), Coastbusters developed the 'Mussel Shaker' and 'Biofacilitating Anchor'. The shaker places the dropper lines in a circular configuration to yield a denser mussel reef. The anchor, made from low-carbon emission cement (CEM III/C), gives mussels a hard substrate to kick-start the reef. To investigate the preferred attachment surface of mussel larvae, three sides of the pyramid were applied with (1) smooth concrete, (2) brushed rough concrete and (3) oyster shells. Researchers of ILVO and VLIZ will monitor the settling organisms on the anchor. In order to be able to do so and to track biodiversity, a fixed ARMS (Autonomous Reef Monitoring Structure) has been attached to the fourth side of the anchor, which will be sampled and analysed by VLIZ within the framework of the European Lifewatch biodiversity programme.

to understand the impact of these novel materials in offshore deployment conditions.

Complementary to the composition, surface micro-relief or roughness of the material is known to influence fouling communities. Substantial research is still needed on coatings and surface treatments to attract species-specific assemblage of marine organisms. This applies to the floating structures, such as longlines and droppers, but also to the anchors that keep them in place as these will, over time, become part of the reef. Coastbusters is testing an environmentally friendly concrete composition compared to standard Portland cement and several surface treatments, to assure the attractiveness of blue mussel spat and even flat oyster larvae (*Ostrea edulis*) in time (see reference box: Mussel Shaker and Biofacilitation Anchor).

Modular configuration and design

The conventional linear longline prototype with modified dropper lines has proven to resist offshore conditions off the Belgian coast of De Panne (on the sheltered leeward side of the Broersbank) and successfully facilitated initial biogenic-reef formation. However, the modularity and scalability of the coastal protection design is very important. The design should be generally applicable across an extended coastal zone in different locations around the globe and adaptable to local conditions, such as currents, depth, type of seabed, etc. To check if the envisaged innovations can withstand more exposed hydrodynamic conditions, a twin setup was deployed on the seaward side of the Broersbank. This means that the bivalve reef 2.0 facilitating infrastructure is being tested in a sheltered zone (representing a less erosive foreshore) and in an exposed zone (representing a more erosive foreshore). The performance of the twin setup in the erosive zones (due to several factors such as increased seabed instability for instance), will be the key for the global operational deployment of Coastbusters.

For a number of benthic ecosystems such as mussel beds, studies suggest that the spatial distribution within the bed is self-organised (e.g. behaviour amongst mussels or external predation pressure) and not per-se imposed by underlying landscape features (e.g. shape and height of sand ripples under the reef). Scientists concluded that the spatial distribution and density of the reef influences the resilience of the reef (De Paoli et al. 2017). For instance, an area of reef with a low density of mussels is more sensitive to predation. In addition, suspended mussels on vertical substrates, compared to naturally occurring horizontal seabed mussels, develop a significantly firmer attachment to the substrate and a closer aggregated structure. This gives suspended mussels a better resistance to predators, such as the shore crab (*Carcinus maenas L.*) and hydrodynamic stress. Therefore, the configuration and design of the facilitating structure yielding the falling mussel clumps, will impact the persistence to wave action of the newly formed reef.

Thus, Coastbusters is in search of the optimal configuration of floating facilitation structures. This research will reduce deployment costs and improve both technical and environmental performance. One of the alternative configuration prototypes is currently being tested (see reference box: Mussel Shaker and Biofacilitating Anchor).

Advanced environmental monitoring

The monitoring programme evaluates the success of the reef-facilitation structure and the production of an early stage natural biogenic mussel reef under the floating structure. Nonetheless, to understand the underlying processes of reef development, a specialised environmental monitoring strategy needs to be developed. As such, the main objectives of the monitoring is

FIGURE 8

Coastbusters scientists monitoring the mussel growth on the dropper lines.

twofold: (1) develop an integrated scientifically underpinned monitoring strategy and (2) detail the ecological and morphological evolution of the reef.

Using advanced and dedicated monitoring techniques such as Unmanned Surface Vehicles (USV), will allow the consortium to cover the key parameters of reef development over a wide spatial-temporal scale. One of the major advantages using marine robotics is the ability to measure various parameters at the same time. The multi-sensor deployment of the Coastbusters monitoring approach (e.g. side-scan sonar, sub-bottom profiler, wave motion sensors), the advanced processing of multi-beam water column and backscatter data and vicinity to the seabed/infrastructures, adds to the resolution and magnitude of the yielded data. Coastbusters is thus taking a leading role in the development of automatic monitoring alternatives for the often risk-bearing and costly diving and vessel bound surveys. This will result in better and more data at lower cost, whilst improving safety.

Coastbusters is in search of the optimal configuration of floating facilitation structures.

Ecosystem values and services

Coastbusters also aims to unravel the boundary conditions and feedback mechanisms of the sheltered and exposed test sites. This knowledge will define the parameters that are essential to evaluate the status and success of the mussel reef. In other words, is it possible to strengthen or partly replace conventional engineering constructions for coastal protection by ecological elements such as biogenic reefs?

To answer this question, an ecosystem service assessment is proposed. This approach is increasingly being advocated to ensure sustainable use of the environment, through a set of defined indicators incorporated in an ecosystem services tool. The ecosystem services concept offers a framework to make the linkages between ecological and socio-economic properties. Coastbusters identifies the ecosystem service provision in terms of the biogenic reef impact (e.g. sediment stabilisation, reduction of wave energy and changing shoreline), the creation of valuable habitat (e.g. a reef in comparison to bare sand) and changes in biodiversity levels (e.g. within and adjacent to the reef).

The seasonal aspect of working with biology is one of the challenges faced by nature-based solutions. If we look at dunes and wetlands for instance, their growth is known to be dynamically complex: A period of steady growth, leading to stabilisation, may be followed by a period of discrete and major decline, inducing a temporary erosion and protection failure. The same applies to mussel reefs as shown by the partial disappearance during the winter period. Consequently, depending on chosen ecosystem engineering species, a hybrid coastal defence model seems to prevail as ecological components follow a biological window with its boundary conditions. However, the residual indirect effects (e.g. the consolidation of sediment under the reef, change of underwater seabed profile and increased biodiversity and ecosystem services) generate a clear benefit for the coastal zone over a longer period. As a result, an integrated nature-based solutions coastal management alternative seems to be the way forward.

Nature-based solutions business model

The trademarked Coastbusters brand represents a broader philosophy of nature-based solutions (NBS) projects. As such, the first projects should be regarded as part of a chain of various research and innovation projects, tackling different aspects of the broader technical, ecological and social engineering topics at hand.

The benefits of NBS have been found to outweigh the costs of implementation and maintenance in a range of conventional grey coastal risk reduction measures (Fordeyn et al. 2019; Seddon et al. 2020). Multiple examples corroborate the evidence that NBS can be more cost-effective than conventional engineered alternatives, at least when it comes to less extreme hazard scenarios. In other words, the absolute level of protection provided by the NBS strategy depends on many factors. For example, efficacy can vary with intensity and frequency of storm events and the resilience of the ecosystem engineer to withstand impacts will depend on intrinsic biological cycles.

Hence, attention must be paid when comparing NBS to conventional solutions. Focus on one service solely (e.g. absolute coastal protection) will underestimate the NBS potential to deliver a wide range of benefits at both local and global scale, especially over the long term.

FIGURE 9

VLIZ's unmanned surface vehicle, Adhemar, surveying the Coastbusters test site. Photo © Kobus Langedock, VLIZ.

Implementing nature-based solutions requires a new business model approach in economic thinking.

For instance, benefits of higher fisheries catch, carbon sequestration and space for recreation are not accounted for. Conventional solutions are usually implemented with relative certainty about the type and timescale of benefits, whereas NBS generally offers more flexible long-term solutions with benefits that might not be directly felt by stakeholders. As a result, the response of ecosystems is much harder to value and cost than conventional grey infrastructures.

Therefore, Coastbusters is of the opinion that, in areas where relatively little space is available, the combination of nature-based solutions and (existing) grey infrastructure is the best coastal management solution. Such hybrid-integrated solutions are capable to address a range of climatic impacts, provide additional ecosystem services and can be managed over the long term.

The question at hand is how to finance this integrated solution to reconcile economic development with the stewardship of ecosystems. Currently, most funding comes from public funds (e.g. green climate fund, green deal) or private funds from the voluntary market such as financial institutions. However, these rarely cover the large-scale implementation/installation costs. In addition, the short-term nature of the financing sector decision-making hampers the longer-term planning and maintenance required for the provisioning of NBS benefits. Moreover, many of the benefits associated with NBS cannot be capitalised by one specific stakeholder only, making ownership almost impossible. Therefore, conventional finance where the risks are mainly carried by the project owner is not viable. The return benefits are not solely measured in material and financial capital, but mostly as human, social and natural capital.

Future coastal management business models will therefore have to take into account the valuation of ecosystems and biodiversity within the economic system, and the added value it provides to society as a whole. This new nature-positive business solution will have to frame nature as an asset ('capital') and mark biodiversity as a characteristic of those assets that enables them to be more productive and resilient. Concepts such as Ecosystem Services and Natural Capital Accounting can create an extension of the global project valorisation, including the 'sustainable economics' and the 'whole life cycle cost' of these nature-based solutions. Monetising co-benefits or revenues generated by ecosystem elements (i.e. framing the value of natural capital within the context of economic prosperity and human well-being) will form a key enabler.

More fundamentally, implementing nature-based solutions requires a new business model approach in economic thinking. Shifting from a focus on infinite economic growth to a systemic thinking framework that accounts for multiple ecosystem services and goods from the perspectives of different stakeholders.

Conclusions

Nature-based solutions (NBS) offer huge potential to address climate change whilst supporting biodiversity and generating ecosystem services on which human socio-economic well-being depends. In this framework, the Coastbusters public-private consortium deployed three biogenic-reef facilitating pilots in Belgian coastal waters.

Each pilot targeted a specific ecosystem engineering species: (1) sugar kelp (*Saccharina latissima*), (2) sand mason worm (*Lanice conchilega*) and (3) blue mussel (*Mytilus edulis*). The survivability and biogenic-reef building capacity have been monitored and each reef yielded distinct outcomes. The flora-reef arrangement has not been able to germinate, due to unfavourable local conditions. The lanice-reef field test demonstrated successful colonisation by naturally occurring larvae forming an elevated consolidated reef. The bivalve-reef setup proved to be the most successful biogenic-reef facilitator. It generated a natural diverse reef ecosystem for consecutive seasons with a reduction of the reef extent during storm periods. The bivalve reef became the Coastbusters nature-based solutions flagship. A newly started 2.0 pilot in more exposed waters will prove the resilience of the Coastbusters biofacilitating structures. Together with novel tuneable bio-based materials, advanced observation techniques (i.e. marine robotics) and revolutionary designs, Coastbusters will benchmark the future of NBS projects.

Incorporating NBS as a crucial element into (future) coastal zone management, results in a more sustainable, ecosystem-based and cost-effective management approach. Developing such NBS alternatives will lift up coastal engineering towards a more integrated and multidisciplinary future.

However, NBS cannot always be seen as a stand-alone coastal management answer as ecosystem conditions, sufficient space and local stakeholder support is required. Subsequently, under certain local conditions NBS should be integrated with conventional coastal management. In addition, NBS requires a new approach in economic thinking valuing the natural capital through ecosystem services assessments. Therefore, Coastbusters is of the opinion that the synergy of scientifically underpinned and stakeholder-wide supported nature-based solutions and where necessary in combination with (existing) grey infrastructure is the best coastal management solution. Such Coastbusters integrated solutions are capable to address a range of climatic impacts, provide additional ecosystem services and can be feasibly implemented and managed over the long term.

Summary

Conventional coastal protection solutions, such as dykes, embankments and beach reclamations, are being challenged in terms of life expectancy and maintenance cost by climate change and sea level rise. The Coastbusters brand stands for innovative nature-based solution (NBS) alternatives for a more sustainable and resilient coast. Through engineered facilitation of biogenic-reef formation, this integrated coastal management approach induces a self-sustaining stabilisation of the foreshore that enriches the ecosystem in place, yielding supplementary ecosystem services.

The pioneering public-private Coastbusters consortium embraces the ecosystem approach and since 2017 has deployed multiple proof-of-concept pilots at the Belgian North Sea coast. Successful biogenic reefs of sand mason worms and blue mussels were formed in the intertidal and subtidal foreshore, respectively. Coastbusters scientifically underpinned research lines provide a first solid knowledge on the technical requirements for biofacilitating infrastructures' modularity, optimal design configuration, selection of bio-based materials, innovative environmental monitoring and delivered ecosystem services. In the near future, the consortium will implement novel spin-off projects within a broader multiple-use of space framework to push sustainable coastal management forward.

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