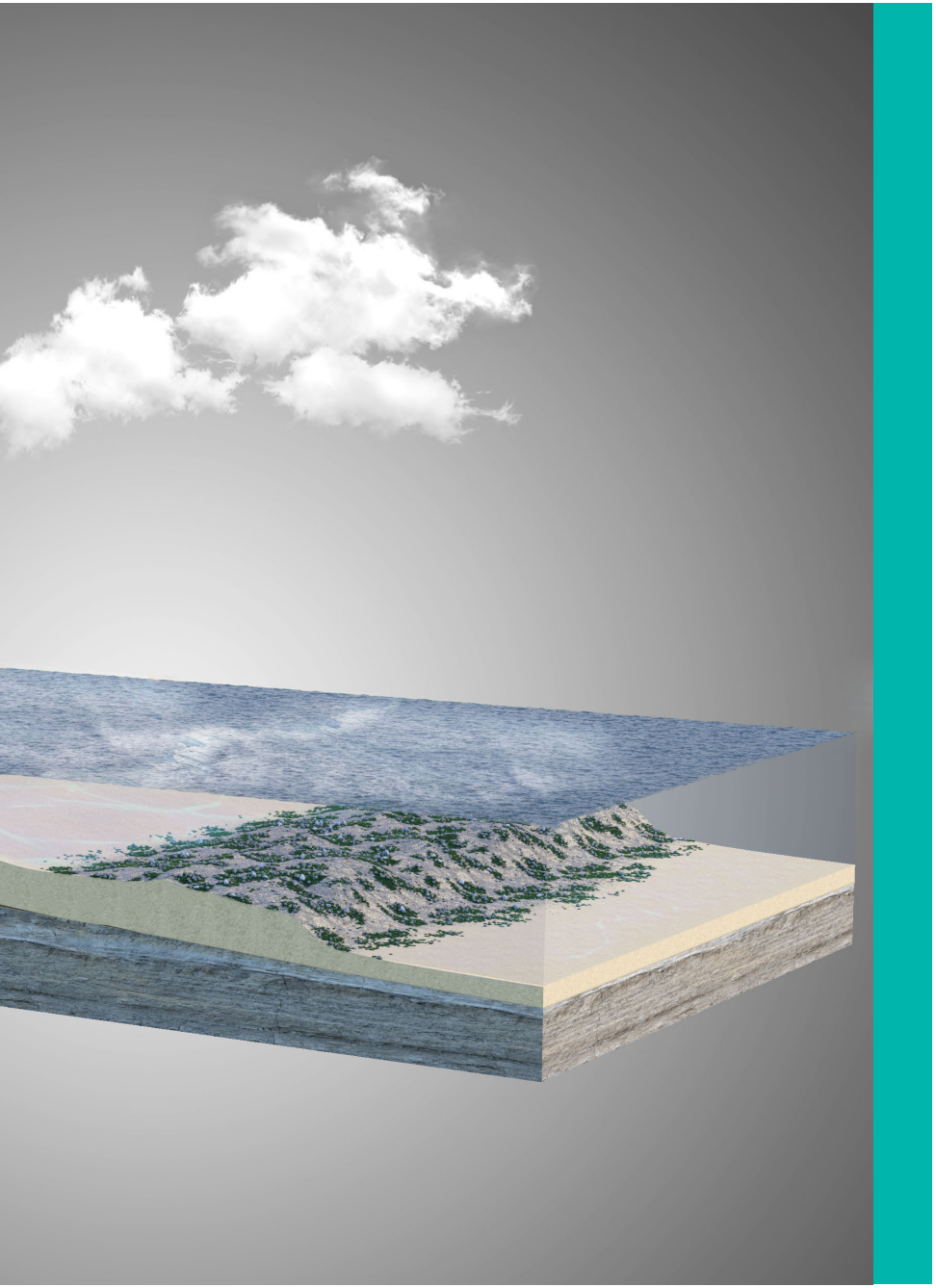


Coastbusters

COASTBUSTERS 2.0

ECOSYSTEM BASED COASTAL MANAGEMENT

THE NEXT STEP TOWARDS
NATURE BASED SOLUTIONS



© ILVO

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THE COASTBUSTERS HAVE COME A LONG WAY.

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1 PROLOGUE

THE COASTBUSTERS HAVE COME A LONG WAY.

We have always had believers and non-believers. When we started, the term Nature Based Solutions (NbS) was still largely unknown and biogenic reefs were considered more a side issue than a serious improvement. A special thanks to our team and all our believers for their enthusiasm, faith and drive for output and results (see also section below). They are true pioneers doing things that have never been done before.

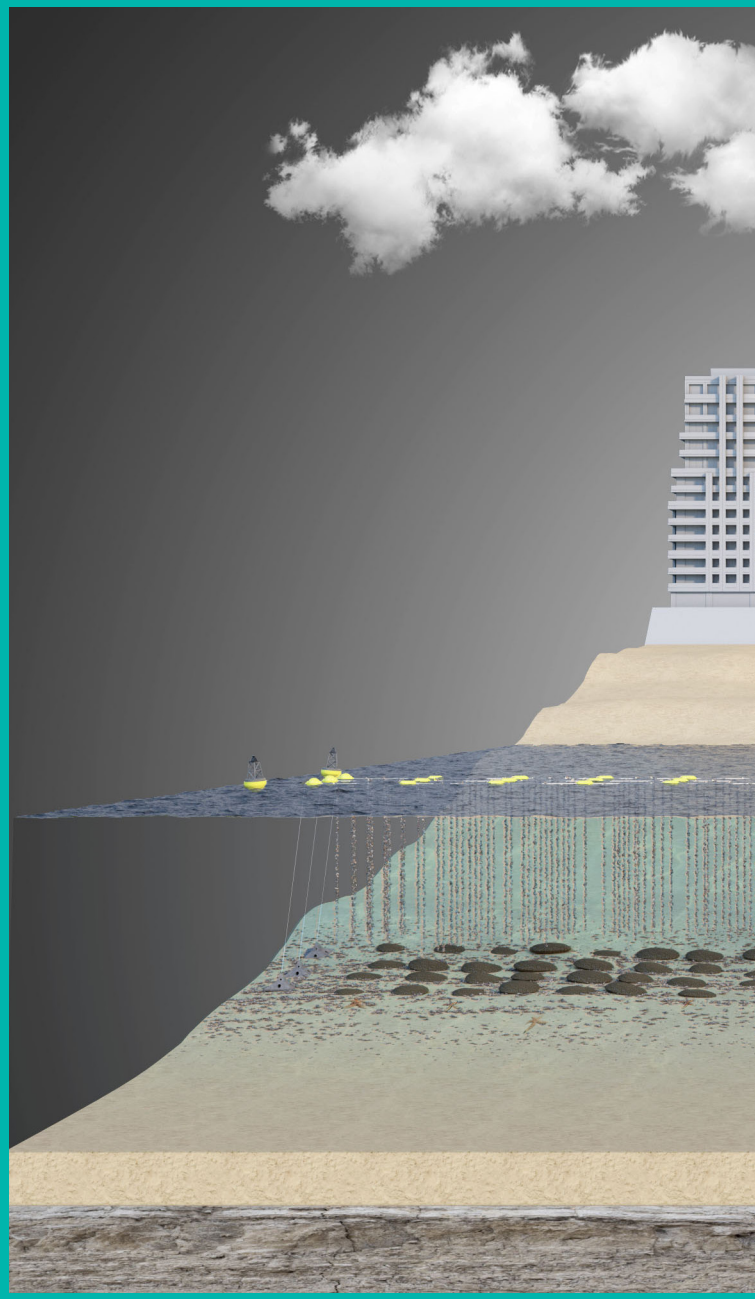
As coordinator, I'm proud and humbled by the overall positive feeling towards Nature based Solutions the Coastbusters seem to transmit. We can consider this a great achievement.

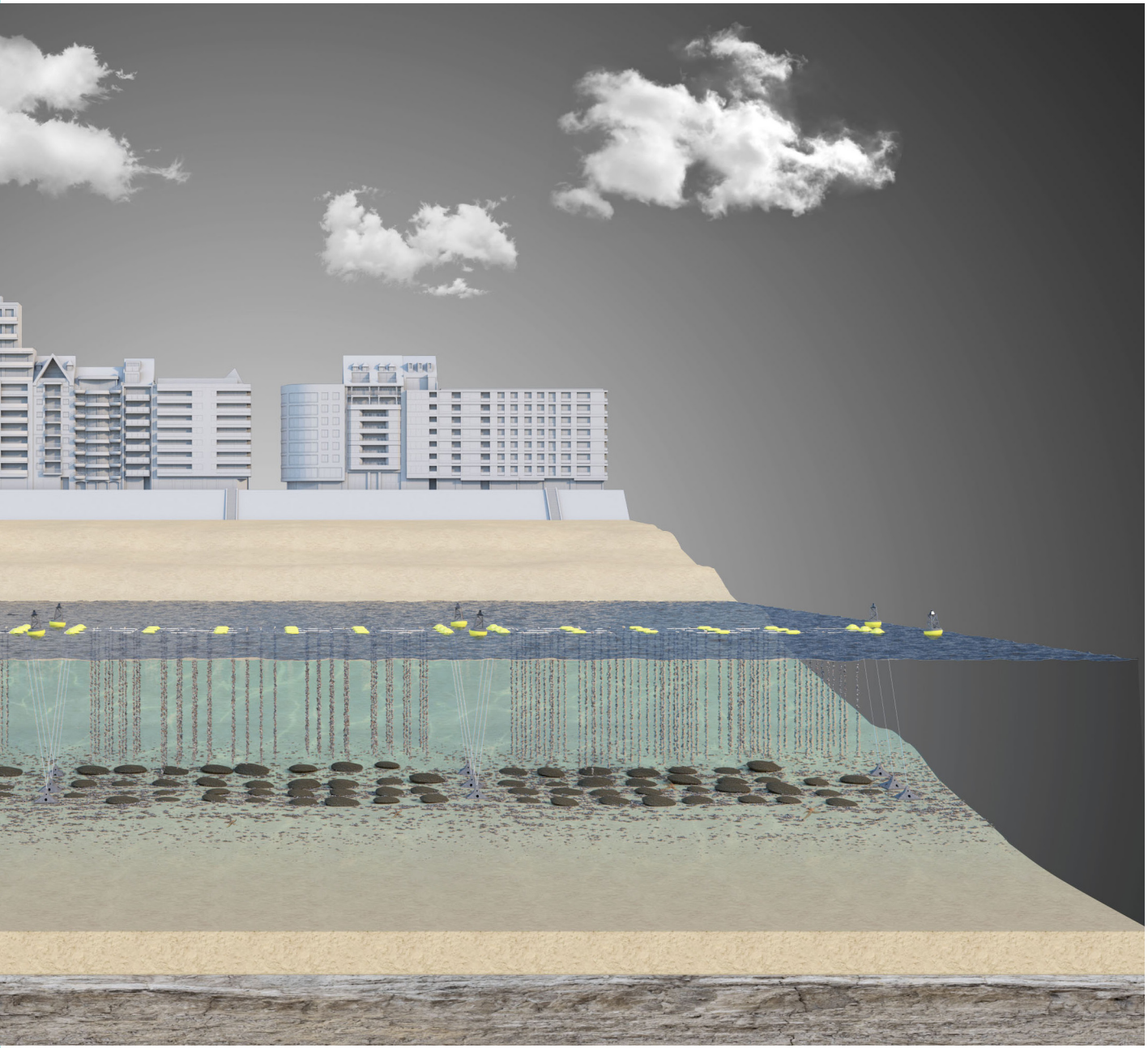
In the preface you will find some of our sources of inspiration and critical supporters, namely people who have guided us on our path.

Thank you and let's keep our nose to the grindstone!



Tomas Sterckx
Coordinator
of the Coastbusters





Coastbusters 2.0, a consortium between ILVO, DEME, Jan De Nul, Sioen and VLIZ funded by the Agency for Innovation and Entrepreneurship (VLAIO) with the help of the Blue Cluster. Started in February 2020 and ran for more than three years. Presented approaches and shared ideas received an ever growing support from several players and stakeholders in society (civilians, universities, governmental organisations, etc.) - creating inspiring awareness on our future coastal management.

PARTNERS

DEME

ILVO
Flanders research institute for agriculture, fisheries and food

Jan De Nul GROUP

VLIZ

SIOEN

VLAIO

BLUE CLUSTER

Clusters for Growth



② PREFACE



Vincent Van Quickenborne
Deputy Prime Minister
and Minister of the North Sea

In March 2023, we made a huge step forward in protecting underwater life. In New York, the United Nations adopted the BBNJ Treaty on protecting 30% of the oceans by 2030. Belgium, one of the founders of the international Blue Leaders, had been working towards this for many for years. The ocean plays a major role in the fight against global heating and needs to be protected appropriately.

We do this ourselves. The North Sea is home to the largest nature reserve in Belgium. Over 37% of the Belgian North Sea is listed as a nature conservation area in the Marine Spatial Plan, which outlines the use of space at sea.

Belgium was the first country in Europe to introduce such a plan. We are currently working on the next MSP for the 2026-2034 period. This plan will also pay appropriate attention to a clear vision on coastal management.

As a matter of fact, climate change is inextricably linked with biodiversity and nature restoration. Rising sea levels, increasingly frequent storms and coastal protection are special challenges for which we need to come up with solid solutions in the short term.

Society therefore needs to invest heavily in a healthy coastal ecosystem. To achieve this, the Belgian government focuses on innovation and Nature based Solutions. Smart solutions such as Coastbusters, which help support nature, are exactly what we need. The Belgian North Sea is an ideal breeding ground for this kind of research and innovation.

It is essential to connect our economy, security, natural values and recreation even more deeply to ensure a safe, sustainable and affordable future at the beach. This will once again make the Belgian North Sea a prime example of a good and far-sighted policy.

I would like to sincerely thank the people of the Coastbusters project for this.

See you soon.



Nathalie Balcaen
Administrator-General
of the Flemish Agency
for Maritime and Coastal
Services

The sea gives and the sea takes. It is an old saying but it remains as relevant today. As the Agency for Maritime and Coastal Services we constantly remind ourselves about this saying and aim to live our lives and conduct our work in harmony with the sea. We take advantage of the power of the sea to protect our coast where we can. But to protect our cities, hinterland and ports, sometimes we have to fight against the sea. Traditionally we use structures such as dikes and seawalls, and in Belgium we are currently also building our first storm surge barrier in Nieuwpoort. But there are other solutions too. 'Soft where possible, hard where needed' is our approach to coastal management as part of our Master Plan for Coastal Protection. This plan lays out our approach up to 2050 to protect coastal areas against the impact of flooding and storms. We will use concrete and steel when needed, but first we will always explore solutions to curb the impact of the sea using soft coastal protection interventions. We will assess Nature based Solutions to protect us from the impact of waves, tide and wind.

For example, by using dunes and therefore we are studying how planting dune grasses can strengthen those dune structures. On the beach of Raversijde, Belgium, we have re-introduced dunes and are studying the impact of wind on the beach system. Further along the beach we opened a research facility last year, where we can study the power and impact of waves on a coastal protection dike. The tagline on the wall of this living lab says it all: Be quiet please, we're listening to the sea here. And by listening to the sea, together we will be able to find new solutions. Below the waterline we can also make interventions to protect our coast, and by working in tandem with the sea we can maybe even create opportunities for valuable ecosystems to establish themselves. This is where Coastbusters has a crucial role to play.

Within living memory, coastal areas have attracted people, and nowadays more than 3 billion people or about 40% of the world population lives within a distance of 100 km from the coast. To accommodate our changing and growing needs and optimise human use, we have reshaped the natural coastal environment into a man-made environment. In doing so, we have changed many natural processes shaping the coastal environment and its complex ecosystems. Recent scientific insights, however, have made it clear that the resulting loss in biodiversity also leads to the loss of many ecosystem services such as flood protection, erosion control, and productivity, and that the static environment we have created is not resilient to accommodate the major challenges of climate change, and especially sea level rise. It was Einstein who said: "We cannot solve our problems with the same thinking we used when we created them"; indeed, a paradigm shift is necessary. We need to create a more dynamic rather than a static coastal environment that is resilient and can adapt to changing conditions. Nature based solutions offer us a great chance to make this paradigm shift. Indeed, a growing body of scientific literature shows the enormous multiple benefits provided by Nature based Solutions. The use of bio-reefs, dunes, vegetation etc. not only enhances biodiversity, but also provides many ecosystem services, not least flood protection. The potential of these measures is enormous, but large-scale application requires further scientific work and insights that can only come from implementation and careful monitoring of pilot projects. This is exactly the purpose of Coastbusters, gathering knowledge based on real-life experiments so as to have enough scientific evidence to apply these measures on a large scale. The primary goal of 21st-century coastal zone management will be to achieve a dynamic and climate-robust coastal area that delivers ecosystem services and accommodates human activities.



Patrick Meire
Prof. Emer. UAntwerpen



Piet Opstaele
DBC

Our coasts are increasingly under pressure. On top of the climate crisis, with global sea levels rising and increasingly frequent and intense storms, we are also facing a biodiversity crisis. To tackle these global challenges, we need to include more natural solutions in our efforts to protect our coasts.

> **We cannot solve our problems with the same thinking we used when we created them.**

Coastal protection should not be regarded as a mere protection measure, but rather as a fundamental part of a complete ecosystem. It involves multiple actors and functions, each with their specific challenges, and is embedded in an environment under pressure.

Within this scope, the Coastbusters have developed integrated solutions that offer long-term coastal resilience and embrace the naturally changing ecosystem. These solutions go beyond traditional coastal protection measures and support the marine ecosystem while providing coastal protection at the same time.

Close collaboration between the partners has been essential in the success of the project. Each partner has made their own valuable contributions. Going forward, it will be necessary to incorporate ecological, social and engineering aspects to increase public support.

At Blue Cluster, we are convinced that the Coastbusters have a lot more to offer both at a national and at an international level. We are very proud to support this project, and are keen to see what the future brings.

③

INTRO

Coastal areas are one of the most productive, diverse, and valuable ecosystems in the world (see Costanza *et al.*, 2017 and references therein)[1]. When considering the combined benefits and services they provide, these ecosystems account for about 60% of the total economic value of the biosphere (Zamboni *et al.*, 2021 and references therein)[2].

At the same time, our coastal zones are increasingly affected by climate change, which induces sea level rise and more frequent weather extremes such as storms and floods. In addition, intensified human activity is heavily reducing the resilience of our coastal ecosystems. Conventional solutions that combat these problems may become unsustainable in the future.

To tackle this, Nature based Solutions (NbS), which address societal challenges through the protection, sustainable management and restoration of both natural and modified ecosystems, will benefit biodiversity and human well-being[3]. Thus, in order to achieve this paradigm shift for long-term sustainable coastal resilience, whilst embracing the naturally changing ecosystems, Coastbusters has developed pioneering steps towards facilitating natural biogenic reef formation for this innovative coastal zone management approach. Bringing together sandy foreshore stabilisation as a direct coastal protection contribution with enhanced biodiversity and increased water quality reflects this integrated sustainable NbS concept[4].

Therefore, the public-private Coastbusters consortium investigates the deployment of reef-facilitating infrastructures as a NbS for coastal protection. Coastbusters 2.0 was the first up-and-running research project explored within the framework of Blue Cluster, the Flemish spearhead cluster for the blue economy. Coastbusters technology has received ever-growing support from several players and stakeholders in society (civilians, universities, governmental organizations, etc.), creating inspiring awareness on our future coastal management.

The first Coastbusters project (2017-2020) investigated the overall feasibility of three Nature based Solutions (NbS) biogenic reef designs (Flora, sand mason worm *Lanice conchilega* and Blue mussel *Mytilus edulis*) to enhance coastal resilience. A dedicated report reflects on this pioneering assessment excercise

Coastbusters-type: Nature based Solutions for coastal zone management deliver several ecosystem services.

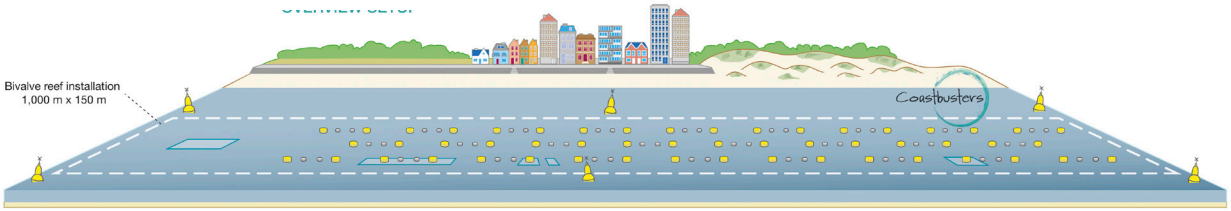
Coastbusters 2.0 (2020-2023) looked further into the blue mussel biogenic reef concept as the most promising innovative subtidal bio-stabilisation solution. Different materials and setups were deployed to induce and facilitate the early stages of mussel biogenic reef formation in two different hydrodynamic coastal environments (a sheltered site and a more exposed site) on the foreshore of the sandy Belgian coast. The purpose of this blue mussel (*Mytilus edulis*) biogenic reef is to induce natural accretion and (bio)stabilisation of sediment and enhance (local) biodiversity. This approach is envisaged to reinforce the foreshore against coastal storm impact, resulting in a more resilient and healthier coastal ecosystem.

Research on marine biodegradable & sustainable (bio)materials to replace standard synthetic materials such as PET or nylon - especially for their bio-facilitating properties (e.g. integration into anchoring systems) – is crucial to support and facilitate Coastbusters' building blocks for ecosystem-based coastal development and optimising the design of the setup to further stimulate reef development.

A high-quality science-based monitoring plan was developed and applied in high resolution for both dynamic environments and monitoring of the tested material, reef growth and decline. This monitoring approach can be implemented worldwide and under various conditions.

Next to technical, economic and social values, a dedicated assessment of the environmental benefits shows the ecosystem services provided by our Coastbusters type solutions.

The overall feasibility of the basic concept has been demonstrated in the pilot study off the Belgian Coast. A blueprint for operational excellence of biostabilisation for engineered dynamic resilience, storm survivability, ecosystem household and biodiversity is explored as a general guidance and source of inspiration towards worldwide nature inclusive coastal management and engineering.



A TYPICAL COASTBUSTERS SETUP FOR A SECTION OF THE COASTLINE.

BEFORE





Sediment profile

TEMPORARY INSTALLATION



AFTER





Sediment profile

THE COASTBUSTERS

Within the Coastbusters project, we have investigated a new innovative approach: ecosystem creation and/or restoration by building biogenic (not artificial) reefs that enhance biodiversity and ecosystem services, using biobuilder species and living organisms that reinforce the natural processes, flood and coastal defense etc. with one overall long-term goal: Nature based Solutions for large-scale ecosystem generation.



1 Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., & Grasso, M. (2017). Twenty years of ecosystem services: how far have we come and how far do we still need to go?. Ecosystem Services, 28, 1-16. https://doi.org/10.1016/j.ecoser.2017.09.008

2 Zamboni, N. S., Filho, E. M. N., & Carvalho, A. R. (2021). Unfolding differences in the distribution of coastal marine ecosystem services values among developed and developing countries. Ecological Economics, 189, 107151. https://doi.org/10.1016/j.ecolecon.2021.107151

3 Cohen-Shacham, E., Walters, G., Janzen, C. and Maginnis, S. (eds.) (2016). Nature based Solutions to address global societal challenges. Gland, Switzerland: IUCN. xiii + 97pp.

4 Mascart T., Sterckx T., Delerue-Ricard S., Fordeyn J., Huygens M. Coastbusters: A Nature based Solutions coastal management alternative. Terra et Aqua 163 (June 2021) 3, pp 26-37.

Our experiments in the test zone of the Belgian Marine Spatial Plan near De Panne confirm the potential of bivalves as biobuilder species for biogenic reefs. It works!



Checking the setup. (©ILVO)

Close-up of a dropper line with fish feeding on the fouling species. (©ILVO)



BIOGENIC REEF



FLORA REEF
Seagrass
and seaweeds (algae)



BIVALVE REEF
shellfish type mussels
and oysters



LANICE REEF
Sand mason worms
or tube building worms



DROPPER LINES



BIO-FACILITATING ANCHOR



LONGLINE



MUSSEL SHAKER

Biodegradable materials
Sustainable eco-friendly building blocks
Pioneering configuration and modular design
Novel monitoring methodologies
Ecosystem services approach

④ DESIGN

INTRODUCTION

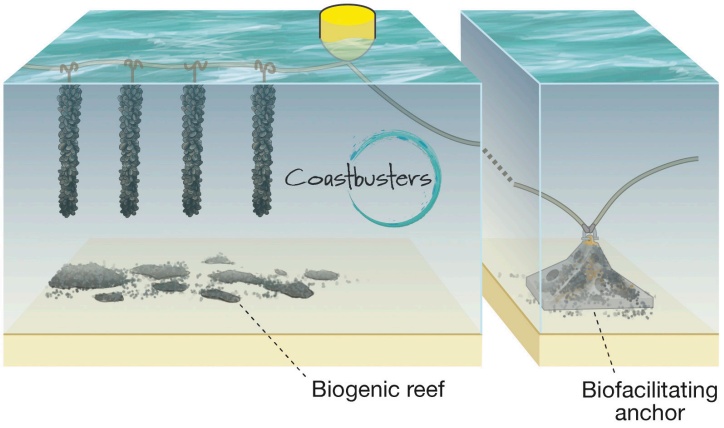
The Coastbusters approach is based on the adaptation of traditional aquaculture techniques. However, instead of harvesting mussels, the mussel dropper lines are left in place and mussels are allowed to grow undisturbed. Over time, the hydrodynamic drag force and weight eventually causes large clumps of mussels to break off and descend to the seafloor, ultimately establishing reefs. So basically, an aquaculture hanging culture system is adapted to initiate a mussel flux from the droppers towards the seabed to kick-start a biogenic reef development.

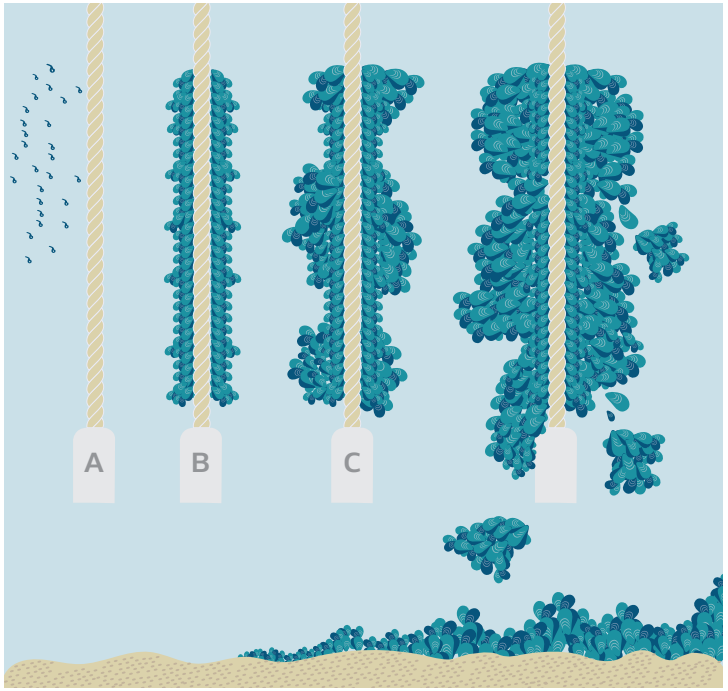
To assess survivability and biogenic reef development we investigated the performance and behaviour of the innovative long line set up in two study sites with sheltered and exposed environmental conditions respectively.

The Coastbusters setups typically consist of two anchor points (either gravity based or screw anchor), connected by a horizontal backbone rope which acts as the main supporting structure. Vertical dropper lines are at regular intervals attached to a horizontal backbone for capturing mussel spat and growing mussels. The structure is kept buoyant with floaters positioned at regular intervals to provide buoyancy to the backbone system. Special connectors to attach the dropper lines to the backbones were designed, manufactured and tested specifically for this project. These are short sticks that allow easy handling, maintenance and monitoring of the overall setup. To increase the extent and the density of the biogenic mussel reef on the local seabed, multiple longline setups were installed parallel to each other.

> The traditional aquaculture set-up is adapted to kick-start a biogenic reef.

MUSSEL LONGLINE FACILITATION SYSTEM





(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 form a reef. (©ILVO).



The backbone is kept buoyant by several floaters.



Backbone prior to assembly and installation.



The state of the backbone after several years at sea.

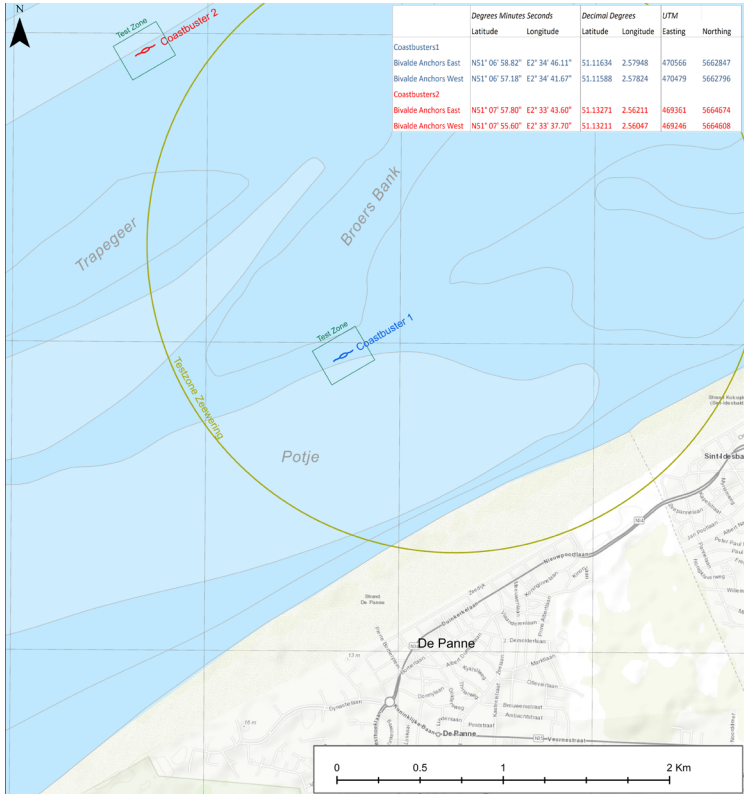


5 out of 6 backbones were anchored by means of large screw anchors.



1 out of 6 backbones were anchored by means of 2 different gravity anchors of approximately 15-16T.

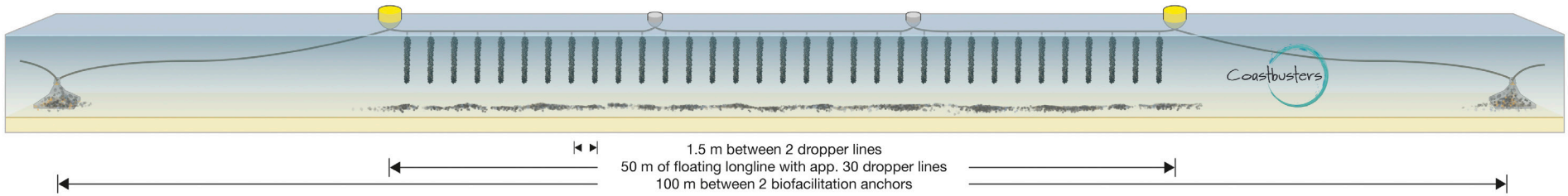
Pictures of the Coastbusters set-up.



	Degrees Minutes Seconds		Decimal Degrees		UTM	
	Latitude	Longitude	Latitude	Longitude	Easting	Northing
Coastbusters1						
Bivalde Anchors East	N51° 06' 58.82"	E2° 34' 46.11"	51.11634	2.57948	470566	5662847
Bivalde Anchors West	N51° 06' 57.18"	E2° 34' 41.67"	51.11588	2.57824	470479	5662796
Coastbusters2						
Bivalde Anchors East	N51° 07' 57.80"	E2° 33' 43.60"	51.13271	2.56211	469361	5664674
Bivalde Anchors West	N51° 07' 55.60"	E2° 33' 37.70"	51.13211	2.56047	469246	5664608

Overview of the coastal defence zone by marine spatial plan with the location of the Coastbusters set-up.

MUSSEL LONGLINE FACILITATION SYSTEM



BIO-FACILITATING ANCHOR

In search of a more sustainable Nature Based Solution, special bio-facilitating anchors were designed to assist in providing suitable habitat for surrounding ecosystems and to stimulate the recruitment of important target species. Thus, the anchor blocks became an integrated part of the ecosystem-based setup, being able to sustainably maintain the ecosystem over time. The sloping pyramid shape has been determined as a good balance between anchor capabilities with its low centre of gravity and bivalve spat recruitment with its high structure off the seafloor. Different design characteristics such as crevasses, macro relief, micro relief and eco-concrete were used and added to enhance biodiversity and reduce the environmental footprint.



Bio-facilitating anchor with oyster shells as substrate and holes to serve as shelter for organisms.



Bio-facilitating anchor. Smooth side with pins for the Autonomous Reef Monitoring Structures (ARMS) and rough side with oyster shells as growing substrate.



Mussel shaker and bio-facilitating anchors on deck of the installation vessel.



Bio-facilitating anchor during installation.

BIODEGRADABLE MATERIALS

Textiles (i.e. ropes) are an important element of the reef facilitating system of the Coastbusters setup. Project partner SIOEN put a lot of effort into the development of **biobased/biodegradable** and sustainable yarns and ropes. The main reason for this shift from traditional textiles such nylon, polyester and polypropylene to marine biodegradable textiles is that the use of such traditional textiles in the marine environment is strongly discouraged as these materials contribute to the global problem of micro and macro-plastics in our seas and oceans.

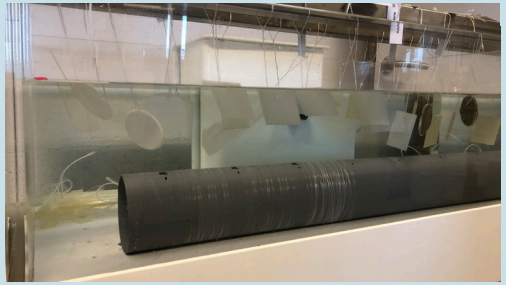
We specifically targeted the in-house research and development of innovative, tuneable, marine biodegradable materials and textiles on lab- and field-scale. More sustainable yarns and ropes had to fulfil a number of criteria: readily available materials, similar functional lifetime as traditional ropes, marine biodegradability within 1-10 years under marine conditions, environmentally safe, appropriate tensile strength for the targeted application, abrasion resistant, UV stable, etc.

Starting from commercially available biopolymer granulates (e.g. PLA, PBSA, PCL, PBS, PHBH, etc.) we studied more than 25 different homopolymers and polymer blends. The most critical step was to identify spinning conditions to convert these materials into multifilament yarns with the targeted properties. The resulting yarns were subsequently tested in seawater to follow up their mechanical properties over time. After 6-12 months we identified one material (PBS) with good properties. This material was subsequently bought at ton scale, spun into multifilament yarns and finally converted into 32 mm ropes. These ropes were then deployed and tested as mussel droppers in the test zone in De Panne.





Biobased ropes deployed as mussel droppers at sea being tested on biodegradability. (©ILVO)



Various multifilament yarns being tested in a homarium filled with sea water. (©Sioen)

Biodegradable materials, defined by their ability to break down into substances found in nature within a reasonable timeframe, are crucial for ecosystem based solutions.



A dropper line of PBS filamentous overgrown with mussels at the sheltered site during the September 2022 campaign. (©ILVO)

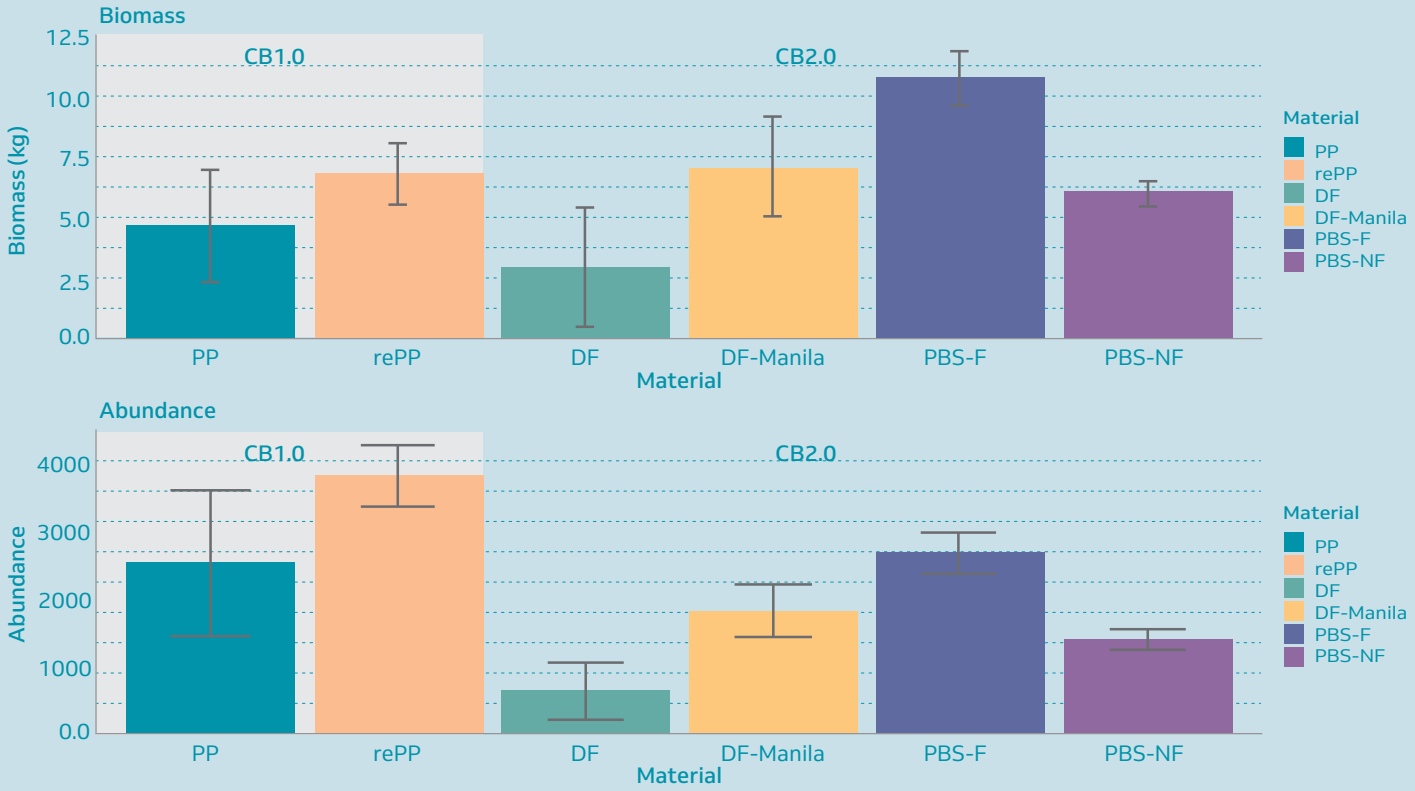
DROPPER LINES

Over the course of the project, design optimisation was achieved through extensive testing and monitoring of different types of **dropper lines**. A well-established monitoring plan which included dedicated observation techniques, such as crane scale measurements, photo image processing and laboratory analysis allowed the team to conclude that thick filamentous ropes (e.g. PBS-F) in combination with a growth period of ~1 year resulted in a high mussel biomass and effective rope detachment.

Good timing of bivalve detachment is essential for biogenic reef formation.

Good mussel attraction and growth can be achieved when the structure of the material is complex (filamentous).

Average Biomass and Abundance per 1m Line by Material, CB1.0 and CB2.0



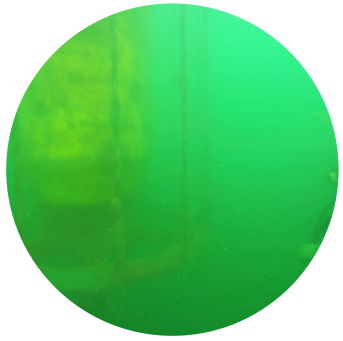
Average biomass (top) and abundance (bottom) per 1m line by material (PP, Polypropylene; rePP, Re-used and cleaned Polypropylene; DF, Deltaflex; DF-Manila, Deltaflex covered with Manila; PBS-F, Poly(butylene succinate) made filamentous; PBS-NF, Poly(butylene succinate) non-filamentous). Grey shaded regions represent materials from CB1.0; non-shaded regions represent materials from CB2.0. Due to insufficient data, the following materials were left out of the analysis: natural materials from CB1.0; and BB; BB_Manila from CB2.0. (©ILVO)

MUSSEL SHAKER

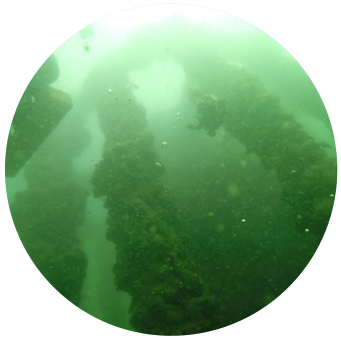
The **Mussel Shaker** constitutes a further design development of the reef inducing infrastructure. The new design of the stand-alone setup aims to extend the spatial biostabilisation zone of the generated biogenic reef in an easier to handle single point buoy configuration. Basically, it serves the same function as the traditional Coastbusters longline setup and has a similar working principle. However, it consists of two main elements: a bio-facilitating anchor and a Mussel Shaker (see picture below).

The Mussel Shaker consists of a submerged buoy surrounded by vertical dropper lines that once more serve as growing substrate for mussels. It's connected to the bio-facilitating anchor and floats at an inclination of approx. 30° in the direction of the current when fully grown. Over time, the Shaker 'shakes' the mussels off the dropper lines, which ultimately creates a biogenic mussel reef underneath.

The Mussel Shaker is an affordable, biodiversity-enhancing and easy-to-install stand-alone system that can be implemented on numerous maritime construction projects.



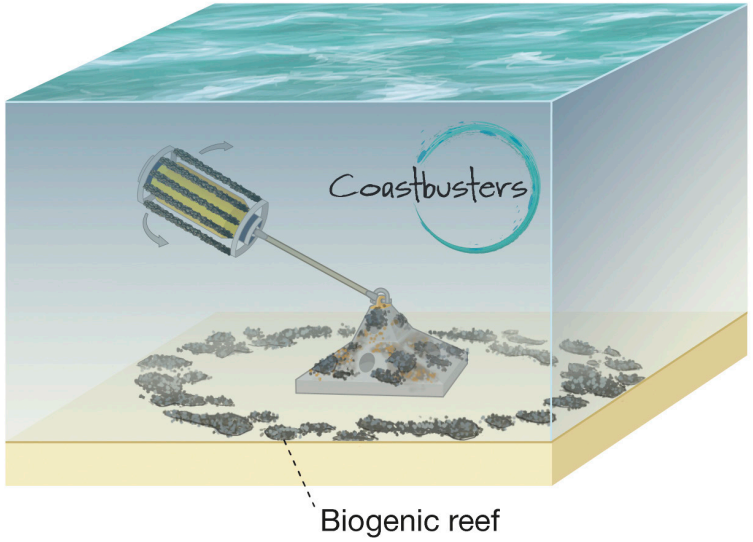
The Mussel Shaker 3 months after installation. (© ILVO)



Grown mussels on the single mooring mussel shaker during the Summer 2022 diving campaign. (© ILVO)



Single mooring mussel shaker during installation.



Scheme of the function of the Mussel Shaker.

5

MONITORING

METHODS AND TECHNIQUES

Coastbusters 2.0 wanted to further investigate knowledge gaps to successfully kick start and facilitate biogenic mussel reef growth in the Belgian part of the North Sea. The knowledge gaps were translated into specific research questions, for which a targeted and extensive monitoring programme was set up. To this extent, longlines were installed in a pilot field at both a more sheltered and a more exposed site off the coast of De Panne. Next to the biogenic reef areas, also control areas for both sites were delineated as reference spots. In addition, the project deployed and evaluated innovative monitoring methods to efficiently capture data on key parameters.

At the start of the Coastbusters 2.0 project, a dedicated monitoring inception plan and an implementation plan for novel techniques were developed. The first plan described the basic monitoring programme to gather the data required to reach the goal of the project: developing a sustainable mussel reef for coastal protection. One of the goals of the research institutes involved in the project was to get more insights into novel monitoring techniques and test their suitability and efficiency for the monitoring of natural processes during biogenic mussel reef development in the shallow conditions of the North Sea. Therefore, the implementation plan of these novel observation techniques outlined known advantages and disadvantages, knowledge gaps and possible developments needed to improve the method for use for our application.



Mussels growing on the Coastbusters dropper lines (© ILVO).

Some of the standard monitoring methods used were grab samples, Sediment Profile Imaging, multibeam for bathymetry and scientific divers. The innovative techniques included the use of an Unmanned Surface Vehicle (USV), Autonomous underwater vehicles (AUV) and seabed mooring frames equipped with a scanning sonar, as well as innovative measurements with accelerometers and multibeam (water column data) and new dropper line weighing/measuring methods to gather data on the setup, its dynamic behaviour and the growth of biomass on the setup.

All lessons learned as well as all guidelines for dedicated monitoring of these biogenic reefs have been included in the Coastbusters monitoring roadmap, a crucial operational management tool for further site applications.

Innovative monitorings methods were developed which proved efficient to monitor, manage and operate the Coastbusters setup.



AUV deployed from the RV Simon Stevin at the Coastbusters site. (©VLIZ)



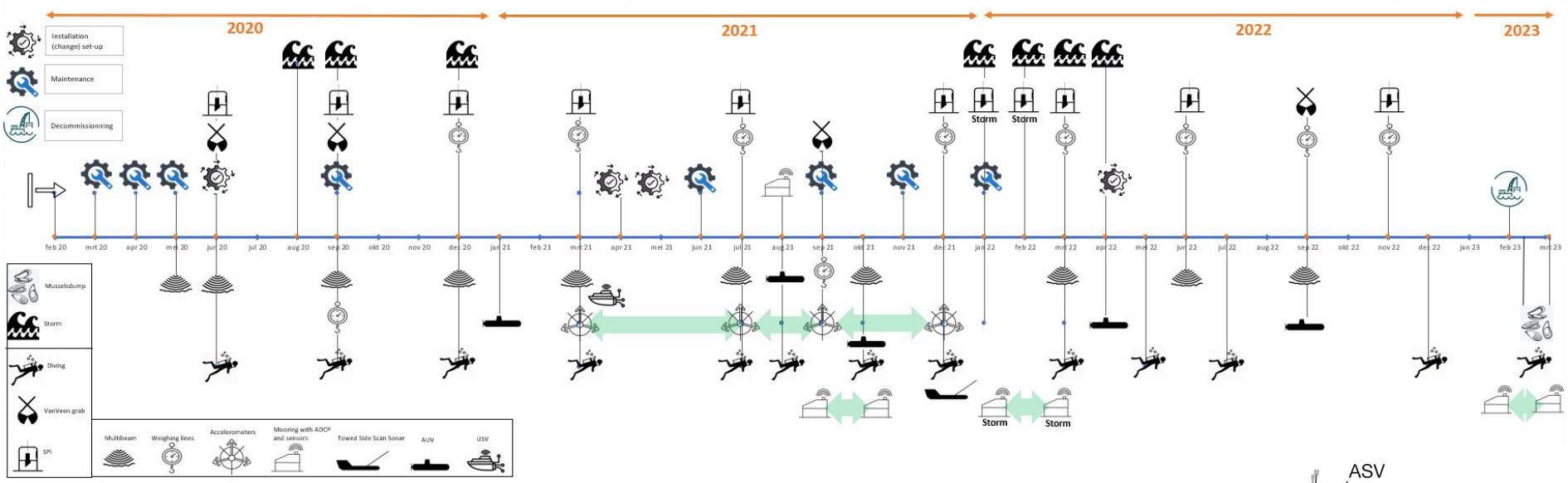
First USV run from the harbour of Nieuwpoort to the Coastbusters test site off De Panne. (©VLIZ)



Sampling campaign using Van Veen Grab and rinsing samples on board the vessel. (© ILVO)

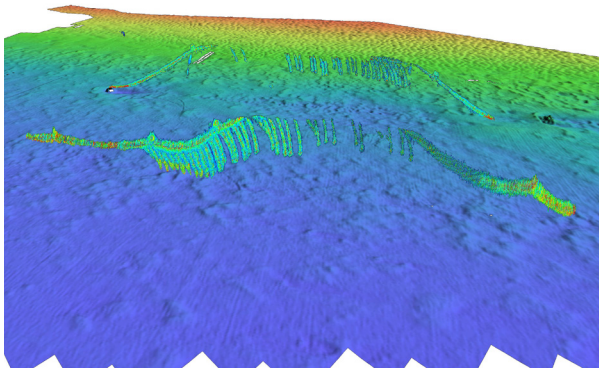


Deploying the Image Sediment Profiler. (© ILVO)

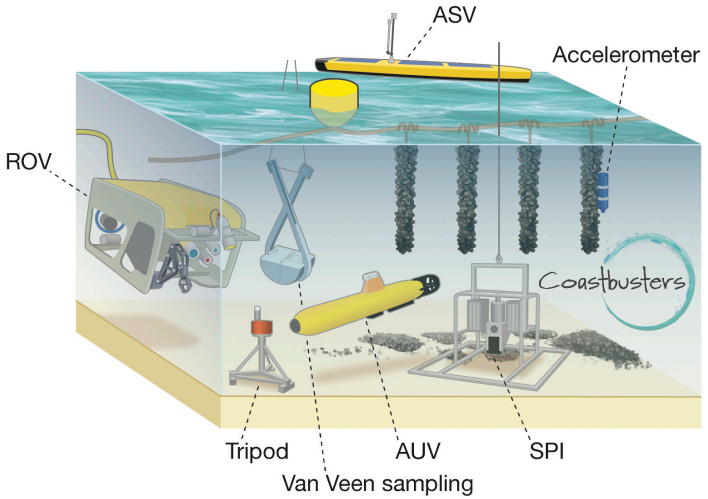


Timeline of Coastbusters monitoring operations.

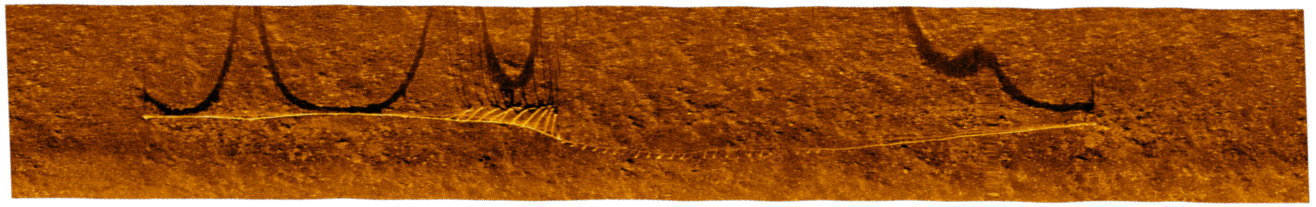
The highly technical monitoring was vital in understanding the dynamic and challenging nature of our study sites. This meticulous approach proved to be imperative in gaining comprehensive insights into the ecosystem's responses to complex natural processes and dynamic changes over time.



Multibeam water column data visualising the setup. (©VLIZ)



Hardware used for the monitoring of the mussel longline and Mussel Shakers.



Side Scan Sonar image captured by the AUV. (©VLIZ)

REEF DEVELOPMENT

Over a three-year period, the seabed ecology and formation of newly created mussel beds were investigated in detail at the two pilot test sites. Different hydrodynamic conditions at the respective research spots strongly influenced the seabed and benthic community, with the sheltered site exhibiting higher density, species richness, biomass, and diversity compared to the exposed site. In relation to the mussel bed developments, mussel patches were found at both sites (higher occurrence in shelter) in the 2nd and 3rd year (mainly in summer towards early winter).

The summary graph (see to the right) illustrates the dominant habitat types over time. The recorded observations illustrate that mussel patches were more frequently observed in the second and third year, with the highest mussel reef coverage observed during Coastbusters 2.0 at both sites: at the exposed site a reef surface of about 42 m² was recorded, while at the sheltered site the biogenic mussel reef covered a surface of 216 m².

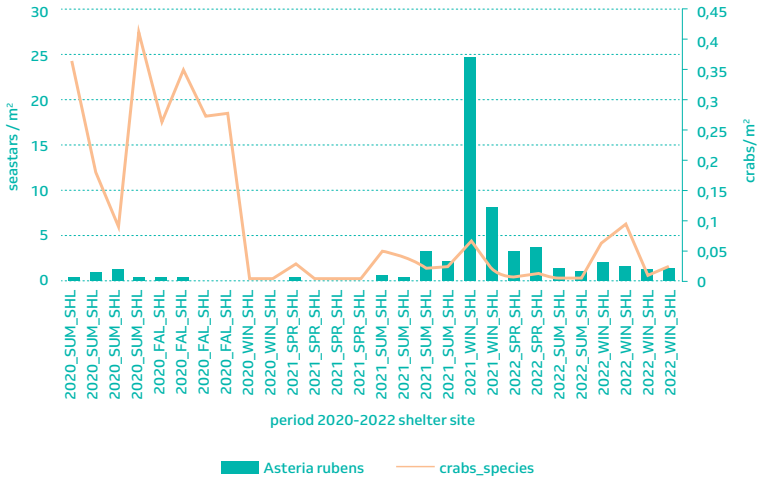
Over the course of the project, the multiple multibeam and diving campaigns have resulted in a timelapse of the local seabed evolution under the biogenic reef development. Detailed assessment of sedimentation and erosion in the area has revealed valuable information on seasonal variations, biogenic mussel reef growth and sediment dynamics in the area.

It's important to acknowledge that differences in environmental factors, such as local hydrodynamics (currents and waves) and local ecological water and sediment dynamics, largely vary from year to year. These natural fluctuations impact mussel larvae

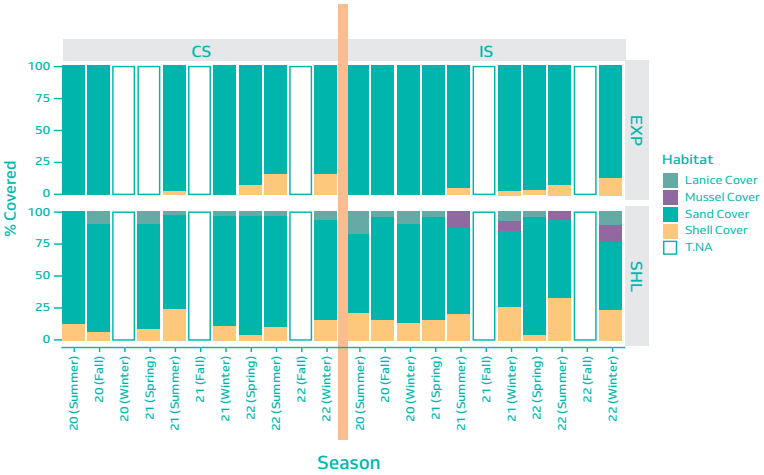
Over time, the initial biogenic mussel clumps may grow into a biogenic reef, not only stabilising the local sea bottom but also inducing further habitat development, which will enhance biodiversity and the overall value of the reef.

capture as well as the growth and the associated success of biogenic mussel reef development. Consequently, the efforts required for proper management, maintenance and enhancement of this nature-based setup are directly linked to the local (complex) seasonal natural dynamics. Recognising this inherent variability is crucial for managing expectations and planning resource allocation effectively. It underscores the need for adaptive strategies that can respond to the dynamic nature of these ecosystems. Our research has shown that a flexible and adaptable approach is essential for achieving sustained success in the development of Mytilus edulis mussel reefs. This is an inherent consequence of having Nature based Solutions in place for coastal zone management.

Another aspect that demands special attention are the long-term effects on and under the aquaculture set-up installation. Achieving the desired ecological differentiation – in line with the targeted marine biodiversity - within the coastal test sites with the scheduled and developed biogenic mussel reefs is not an overnight endeavour. It's a complex and highly dynamic natural process that unfolds over



Amount of sea stars and crab species per m2 and per season over time from 2020 to 2022. Analyses and counts made through diving transects under the installation set-up. (© ILVO)



Temporal variability in mussel reef persistence for the reference sites (CS) and reef sites (IS), separated by the orange line, for the 2020-2022 period, under sheltered (SHL) and exposed (EXP) hydrodynamic conditions. A percentage of the seabed coverage is given for different habitats (Mussel, Lanice, Shell and Sand). (© ILVO)

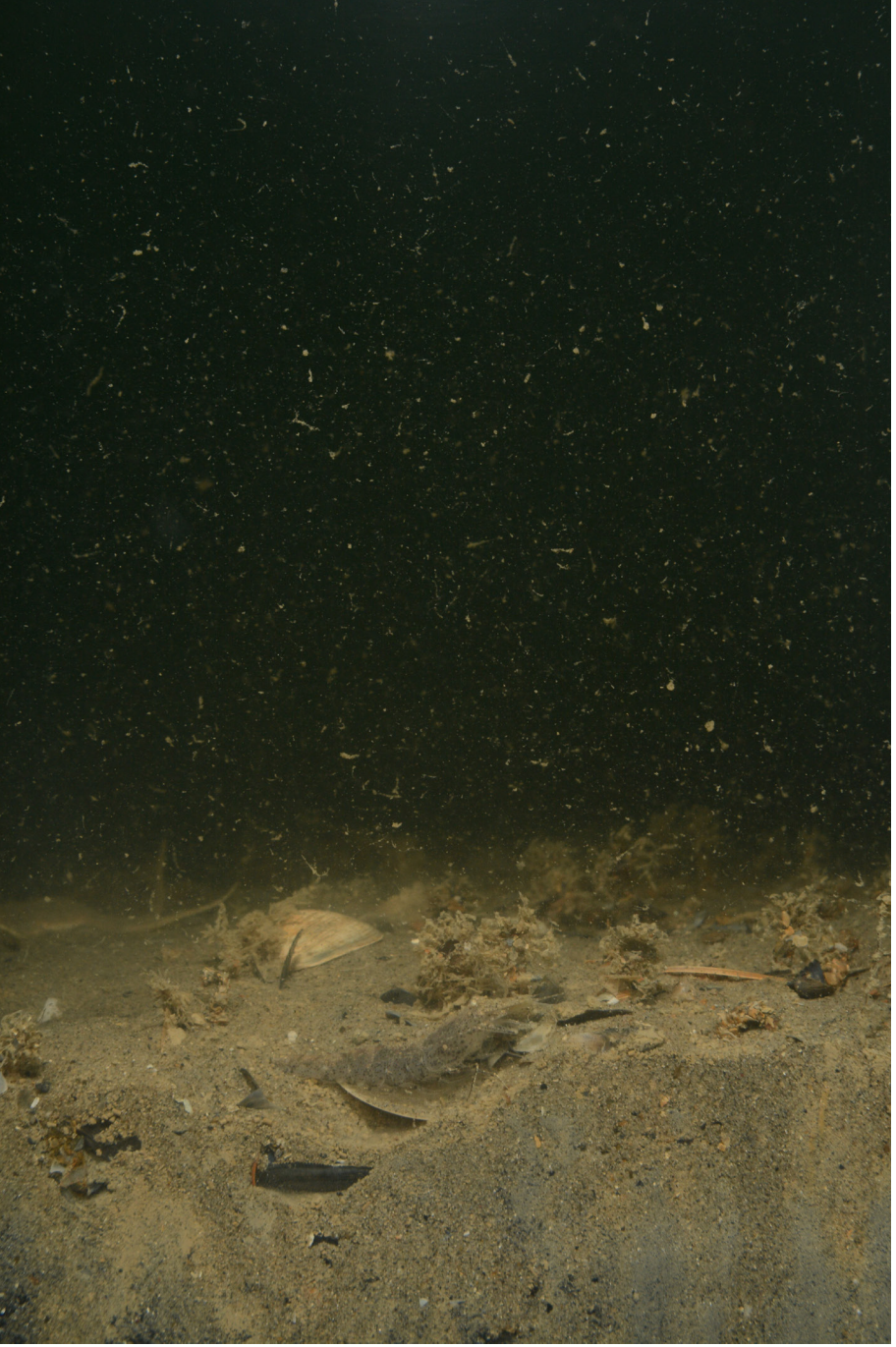


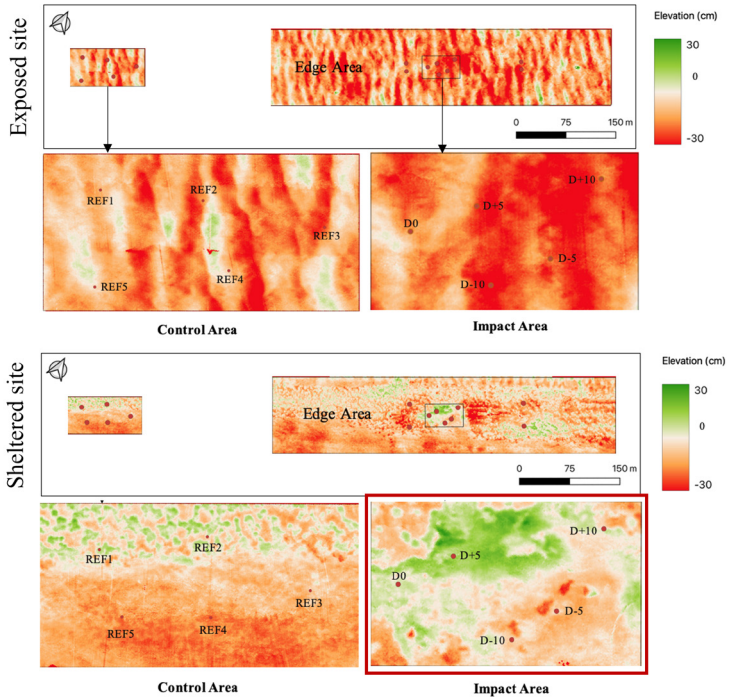
Image taken by Sediment Profile Imaging during 2022 autumn campaign. A brown shrimp is present in the middle of the image. (© ILVO)



Image taken during diving transect in the winter of 2022 at the sheltered reef development zone under the installation. (© VLIZ)



Image taken during diving transect in the summer of 2021 at the sheltered reef development zone under the installation. (© VLIZ)



Changes in elevation between T0 (summer of 2020) and T3 (fall of 2022). A: Exposed hydrodynamic conditions. B: Sheltered hydrodynamic conditions. Red and green colours indicate erosion and accretion respectively. D0, D+5, D-5, D+10 and D-10 are the benthic sampling points for the impact area. REF1, REF2, REF3 and REF4 are the benthic sampling points for the control area (© ILVO). (©VLIZ)



Diving image showing sea stars coming to feed on the mussel reef. (© VLIZ)

several years. The establishment of a stable and self-sustaining biogenic reef requires time for various ecological interactions to develop and mature. Factors such as the recruitment (of associated species) and the gradual buildup of habitat structure contribute to the final ecological differentiation. This extended timeline underscores the importance of patience and persistence in the management of biogenic mussel reef projects as a resilient and adaptive solution for climate proof coastal zone management. It also emphasizes the need for continued monitoring and adaptive management - as crucial operational tools - to ensure that the ecosystem matures in a sustainable manner.

Moreover, a biogenic mussel reef is subject to the influences of various predators, among which the common sea star and various species of crabs play significant roles. Common sea stars are consumers of mussels, employing their tube feet and specialised feeding structures to open mussel shells. Likewise, crabs, with their powerful claws, are also identified as predators of the blue mussels, targeting both juvenile and adult mussels. This predation exerts a selective pressure on mussel populations, influencing their growth, their spatial and temporal distribution and the overall abundance of blue mussels – both at the vertical dropper lines of the Coastbusters setup and on the biogenic mussel reef on the seabed. As a result, the dynamic interplay between mussels and their natural predators contributes to the complex ecological balance of the ultimate survival and resulting enlargement of the biogenic mussel reef environment.-

The journey towards inducing mussel reefs has illuminated the intricate dynamics of the ecosystem. The substantial variability observed, both within and between years, underscores the necessity of meticulous monitoring and adaptable management strategies. While our research has brought us closer to understanding the ecological nuances of these biogenic reef sites, it also emphasizes the ongoing complexity of managing these natural reef systems.



A fully grown dropper line during the September 2021 campaign at the sheltered site. (© ILVO)

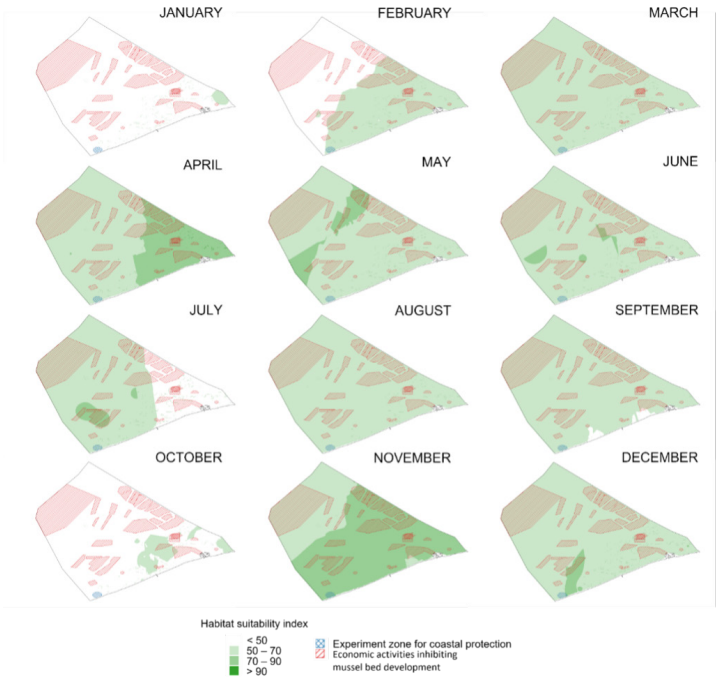


A dropper line grown with mussels and amphipod fouling species Jassa spp.with a clear presence of crabs. (© ILVO)

HABITAT SUITABILITY MODELLING

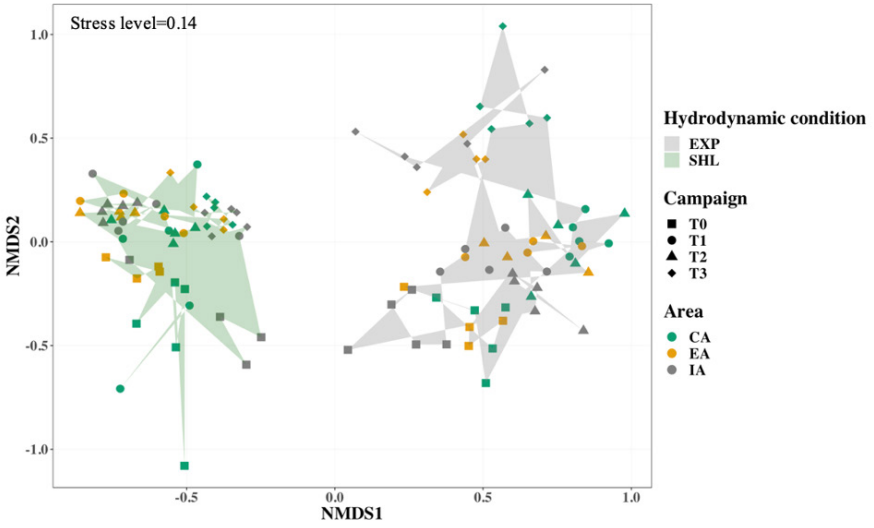
Despite having been present in the past, to date, only relicts of the subtidal mussel reefs are present in the Belgian Part of the North Sea. To gain additional insights in the operational feasibility of the Coastbusters 2.0 project, a habitat suitability model using fuzzy logic has been developed to identify potential locations where mussel reefs could thrive. To do so, nine environmental parameters were included in the model, covering biotic, abiotic, and hydrodynamic conditions. These parameters may interact in complex ways, and the fuzzy logic approach allowed us to conceptualize these interactions. The model was validated after application of the model to the southern North Sea and by comparing the predicted locations for mussel reefs with known locations. Initial results found the habitat suitability of the Belgian Part of the North Sea for subtidal mussel reefs is temporal and spatially variable. The model can contribute to the identification of favourable growth sites of mussel reefs as a nature-based solution in the Belgian Part of the North Sea.

The presented habitat suitability map delineates zones where environmental parameters align optimally with the requirements of the Blue Mussel (*Mytilus edulis*). This tool guides our efforts to explore the Coastbusters pilot in other "proper" marine areas, allowing us to deploy resources strategically and maximise the potential for success.



Initial results of the habitat suitability modelling for M. edulis in the subtidal zone of the BPNS. The habitat suitability is indicated by the green colour scale. White is less suitable, i.e. habitat suitability of < 50%, and light green to dark green is more suitable, i.e. habitat suitability of 50% - 100%. (©VLIZ)

Given these considerable distinctions, it is prudent to conduct separate monitoring and assessments for each site, recognising the unique conditions that shape their respective environmental paths, e.g. the hydrodynamic conditions and differences between the shelter site and the exposed site (see next figure).



Non-metric multidimensional scaling (nMDS) of the macrobenthos community. The analyses were performed using abundance data of species and based on Bray Curtis dissimilarity. The pre-defined factors (site (SHL & EXP), area (reference & installation set-up) and campaign (Van Veen grabs)) were used in the nMDS, which showed clear differences between exposed and sheltered conditions as well as between the sampling campaigns. (© ILVO)

6 ECOSYSTEM SERVICES

Human-induced changes and activities are mostly subjected to environmental and social legislative requirements, especially when they are be executed in marine protected areas (Natura 2000). Therefore, we detailed the legislative framework wherein the Coastbusters concept needs to operate. The criteria and indicators, defined by several EU environmental legislations, which are relevant in evaluating the added value of the Coastbusters concept are outlined. The DAPSI(W)R(M)) (Drivers-Activities-Pressures-State change-Impacts (on human Welfare)-Response (using Measures)) framework was used as guidance for a proper impact evaluation of the Coastbusters concept. It can help in defining the need for certain social and/or environmental measurements to be implemented or operational management (including dedicated monitoring) requirements when setting up the Coastbusters concept. The set of indicators related to this framework allows to evaluate how much added value in structure and functional characteristics of the seabottom ecosystem and their ecosystem goods and services is created by the Coastbusters concept. Doing so, we facilitate the paradigm shift from strict economic profit maximizing towards global (sustainable) value creation in future coastal zone management.

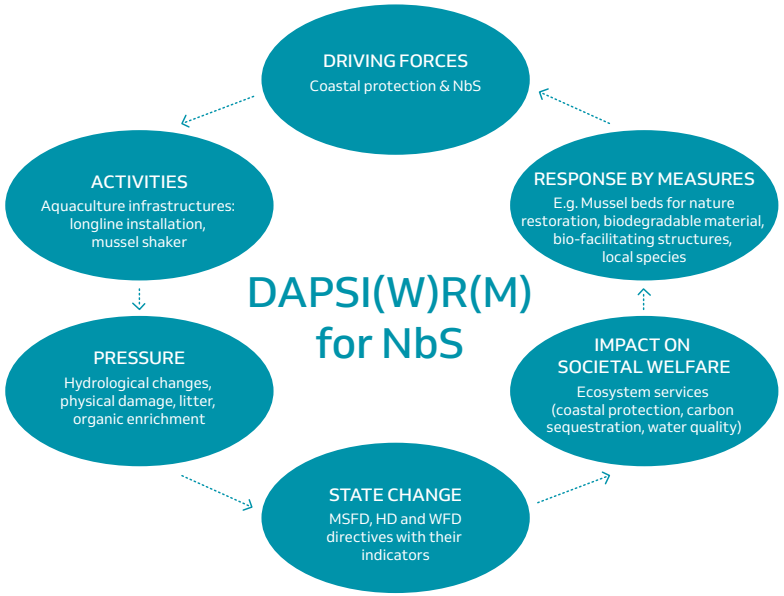
Mussel reefs lead to a gain in overall ecosystem services, indicating a significant increase in sustainable values on coastal resilience.

The biophysical quantification and economic valuation of ecosystem services offered by the biogenic mussel reef at both the exposed site and the and sheltered site yield noteworthy insights (see table on the next page). Specifically, for coastal protection*, the sheltered site demonstrates a gain of 9058.5 euros per year. This assessment is derived by comparing the average net erosion after two years of installation with the net erosion observed at the reference site for both locations. The findings reveal a lower rate of erosion at the sheltered impact site, suggesting a positive influence attributable to the reef installation.

In terms of carbon sequestration**, a loss of -11.86 euros per year is observed. This valuation is based on assumptions about the population structure derived from the longline population, assuming that the entire mussel population (100%) settles on the seafloor. Furthermore, for water quality regulation***, a gain of 80.61 euros per year is estimated. This evaluation accounts for denitrification processes within the biogenic reef. To provide the most accurate representation of a biogenic reef predominantly composed of *Mytilus edulis*, water quality regulation was computed at a specific sampling site (Van Veen Grab Sampler) where the abundance and biomass of *Mytilus edulis* were highest. This calculation was then extrapolated to cover the highest observed mussel density during Coastbusters 2.0 at both sites, encompassing 42 m² and 216 m² respectively.







The essence of DAPSI(W)R(M) is to link the natural and social systems to deliver the Ecosystem Approach, i.e. to protect and maintain the natural system while supporting ecosystem services which then can help to deliver societal goods and benefits (Patricio et al., 2016). (© ILVO)

	Ecosystem service	Biophysical quantification		Economic valuation	
		Exposed site	Sheltered site	Exposed site	Sheltered site
Regulating	Coastal protection*	-1102.50 $m^3 y^{-1}$	1485 $m^3 y^{-1}$	-6725.25 € y^{-1}	9058.50 € y^{-1}
	Carbon sequestration**	-141.65 kg C y^{-1}	-149.65 kg C y^{-1}	-11.23 € y^{-1}	-11.86 € y^{-1}
	Water quality regulation***	0.183 kg N y^{-1}	3.452 kg N y^{-1}	4.27 € y^{-1}	80.61 € y^{-1}
			TOTAL SUM	-6732.21 € y^{-1}	9127.25 € y^{-1}

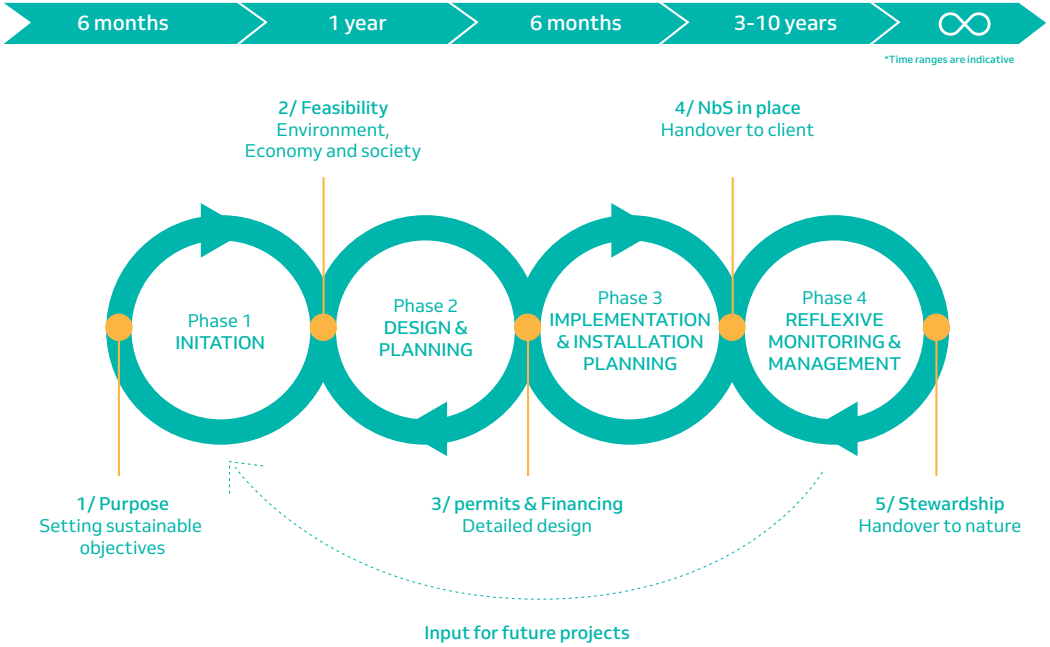
Biophysical quantification and economic valuation of the ecosystem services provided by the mussel reef at the exposed and sheltered sites. In green: gain in ecosystem services; in red: loss of ecosystem services (UA).

7

COASTBUSTERS BLUEPRINT

Implementing Nature based Solutions requires a new business model approach and economic thinking, valuing natural capital

Reflecting on our research activities over the last 6 years, the consortium has compiled a Blueprint to assist the development of sustainable coastal NbS projects along the triple bottom line pillars (social inclusion, economic growth, and environmental protection) or the three sustainability P's (people, profit, planet). The Blueprint framework should be seen as a transdisciplinary approach involving all stakeholders, based on natural processes, system understanding and a practical implementation point of view. This guide will hopefully lead to upscaling of similar concepts, which in term will generate future business applications and large-scale co-benefits for local coastal communities.



Coastbusters NbS project implementation Blueprint.

Based on our research, expertise, and pilot projects, 4 phases and 5 stage gates are key for successful implementation of sandy foreshore NbS solutions. Doing so, the presented Blueprint combines all different building blocks of the Coastbusters R&D towards an operational development tool, bringing the NbS application of Coastbusters to the business market.

The main motivation for the implementation of NbS for coastal adaptation (Moreas et al. 2022)[1] is the need for improvement of existing static and single-use coastal defences and additionally the search for co-benefits, which leads us to our first "Purpose" stage gate, where defining sustainable objectives will frame the initiation phase.

The initiation leads to a feasibility report in which main technical constraints, to be considered in the subsequent design process (e.g. suitability of the environment, biotic & abiotic parameters, key ecosystem engineering species, multi-stakeholder assessment, local community involvement and financing schemes), delineate site-specific boundary conditions.

The main motivation for the implementation of NbS for coastal adaptation is the need for improvement of existing static and single-use coastal defences.

At the start of the Design & Planning phase, different feasible Nature based Solutions will be compared to each other and to conventional solutions. Considering the above-mentioned social inclusion, economic growth, and environmental protection criteria, a decision will have to be made to estimate yielded co-benefits, execution timeline, foreseen costs and the permitting process of a chosen solution. Subsequently, based on the final detailed design, preparations for implementation, installation, and baseline monitoring can start.

Once the kick-starting facilitation infrastructures have been fully installed, a handover to the project initiator can take place, triggering mid-, and long-term monitoring to evaluate the evolution of the generated biogenic reef. The results will trigger a reflexive adaptive management strategy, allowing to tweak where necessary at multiple levels (i.e. technical resilience, community involvement, and monitoring strategy).

In the final stage gate, the generated natural reef becomes self-sustainable and doesn't require adaptive interventions, nor facilitating infrastructures. At that point, the project should be handed over for stewardship to the local community and fully given back to nature's natural cycle.



© ILVO

By implementing this Nature based Solutions Coastbusters Blueprint, project initiators will yield co-benefits for local coastal communities, including improved integrated coastal zone management against flooding[2], reduced maintenance costs of existing structures, increased lifespan and lower whole life cost, positive socio-environmental results, and biodiversity enhancement.

1 Moraes, R. P. L., Reguero, B. G., Mazarrasa, I., Ricker, M., & Juanes, J. A. (2022). Nature-Based Solutions in coastal and estuarine areas of Europe. Frontiers in Environmental Science, 10, 829526. https://doi.org/10.3389/fenvs.2022.829526

2 Pontee, N., Narayan, S., Beck, M. W., and Hosking, A. H. (2016). Nature-Based Solutions: Lessons from Around the World. Proc. Institution Civ. Eng. - Marit. Eng. 169 (1), 29–36. doi:10.1680/jmaen.15.00027

8 FUTURE OUTLOOK

In conclusion, the Coastbusters concept is executable and scientifically measurable in a North Sea foreshore environment. The consortium has developed new designs, enhanced configurations and modularity, yielded co-benefits, and gained insight in the highly dynamic behaviour of the offshore facilitating infrastructure and newly formed natural biogenic reef. The operational experience and fundamental knowledge induce a much more better understanding and grip on the long-term effects of the Coastbusters-setup.

The synergy of a stakeholder-wide supported endeavor,scientifically underpinned data analysis, and a successful pilot, have given Coastbusters the opportunity to establish a blueprint for design, installation, maintenance, monitoring & stewardship for ecosystem based coastal management of sandy foreshores.

But most of all, the Coastbusters concept has been growing from a crazy idea of a few ecological believers towards a quality trademark for nature - inclusive coastal management and engineering – inspiring others to believe in (hybrid) NbS and fully explore its sustainable potential.

We are ready to explore… and bring Coastbusters to new coastal challenges.

9 A SPECIAL THANKS GOES TO

- VLAIO and Blue Cluster.
- Sioen, DEME, Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), Jan De Nul and Flanders Marine Institute (VLIZ), partners in the project.
- Flemish Agency for Maritime and Coastal Services (MDK), Management Unit of the North Sea Mathematical Models and the Scheldt estuary (MUMM), Maritime Rescue and Coordination Centre (MRCC) and the municipality of De Panne.
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- The crew of the RV Simon Stevin and the Zeekat to enable the multiple monitoring and diving campaigns.
- The department of Hydraulics and Geotechnics of the KU Leuven and the Ecosphere research group of the Antwerp University.
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- Local coastal communities and a bunch of enthusiastic students looking for a challenging topic for their internship or thesis work and coming up with refreshing ideas.
- Universities and university colleges for their open mind and confidence in Coastbusters as an inspiring research topic, as well as all students who have worked with full dedication on this project.



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Coastbusters

