# North Sea ReViFES

lessons learned for North Sea reefs

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Waardenburg Ecology · NIOZ · Wageningen University & Research · TU Delft

*Colofon*


**ACKNOWLEDGEMENTS**

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**IMAGE CREDITS**

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# Contents



# Synthesis

## Why the North Sea ReViFES scientific program?

**The North Sea ReViFES scientific program was designed to create building blocks for reef restoration in the North Sea. More specifically, it aims to 1) quantify the ecosystem services that restored reefs provide, and 2) develop new techniques for reef restoration in the North Sea. As such, it provides insight in reef enhancement options in (future) wind farms.**

The program is built around four building blocks:

1. **Quantify ecosystem services of natural reefs:** Provide empirical data on biodiversity output and other ecosystem benefits of reefs in the North Sea.
2. **Develop techniques for oyster hatcheries and settlement:** Optimization steps focusing on providing sufficient healthy oyster larvae and settled oysters to serve as source material in restoration projects.
3. **Collect empirical data on reef enhancement measures in wind farms:** Provide empirical data on biodiversity output and other ecosystem benefits that directly result from implementing eco-friendly designs in offshore wind farms.
4. **Design principles for reef enhancement in wind farms:** Substantiate knowledge on how to design effective reef restoration and biodiversity enhancement measures in offshore wind farms.

### Need for North Sea reef restoration

Human activities have had a significant impact on North Sea marine ecosystem. Vast areas of biogenic reef habitat, such as reefs of the European flat oyster *Ostrea edulis*, were lost in the twentieth century due to bottom disturbance and overfishing. There is growing interest worldwide in restoring biogenic reefs to revive ecosystem services like biodiversity, carbon storage, shoreline protection by coastal reefs and water filtration. Since their decline, major changes in both the environment and human activities have occurred, calling for contemporary restoration strategies for North Sea reefs. Offshore wind farm developments give rise to reef restoration opportunities.

### Opportunities for reef restoration in the North Sea: wind farms

There is potential for broader reef restoration efforts in MPAs, but at present these areas in the North Sea are not yet sufficiently protected from bottom disturbing activities such as fishing and sand extraction. By contrast, where at offshore wind farm sites, bottom disturbing activities are generally excluded to protect infrastructure like foundations and cables. This results in areas of undisturbed stable seabed, a condition that hasn't occurred in the North Sea for well over a century. This gives rise to the opportunity for benthic ecosystem recovery, or even active restoration. At the same time, the foundations of wind turbines and other infrastructure, such as scour protections, provide stable, hard substrates that serve as settlement surfaces for reef-building species like oysters, and function as artificial geogenic reefs.

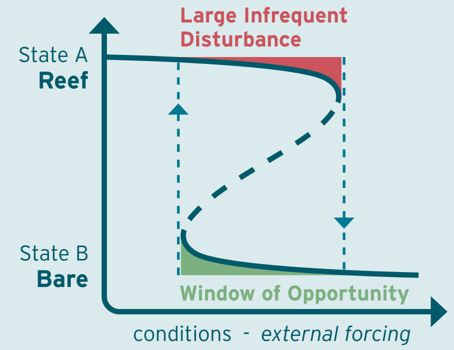
### 15-fold increase of offshore wind developments

With the demand for renewable energy surging, global offshore wind development takes on a gigantic scale, with the North Sea basin being front runner. In the Dutch North Sea alone, 70 gigawatts will be realized by 2050, while to date only 4,7 gigawatts is installed. That is a 15-fold increase of an already large industry in next two decades.

### Fast tracking restoration with Windows of Opportunity

Why is there a need for active ecosystem restoration? Is protection of reefs to recover without human interference not sufficient?
The need for active restoration is explained by the concept of 'Windows of Opportunity': Complex habitats such as reefs or vegetated coastal systems alter their environment and thereby make it more suitable for themselves. For instance, they reduce currents near the seabed and stabilise the sediment, so that young reef organisms or seedlings can settle in calm conditions and grow. Without the reef or vegetation to buffer such disturbances, periods of calm conditions suitable for young recruits to settle, so called 'Windows of Opportunities', are extremely rare. As a result, natural ecosystem recovery is rare and unpredictable and may take decades or longer. Therefore, action is needed to create optimal establishment conditions. By providing active restoration measures, either by creating suitable Windows of Opportunity or surpassing establishment bottle-necks, ecosystem recovery will be greatly accelerated.






### North Sea artificial reef enhancement in the past decade

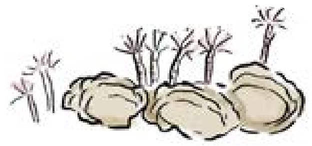
The earliest studies on benthic developments in offshore wind farms documented rich communities on the artificial hard substrates but failed to demonstrate natural recovery of the surrounding seabed within short time spans. Furthermore, when compared to other undisturbed reef-like habitats such as shipwrecks or natural gravel beds, benthic biodiversity output of wind farms was relatively low. It was then hypothesized that with incorporating ecology-focussed design principles, wind farm subsea infrastructure could be designed in such a way, that biogenic reefs can be restored, fish populations increased and biodiversity output maximized. Nature enhancement and so-called Nature Inclusive Design principles focus on integrating habitat requirements of focal species in marine infrastructure designs. This has recently seen implementation into real life designs in wind farms where the goal is often enhancement of European oyster or cod and pilots are installed and evaluated. At the same time artificial reef effects of wind farms without special designs or measures have been quantified in more detail.

### Knowledge gaps for reef development

Biodiversity predictions, however, are mostly based on reef studies in coastal habitats or studies with another purpose. To this end, there were limited empirical data available of natural offshore North Sea reefs to explain what a natural reef means in terms of ecosystem services and how we can learn from these reefs for restoration and enhancement purposes. In addition, there was no substantiated knowledge available on how to design restoration or biodiversity enhancement measures in a successful way and evidence based. Also, field data showing that optimized designs will indeed lead to higher biodiversity output or increased restoration opportunities were lacking.
The North Sea ReViFES program is designed to fill in these knowledge gaps for the benefit of successful ecosystem restoration in the undisturbed seabed environments in offshore wind farms.

## What lessons have we learned from North Sea ReViFES?

**So far, the North Sea ReViFES program resulted in ten scientific publications and one PhD thesis, with a second PhD thesis and more than five scientific publications still in preparation. The main lessons learned are highlighted below:**



### Natural reefs

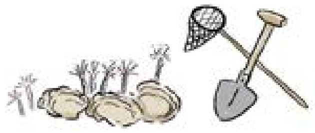
*Quantifying ecosystem services of natural North Sea reefs*

1. **Biodiversity increase through North Sea reefs.** A strong scientific base developed through firsthand empirical field data shows that natural reefs in the North Sea indeed lead to higher biodiversity, higher species abundance and more complex food webs. *(p. 19)*
2. **All types of reef matter.** Biogenic reefs are more dynamic than geogenic reefs, but have similar impact on biodiversity and food web complexity non the less. *(p. 19)*
3. **Don't forget the tubeworms.** Contrary to expectations, tube worm reefs support equally biodiverse benthic communities than oyster reefs do. Though short-lived, these reefs are biodiversity hotspots and well worth restoring. *(p. 19)*
4. **Reefs are important for fish.** Fish diversity is higher in reefs compared to nearby sandy bottom habitats. This holds true for several commercially important species, species with a special conservation status as well as common species. For some fish species reefs are important nursery habitats for juveniles. *(p. 21)*
5. **Reefs enrich the sediment.** Filtering reef organisms enrich the sediment with carbon rich organic material and silt. In doing so, they contribute to carbon storage in marine sediments and enhance the sediment quality, benefiting other species. *(p. 25)*

### European Oyster

*Develop techniques for oyster hatcheries and settlement*

1. **Diet optimisation with novel microalgae.** Increasing poly unsaturated fatty acids (PUFA) proportions may be crucial to overcome production bottlenecks. Flagellate *Ruttnera spectabilis* can replace other microalgal diets and is a likely candidate for diet optimisation in European oyster hatcheries. *(p. 29)*
2. **Poor swimmers need accurate positioning.** European oyster larvae cannot swim against dominant tidal currents, so placing larvae with accuracy to contain them in your restoration site is essential. On a micro-scale larvae can actively swim and choose the substrate they prefer for settlement. *(p. 31)*
3. **Substrate selection advances oyster settlement.** European oyster larvae show clear preference for certain substrate types for settlement. Calcareous, bioinspired or materials with natural shell achieve the highest settlement. Providing appropriate materials increases settlement success. *(p. 33)*
4. **Knowledge gain increases with state-of-the-art techniques.** Working to restore oyster reefs is a highly specialized business, but techniques have been developed that will continue to progress knowledge gain. Researchers can now determine swimming behaviour of oyster larvae and preference for settlement substrates from microscale to field conditions at sea. *(p. 31)* &*(p. 33)*



### Wind farms

*Empirical data from reef enhancement in the North Sea*

1. **Scour protections act as artificial reefs.** Scour protections, functioning as artificial reefs, hold rich epibenthic biodiversity, and different rock types hold different communities. *(p. 39)*
2. **Species community differences increase with geographical distance.** Scour protections of wind farms harbour rich biodiversity, and the community difference increases with geographical distance. Enhancement of wind farms with a wide geographical spread. *(p. 39)*
3. **Increased rock surface area leads to greater biodiversity.** Firsthand empirical field data shows that a larger surface area within a scour protection indeed leads to increased benthic biodiversity output. This provides strong evidence that investing in optimized, eco-friendly scour protection delivers ecological benefits. *(p. 43)*

### Design principles and measures

1. **Setting clear objectives is crucial for reaching system scale impact.** Take a step-by-step approach to translate strategic objectives into clear, actionable goals is key to achieving successful restoration outcomes. *(p. 49)*
2. **Quantify predicted outcome of investments for cost-efficient reef restoration.** A question that many developers have when considering investment in Ecological Restoration or Biodiversity Enhancement measures is: "How much investment is required to achieve a specific amount of ecosystem restoration?" A method is developed to design measures at scale in offshore wind farms, and to quantify the predicted outcome. Investments in oyster reef restoration are hence no longer a 'black box'. *(p. 51)*
3. **Expanding the reef restoration community is important for upscaling.** To scale up reef restoration effort it is important to expand the restoration community beyond ecologists. Five golden principles summarise how marine contractors can support ecosystem restoration in an optimal way. *(p. 55)*
4. **Towards multi habitat approaches for future restoration success.** Coastal marine habitat restoration shows that multi habitat approaches greatly increase success rates. Avoid concentrating restoration efforts on just one habitat and instead, promote positive interactions by restoring multiple habitats at the same time. *(p. 59)*



## Conclusions

**Five years of joint research by academic and applied experts from various institutions and companies in the North Sea ReViFES program gathered valuable transdisciplinary knowledge to support ecology-focused investments in offshore wind farms and improve temperate reef restoration efforts.**

### Temperate reefs matter

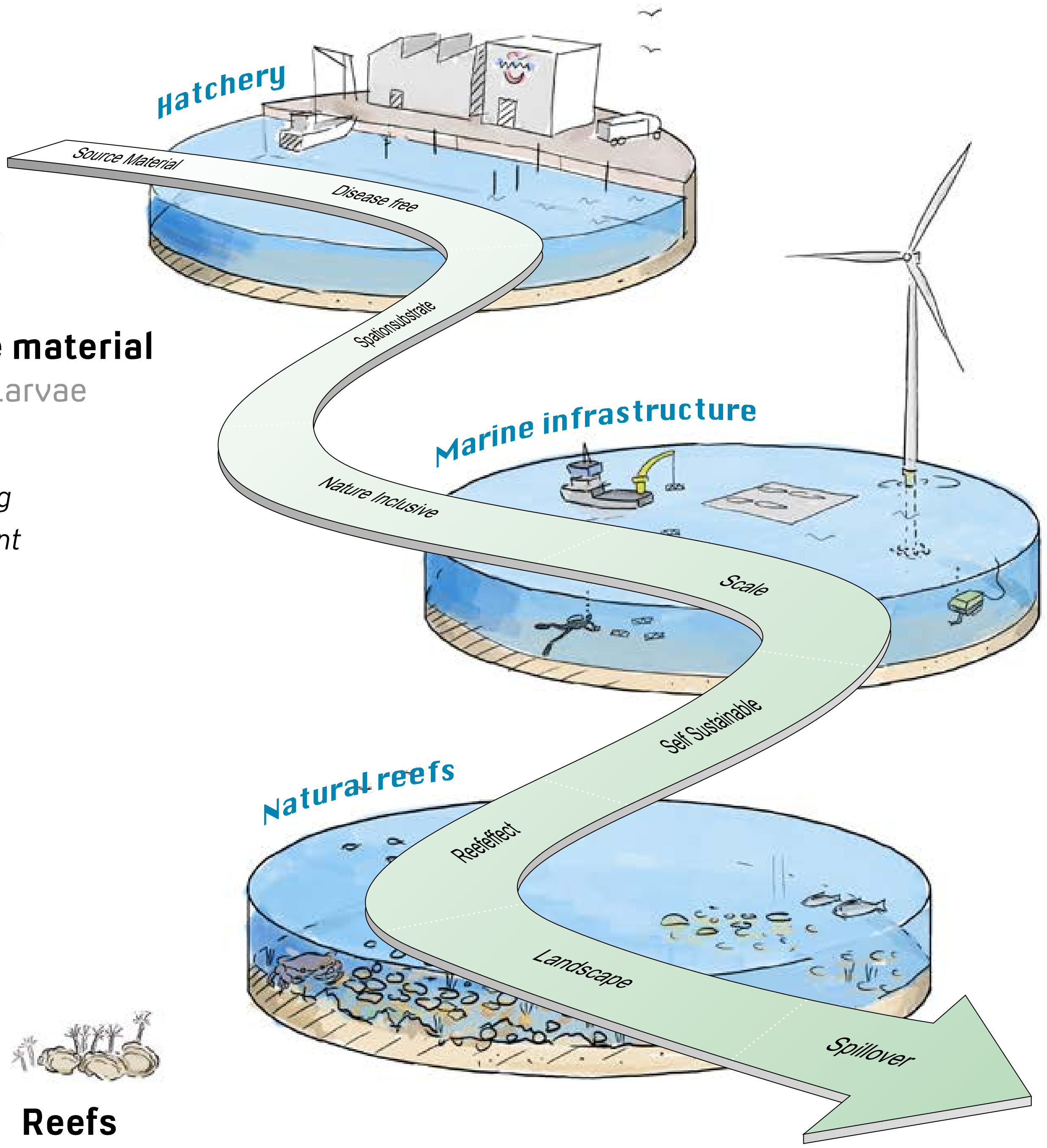
Multiple natural reefs have been studied, to help predict and substantiate the benefits of successful reef restoration. One of the main achievements is that we can firmly conclude, based on firsthand empirical evidence: **Reefs are important for the ecology of the North Sea.** This was theorised before but is now substantiated for temperate reefs in North Sea conditions. Natural reefs in the North Sea increase biodiversity, food web complexity and provide habitat for endangered, iconic or otherwise relevant species such as native oysters, *Sabellaria* tubeworms and even sharks and rays. They also enrich their local environment, thereby also storing carbon in the marine sediment.
One clear result from the natural reef studies is that reef restoration aimed at increasing local biodiversity, does not always need to focus on oysters: Tubeworm reefs of both *Lanice* and *Sabellaria* species also harbour very rich and biodiverse benthic communities.

### Offshore reef restoration and enhancement: tightening knowledge gaps step by step

Another major achievement of the North Sea ReViFES programme is solid empirical evidence that incorporating ecology-focused design principles in wind farm infrastructure such as scour protections, leads to higher biodiversity output. It is no longer hypothesised or solely based on expert judgement: **certain designs of scour protections can boost biodiversity output or target enhancement of focal species.**

Some clear recommendations have been made and substantiated that translate into practical guidelines: For instance, **how to design a scour protection for increased biodiversity output and what material to select to optimise oyster settlement.** A concise step by step framework has been developed focussing on oyster reef restoration. It focuses on steps to take, starting with the system you intend to work in, defining goals and investments, and quantifying the predicted outcome. This combines the operational steps in a wind farm with steps from ecosystem restoration projects.

Working on ecosystem restoration in offshore environments is specialized, challenging and can be very uncertain due to an array of unforeseen natural circumstances. Both success rate and return on investment are hard to predict, making investments uncertain. The North Sea ReViFES results however, provide applied knowledge to tighten this gap. Targeting multiple habitats, setting clear objectives, engaging with relevant stakeholders and quantifying predicted outcomes will help to decrease uncertainty and justify investments that need to be made.




## Source material

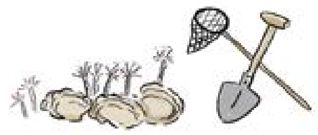
Oyster Larvae

*Diet*
*Swimming*
*Settlement*

## Reefs

Ecosystem Services

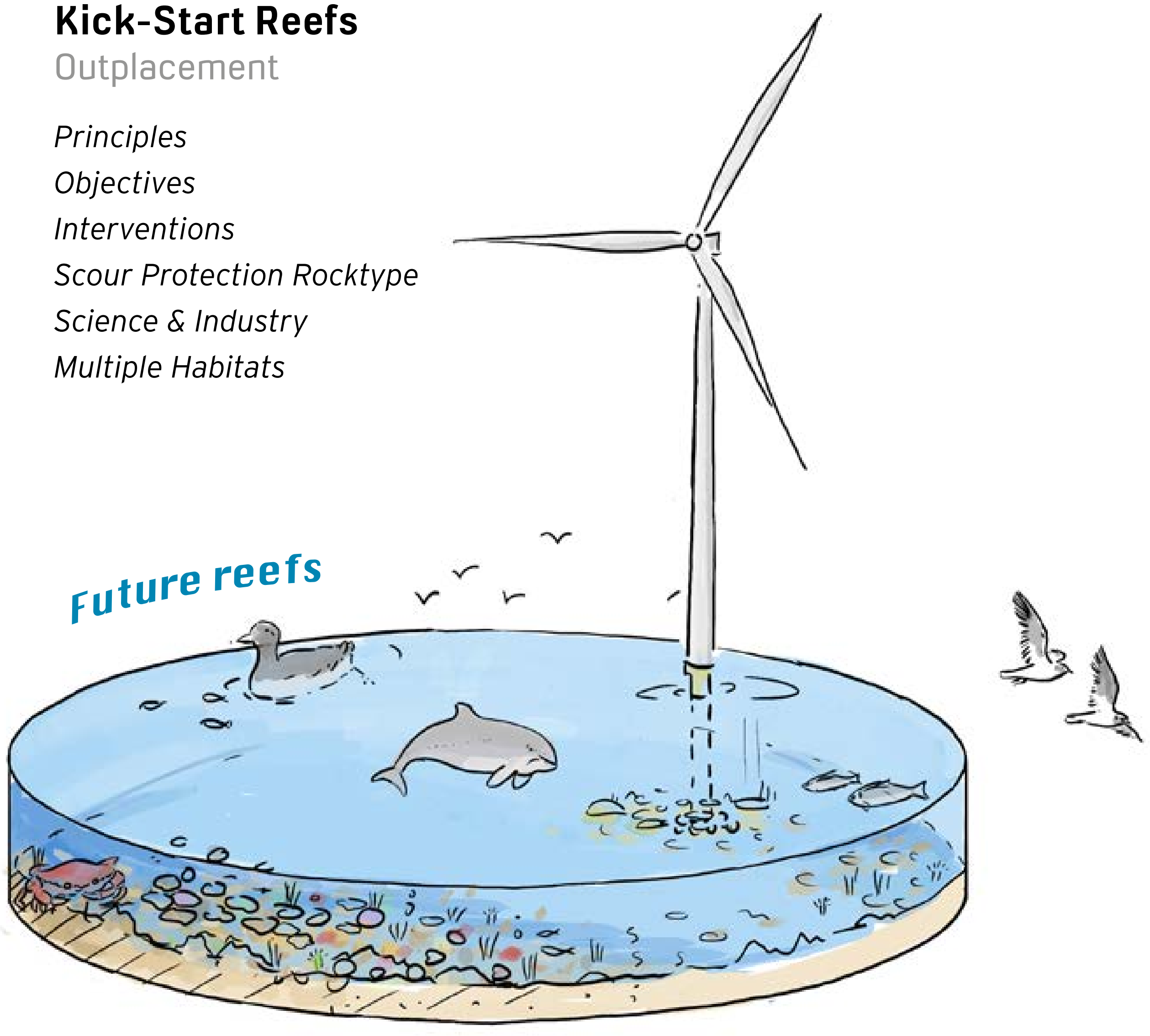
*Biodiversity*
*Benthic Communities*
*Foodweb*
*Fish Communities*
*Carbon*



## Kick-Start Reefs

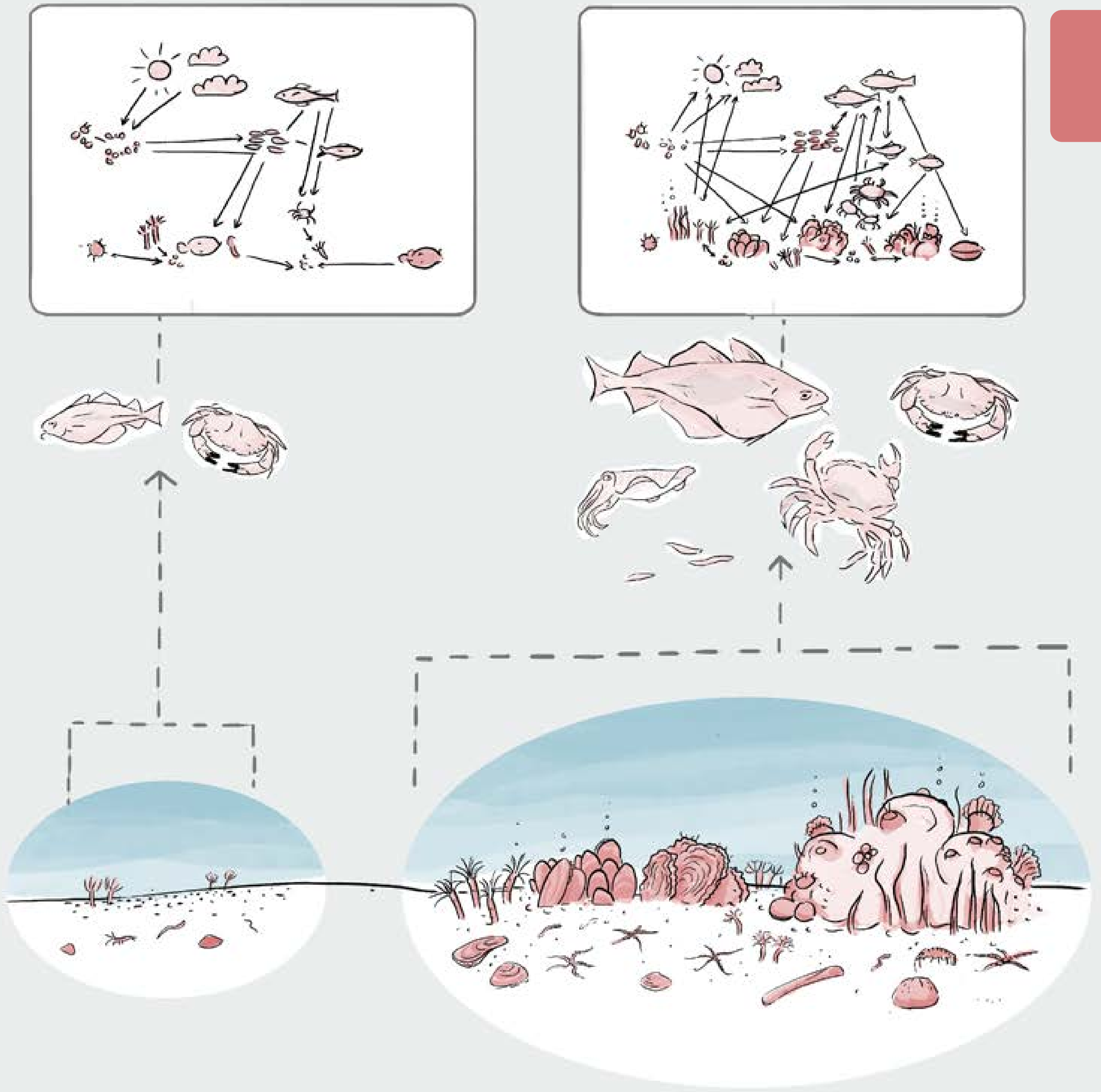
Outplacement

*Principles*
*Objectives*
*Interventions*
*Scour Protection Rocktype*
*Science & Industry*
*Multiple Habitats*



# Part 1

## Natural North Sea Reefs



# North Sea Reefs: Biodiversity and Food Webs of Subtidal Reefs

**Towards self-sustaining reefs: learning from natural subtidal reefs.**

**For the first time, this study explores the benthic community structure, biodiversity and food webs of remnant natural reefs in the North Sea. Specifically, to test if these reefs indeed enhance biodiversity and food web complexity, a hypothesis that is often presented to support reef restoration efforts. The results contribute to a solid knowledge base for natural subtidal reefs in the North Sea to aid future restoration efforts.**

**Implications for reef enhancement**
Previous studies of various reefs show they can greatly enhance biodiversity and food web complexity, and this is often used as an argument to support the need for reef restoration projects. But is this also true for temperate subtidal reefs? And is there a clear difference between rocky reefs or tubeworm and shellfish reefs? By studying natural reefs this study filled knowledge gaps for temperate subtidal reefs in the North Sea.

The study shows that reefs greatly enhance biodiversity and food web complexity of benthic communities compared to sand habitat. Although the rocky reef was the most structurally complex and the more stable throughout time, the worm and shellfish reefs had an equally strong positive effect on benthic communities. This confirms the importance of subtidal reefs – both geogenic and biogenic – for conservation and enhancement of benthic biodiversity in the North Sea. The predicted upscaling of offshore wind farms offers new opportunities for the restoration and enhancement of temperate subtidal reefs. According to this study, such developments could lead to increased biodiversity and food web complexity.

### Reef sampling in the North Sea

A comparison of sessile and mobile benthic communities in different habitats in the North Sea forms the basis of the study design. At each location two different types of reefs are contrasted to bare sandy areas without reefs. The comparison included rocky reef and sand mason worm reef habitats at the Borkum Reef Grounds and shellfish reef and sand mason worm reef habitats In the Voordelta. Box core and Hamon grabs and baited traps collected faunal assemblages at four to eight stations for each habitat.

### Biodiversity and food web structure

The data confirmed that reefs enhanced both biodiversity and abundance of sessile benthic communities. The effect was similar for a diversity of species groups like arthropods, molluscs and worms. Mobile communities revealed less consistent patterns, with abundance of mobile species higher on the reefs, but not biodiversity. Additionally, reefs - geogenic and biogenic - increased the complexity of food webs.

### Conclusions from natural reefs

So far, the lack of empirical data to support biodiversity benefits of restored reefs hampered the field of active reef restoration. To motivate investments in reef restoration efforts must yield clear and feasible results.
For the first time, we have collected field data of the benthic assemblages of various natural reef types and demonstrated the benefits of temperate reef conservation and enhancement. The results clearly demonstrate the importance of both geogenic and biogenic reefs to increase benthic biodiversity. Additionally, both mobile and sessile taxa such as anemones, bryozoans and hydroids are higher in abundance in reef habitat then in sand. Although biogenic reefs are less stable overtime, they demonstrated to have an equally strong effect on benthic communities compared to geogenic reefs. This first-hand field knowledge offers valuable insights for future restoration and enhancement projects in the North Sea.

**Coral, C., L.M. Kornau, T. van der Heide, J.W.P. Coolen, R. Witbaard, T.J. Bouma & M.J.A. Christianen (2025). Subtidal temperate reefs in marginal seas enhance biodiversity, food web complexity, and ecosystem stability. *Marine Ecology Progress Series.***

Source via QR code: https://doi.org/10.3354/meps14883

Flapper skate (or common skate *Dipturus sp.*)

Clingfish (*Diplecogaster bimaculata*)



# North Sea Reefs: Temperate Reefs as Fish Habitat

### Towards self-sustaining reefs: learning from fish communities of natural reefs

**Temperate reefs enhance fish biodiversity compared to no-reef areas. This hypothesis is often presented to support reef restoration efforts and now tested for natural North Sea reefs. This offshore field study explores the fish community structure and functional diversity of distinct biogenic reefs with non-invasive monitoring techniques. The results contribute to the understanding of how temperate reefs enhance fish biodiversity in the North Sea.**

**Implications for reef enhancement**
Despite their theorized ecological significance, the role of natural shellfish reefs as essential fish habitat in temperate seas like the North Sea is poorly understood. To what extent do shellfish reefs serve as key habitats that benefit fish communities? By studying a mixed bivalve reef and a horse mussel reef this study filled in the knowledge gap for temperate shellfish reefs in the North Sea.

The study shows that fish diversity is consistently higher inside reefs then in the reef surrounding, and diversity decreases with distance from the reef. Commercial fisheries species, including cod, pollock, and mullet increased with reef presence as well as species like gobies, gunnels, clingfish, and sculpins. Reefs may represent key nursery habitats for juveniles of species like ling. This unique data set shows that for many fish species shellfish reefs provide a key habitat. It supports conservation and restoration strategies that focus on reefs as essential fish habitat.

**North Sea sampling inside and outside shellfish reefs**
Sampling took place at stations inside and outside reef areas. The first reef is a mixed blue mussel, pacific and native oyster shellfish reef in the Dutch North Sea, the second a horse mussel reef in the Scottish North Sea. During expeditions with research vessels RV Pelagia and RV Navicula in 2021-2023 sampling methods included two non-invasive techniques at the reef itself and at distances to the reef from 25 meters up to 10 kilometers. eDNA metabarcoding and baited camera analysis (BRUVs) acted as complementary techniques for vertebrate detection. Analysis included species diversity, functional diversity of fish and other vertebrates.

**BRUV and eDNA as non-invasive fishing techniques**
Since most fishing techniques partly destroy reef habitat they are unsuitable for reef research and switching to non-invasive techniques is key. How do results of two non-invasive techniques compare? eDNA identified more species overall, while BRUVs enabled detection of species both in adult and juvenile stages. Both techniques resulted in the detection of unique species including common skate and Atlantic bluefin tuna. This makes them complementary and stresses the importance to use multiple techniques for better-informed biodiversity assessment studies. Although both techniques could not be used for quantitative abundance or biomass estimates of fish 'relative read abundance' (eDNA) and 'maxN' (BRUVs) are a non-metric multidimensional scaling option to assess differences in fish communities.

**Coral, C. & K. Doorenspleet *et al. (in preparation)*. Shellfish reefs as Essential Fish Habitats: complementary insights from eDNA and BRUVs in the North Sea.**

## Biodiversity, fish communities and other vertebrates

Shellfish reefs in the North Sea support significantly higher fish species diversity and relative abundance. These effects are still detectable at a few hundred meters extending beyond the reef itself. The reefs are especially rich in mid-sized fish such as gobies, sand smelt, rocklings, and clingfish, which use the complex reef structure for shelter and opportunistic feeding on the diverse benthic reef fauna. Commercial species like cod and ling are also drawn to the reef. Adults use them as productive hunting grounds, while juveniles benefit from the habitat for shelter and feeding.

## Conclusions from natural reefs

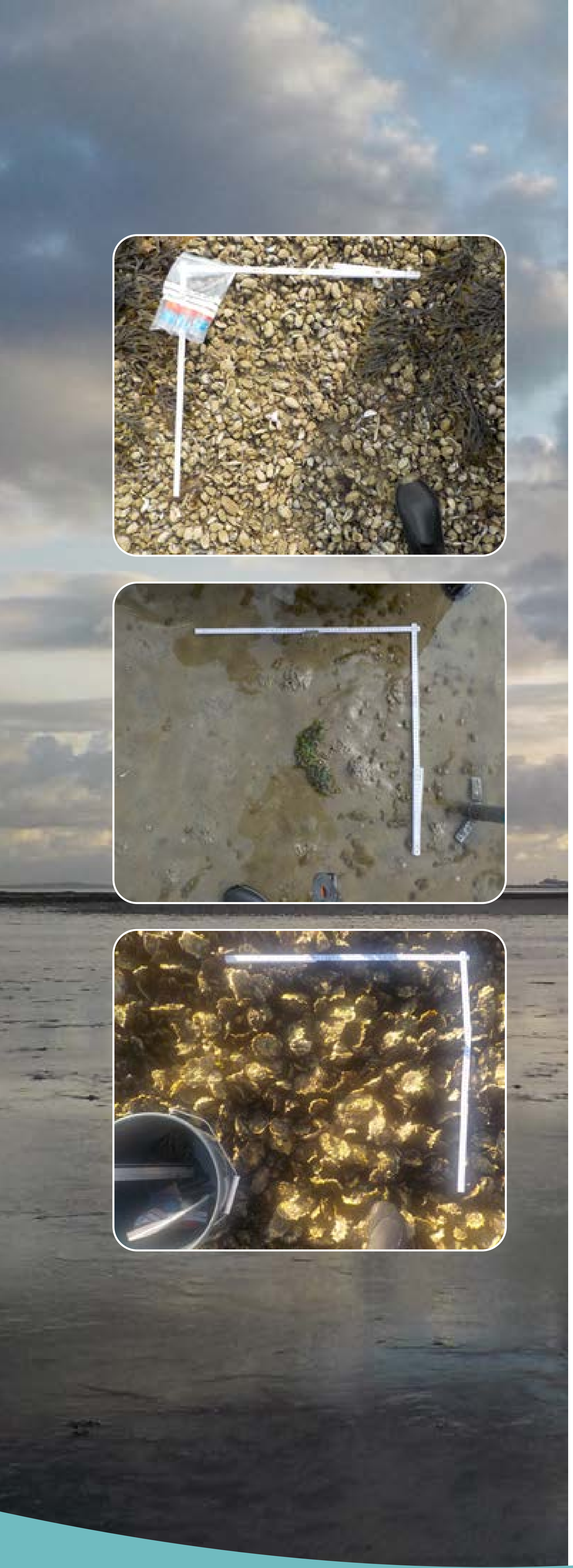
The study clearly shows that biogenic shellfish reefs in the North Sea have a positive overall impact on the biodiversity of mobile vertebrate communities, enhancing the species diversity of fish communities. These findings highlight the importance of conserving and restoring natural temperate reefs, as they serve as valuable habitats for fish.

**Species List ►**
List of species and taxonomic groups identified at or near bivalve reefs in the Voordelta (mixed reefs of oysters and blue mussels) and Noss Head (horse mussel reefs). Species detections with environmental DNA (eDNA; indicated by full circles) and baited remote underwater video (BRUV; indicated by open circles).


Ling (or common ling Molva molva)

*Species detected by:*
● *eDNA*
○ *BRUV*
◉ *eDNA & BRUV*

| Voordelta | Noss Head | Scientific Name | Nederlandse naam | Group |
|---|---|---|---|---|
| ● | ● | *Anguilla anguilla* | Europese aal | Fish |
| ● | | *Conger conger* | Kongeraal | Fish |
| ◉ | | *Atherina sp.* | Koornaarsvis | Fish |
| ● | ● | *Belone belone* | Geep | Fish |
| | ◉ | *Gobiidae* | Grondels | Fish |
| ● | | *Aphia minuta* | Glasgrondel | Fish |
| | ● | *Crystallogobius linearis* | Kristalgrondel | Fish |
| ◉ | | *Gobius niger* | Zwarte grondel | Fish |
| ● | | *Gobius paganellus* | Paganelgrondel | Fish |
| | ● | *Gobiusculus flavescens* | Tweevlekgrondel | Fish |
| ● | ● | *Neogobius melanostomus* | Zwartbekgrondel | Fish |
| ● | | *Pomatoschistus microps* | Brakwatergrondel | Fish |
| ● | ● | *Pomatoschistus minutus* | Dikkopje | Fish |
| ● | ● | *Pomatoschistus pictus* | Kleurige grondel | Fish |
| ● | ● | *Lipophrys pholis* | Slijmvis | Fish |
| ● | | *Parablennius gattorugine* | Gehoornde slijmvis | Fish |
| ● | ● | *Zoarces viviparus* | Puitaal | Fish |
| | ● | *Chirolophis ascanii* | Franjekop | Fish |
| ○ | | *Callyonimus sp* | Pitvissen | Fish |
| | ◉ | *Callionymus lyra* | Pitvis | Fish |
| | ● | *Callionymus reticulatus* | Rasterpitvis | Fish |
| ● | | *Trachinotus ovatus* | Gaffelmakreel | Fish |
| ● | ◉ | *Trachurus trachurus* | Horsmakreel | Fish |
| ◉ | ● | *Clupeidae* | Haringen | Fish |
| ● | | *Alosa sp.* | Rivierharingen | Fish |
| ● | ● | *Clupea harengus* | Haring | Fish |
| | ● | *Engraulidae* | Anjovissen | Fish |
| ● | | *Engraulis encrasicolus* | Ansjovis | Fish |
| ● | ● | *Sardina pilchardus* | Sardien | Fish |
| ● | ● | *Sprattus sprattus* | Sprot | Fish |
| | ● | *Leuciscidae* | Karpers | Fish |
| | ● | *Centrolabrus exoletus* | Rotslipvis | Fish |
| ● | ● | *Ctenolabrus rupestris* | Kliplipvis | Fish |
| ○ | | *Dicentrarchus labrax* | Zeebaars | Fish |
| ● | ● | *Labrus bergylta* | Gevlekte lipvis | Fish |
| ● | ● | *Labrus mixtus* | Koekoekslipvis | Fish |
| ● | | *Sparus aurata* | Dorade | Fish |
| ● | ● | *Gadidae* | Kabeljauwen | Fish |
| | ● | *Brosme brosme* | Lom | Fish |
| ● | ● | *Ciliata mustela* | Vijfdradige meun | Fish |
| ● | ● | *Ciliata septentrionalis* | Noorse meun | Fish |
| ● | ◉ | *Gadus morhua* | Kabeljauw | Fish |
| | ○ | *Melanogrammus aeglefinus* | Schelvis | Fish |
| | ● | *Merluccius merluccius* | Heek | Fish |
| ● | ◉ | *Molva molva* | Leng | Fish |
| ● | ● | *Pollachius sp.* | Pollak | Fish |
| | ● | *Raniceps raninus* | Vorskwab | Fish |
| | ● | *Trisopterus esmarkii* | Kever | Fish |
| ● | ◉ | *Trisopterus luscus* | Steenbolk | Fish |
| ● | ● | *Trisopterus minutus* | Dwergbolk | Fish |
| ● | ● | *Diplecogaster bimaculata* | Tweevlekkige zuignapvis | Fish |
| | ● | *Lophius piscatorius* | Zeeduivel | Fish |
| ● | | *Chelon auratus* | Goudharder | Fish |
| ● | ● | *Mullus surmuletus* | Mul | Fish |
| ● | ● | *Myctophidae* | Lantaarnvissen | Fish |
| ● | | *Osmerus eperlanus* | Spiering | Fish |
| ● | ● | *Agonus cataphractus* | Harnasmannetje | Fish |
| ● | ● | *Ammodytidae* | Zandspieringen | Fish |
| | ● | *Anarhichadidae* | Zeewolven | Fish |
| | ● | *Cyclopterus lumpus* | Snotolf | Fish |
| ● | ● | *Echiichthys vipera* | Kleine pieterman | Fish |
| | ○ | *Eutrigla gurnardus* | Grauwe poon | Fish |
| ● | ● | *Gasterosteus aculeatus* | Driedoornige stekelbaars | Fish |
| | ● | *Spinachia spinachia* | Zeestekelbaars | Fish |
| ● | ● | *Liparis montagui* | Kleine slakdolf | Fish |
| ◉ | ● | *Pholis gunnellus* | Botervis | Fish |
| | ● | *Sebastidae* | Roodbaarzen | Fish |
| ● | ● | *Cottidae* | Donderpadden | Fish |
| ● | ● | *Triglidae* | Zeedonderpadden | Fish |
| | ● | *Micrenophrys lilljeborgii* | Dwergzeedonderpad | Fish |
| ● | ◉ | *Myoxocephalus sp.* | Gewone zeedonderpad | Fish |
| ● | ● | *Taurulus bubalis* | Groene zeedonderpad | Fish |
| | ● | *Triglops murrayi* | Murray's zeedonderpad | Fish |
| | ● | *Triglops pingelii* | Zeedonderpad | Fish |
| | ● | *Arnoglossus laterna* | Schurftvis | Fish |
| ● | ● | *Buglossidium luteum* | Dwergtong | Fish |
| ● | | *Hippoglossoides platessoides* | Lange schar | Fish |
| ● | ● | *Limanda limanda* | Schar | Fish |
| ● | ● | *Microstomus kitt* | Tongschar | Fish |
| ◉ | ◉ | *Pleuronectidae* | Schollen | Fish |
| ● | | *Scophthalmus maximus* | Tarbot | Fish |
| ● | ● | *Scophthalmus rhombus* | Griet | Fish |
| ● | ● | *Solea solea* | Tong | Fish |
| ● | ● | *Zeugopterus sp.* | Gevlekte griet | Fish |
| ● | ● | *Salmo salar* | Atlantische zalm | Fish |
| ● | ● | *Salmo trutta* | Zeeforel | Fish |
| ● | ● | *Scomber scombrus* | Makreel | Fish |
| ● | | *Thunnus thynnus* | Blauwvintonijn | Fish |
| ● | | *Hippocampus hippocampus* | Kortsnuitzeepaardje | Fish |
| | ● | *Nerophis lumbriciformis* | Kleine wormzeenaald | Fish |
| ◉ | | *Syngnathus acus* | Grote zeenaald | Fish |
| ● | | *Syngnathus rostellatus* | Kleine zeenaald | Fish |
| | ● | *Balistes capriscus* | Grijze trekkervis | Fish |
| | ● | *Zeus faber* | Zonnevis | Fish |
| | ● | *Scyliorhinus canicula* | Hondshaai | Elasmobranchs |
| | ● | *Cetorhinus maximus* | Reuzenhaai | Elasmobranchs |
| | ● | *Lamna nasus* | Haringhaai | Elasmobranchs |
| | ◉ | *Dipturus sp.* | Vleten | Elasmobranchs |
| | ● | *Leucoraja naevus* | Grootoogrog | Elasmobranchs |
| | ● | *Raja clavata* | Stekelrog | Elasmobranchs |
| | ● | *Raja montagui* | Gevlekte rog | Elasmobranchs |
| | ● | *Squalidae* | Doornhaaien | Elasmobranchs |
| ● | ● | *Halichoerus grypus* | Grijze zeehond | marine mammals |
| ● | ● | *Phoca vitulina* | Gewone zeehond | marine mammals |
| | ● | *Balaenoptera acutorostrata* | Dwergvinvis | marine mammals |
| ● | ● | *Grampus griseus* | Grijze dolfijn | marine mammals |
| | ● | *Lagenorhynchus albirostris* | Witsnuitdolfijn | marine mammals |
| ● | ● | *Phocoena phocoena* | Bruinvis | marine mammals |
| ○ | | *Sepia officinalis* | Gewone zeekat | |



# North Sea Reefs: Bivalve Reefs and Carbon Rich Sediments

## Towards self-sustaining reefs: learning from sediment enrichment near bivalve reefs

**Temperate reefs can influence the sediments in their surroundings by actively producing carbon rich biodeposits and passively reducing the water flow. This hypothesis is often presented and modelled and now tested in the field for 12 natural bivalve reefs. With this field study sediments around intertidal reefs are characterised up to 400 meters from their borders. The results contribute to the understanding of ecosystem service 'carbon storage' of reefs. More specifically, how reefs impact sediment enrichment in the reef and far beyond its borders.**

### Implications for reef enhancement

Despite their recognized ecological significance, the role of natural shellfish reefs as ecosystem engineers that influence their surroundings is poorly understood. How far-reaching is the impact of shellfish reefs on sediment enrichment both within and beyond the reef boundary? And more importantly, could these ecosystems play a role in carbon storage, contributing to Blue Carbon? Using the Wadden Sea as a model system and field data of twelve bivalve reefs and their sediments up to 400 meters away, this study filled in this knowledge gap for temperate natural shellfish reefs.

The study shows that the presence of reefs increased the concentration of organic matter and silt in surrounding sediments up to 200 meters from the reef edge and 28 cm in depth. The larger and denser the reef, the stronger the sediment enrichment. These findings show that bivalve reefs create sheltered zones that influence the way organic matter moves through the environment. Bivalve reefs trap enriched sediments and shape nearby sediments well beyond the reefs themselves.

### Sediments at locations inside reef and outside shellfish reefs

The Wadden Sea, located in the southeastern part of the North Sea, is the largest system of intertidal flats in the world, containing numerous natural bivalve reefs. Sediment sampling took place at twelve reefs at stations inside and outside reef areas up to 400 meters away from intertidal bivalve reefs. Measurements included total organic matter, sediment grain size and silt content at three different depths (0-1 cm, 9-11 cm and 27-30 cm). To establish the 'reef effect' models connected reef properties, distance to the reef and environmental variables to sediment characteristics. Samples at 350-400 meters away from the reef served as background sediments that classified as 'no-reef' locations.

### Temperate reefs locally retain enriched sediments

The study shows that bivalve reefs locally retain carbon enriched sediments, like organic matter and silt. Organic matter in the upper layer of sediments was ± 5% higher within reefs and silt content ± 30% higher compared to no reef sediments. The effect is related to reef density and water movement.

### Temperate reefs effect sediment enrichment beyond reefs

The sediments surrounding the reef also contain higher levels of organic matter and silt compared to background sediments without a reef. The extent of these effects depended on reef size and density, as well as local water flow, more specifically flow velocity and orbital velocity.
The Influence of reefs extends surprisingly far, on the superficial sediments up to 50 meters from the reef and in deeper sediments even up to 200 meters. This confirms that reefs not only change their immediate environment but also enrich the area surrounding reefs.

### Reef area and reef density matter

Interestingly, reef characteristic like reef area and reef density explain the sediment enrichment effect with denser and larger reefs having stronger effects.

### Reefs as rich sediment traps

Reefs support diverse and productive ecosystems. Shells, calcareous material, excrements from the bivalves themselves and decaying organisms contribute carbon rich organic matter to nearby sediments. Additionally, reefs act as natural barriers that reduce water movement. This reduction of water flow allows finer particles like silt and organic matter to settle within and around reefs. This sediment trap function of reefs extends beyond the reef itself, leading to increased deposition of organic rich sediments into the surrounding environment. As these temperate bivalve reefs enhance sediment quality in nearby areas and contribute to carbon cycling, they serve as valuable resources for further research and coastal restoration efforts.

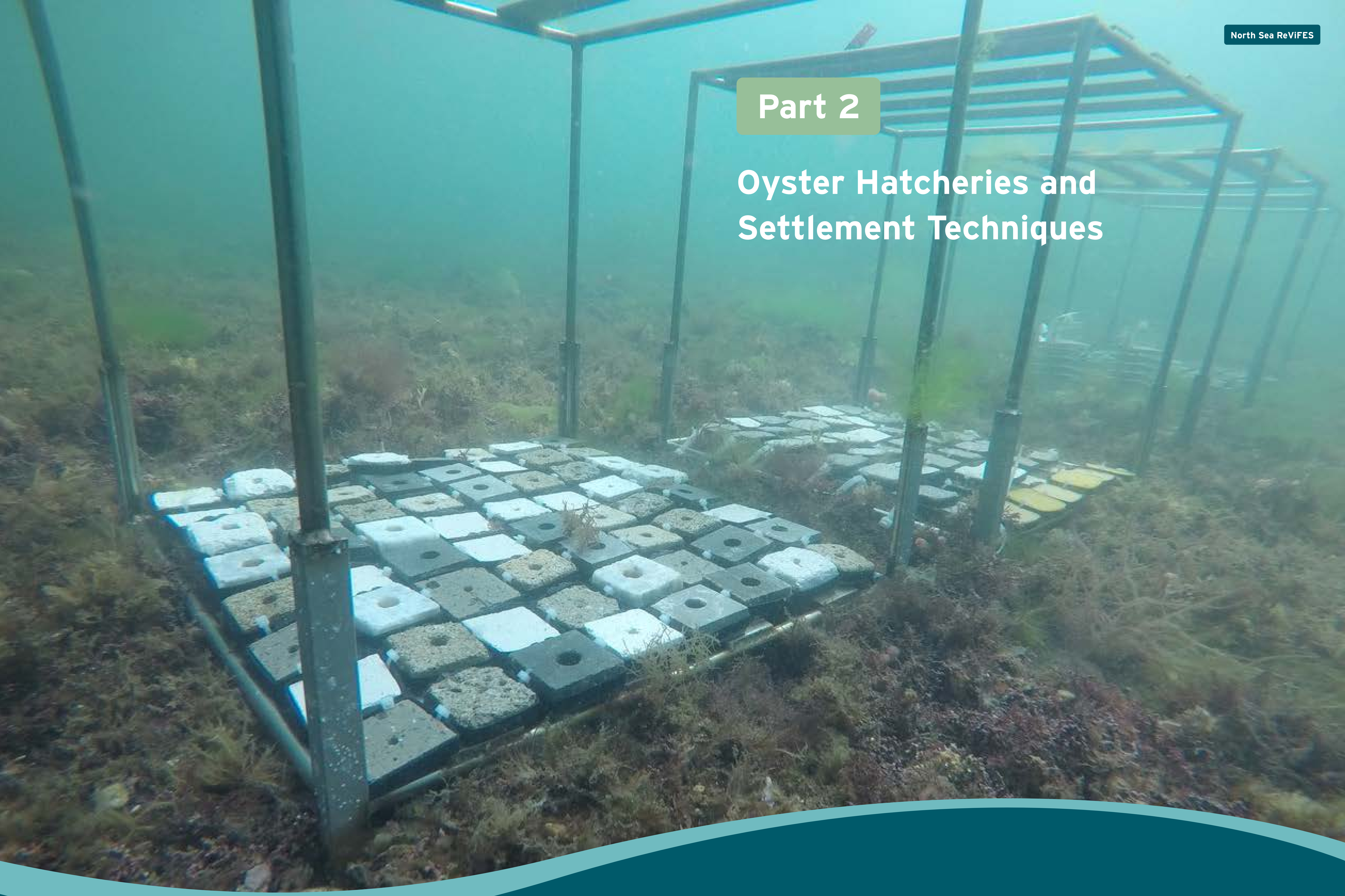
### Conclusions from natural reefs

The study clearly shows that shellfish reefs retain carbon rich sediments, and increase organic matter and silt content in the seabed. The effect extends outside the reefs up to 50 meters and up to 200 meters in deeper sediments. This adds another ecosystem service value to temperate reefs, strengthening arguments for conservation.

**Coral, C. *et al. (in preparation)***
**Bivalve reefs modify sediment properties within and beyond their borders.**

# Part 2

## Oyster Hatcheries and Settlement Techniques



# European Oyster: Diet Optimisation for Hatchery Larvae

**Towards oyster reef enhancement: can oyster larvae diets be optimised for hatchery larvae production?**

**The impact of microalgal diet choice on growth of oyster larvae in hatcheries was assessed with experiments under controlled conditions. This contributes to evidence-based algal diet optimisation for hatcheries that focus on European oyster production and provide source material for oyster reef restoration in the North Sea.**

### Set-up

A literature search focused on feeding requirements of oyster larvae. A main bottleneck is that bivalves have limited or no ability to synthesize poly unsaturated fatty acids (PUFAs). Based on this:

- It is theorized that optimizing PUFA proportions may be crucial to overcome current production bottlenecks in hatcheries.
- Four species already in use in hatchery diets and four novel species are selected that potentially improve algal diets based on PUFAs related feeding requirements of oyster larvae.

The experimental design includes five diets composed as a mix of novel microalgal species. Monitoring included growth through measuring shell length in time under controlled conditions for each diet. The diet yielding highest performance was subsequently tested in an oyster hatchery. Oyster performance defined as growth rate and percentage settlement with the novel hatchery diet, measured over a 3-week period, was compared with standard mix hatchery diet.


Algae species *Ruttnera spectabilis*

### Importance to reef enhancement in wind farms

Scaling up hatchery production of European oysters is vital for native oyster restoration. Oyster hatchery production is erratic with sudden and unexplained mortalities of larvae and spat. Algal diet is one of the possible bottlenecks that needs optimisation. What requirements do oyster larvae have for algal diets? Is diet optimisation increasing performance of oyster larvae? In this study requirements of oyster larvae led to the selection of species of microalgae for oyster larvae diets. A preliminary study with four novel species of microalgae that were tested for larvae performance showed that a single diet of *Ruttnera spectabilis* showed promising results. This species was further tested in a hatchery. The knowledge can be used for diet optimisation in hatcheries that provide source material for oyster reefs within offshore wind farms.

The addition of the microalgae *Ruttnera spectabilis* to oyster diets significantly improved performance of oyster larvae in a controlled test. A second test showed a similar larval performance with a single species diet of *Ruttnera spectabilis* compared to a multispecies 'standard mix' diet.

- *Ruttnera spectabilis* can replace other algal species and can be used for diet optimisation in European oyster hatcheries.

### Novel algal species for diet hatchery diet optimisation

Based on literature, four novel microalgal species are predicted to help overcome feeding bottlenecks. These species *Ruttnera spectabilis*, *Halamphora coffeaeformis*, *Pavlova salina* and *Cyclotella cryptica* were mixed in five diets. Oyster larvae performance was highest for a single species diet of *Ruttnera spectabilis* and a mixed diet of *Ruttnera spectabilis* and *Halamphora coffeaeformis*.

### *Ruttnera spectabilis* in hatchery diets

The novel single species diet of *Ruttnera spectabilis* was further tested against a 'standard mix' multispecies diet. This resulted in a similar oyster growth rate and higher settlement rate for the new diet compared to the standard hatchery diet. *Ruttnera spectabilis* shows to be able to replace other multispecies algal diets.

### Source material for European oyster reefs

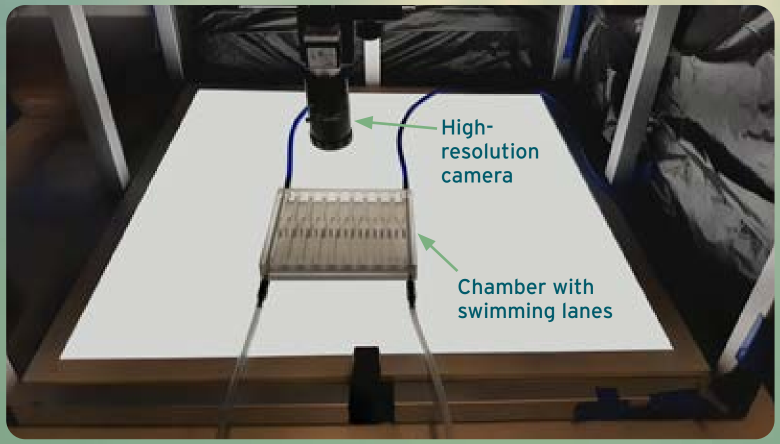
As diet optimisation is likely factor overcoming bottlenecks in European oyster hatcheries, it is vital to address the option of including novel species to oyster larvae diets. Adding or replacing diets with *Ruttnera spectabilis* seems an efficient strategy to optimise hatchery diets. Upscaling the cultivation of *Ruttnera spectabilis* is a next step for the diet optimisation process.

**Kamermans, P. *et al. (in preparation)***
***Ruttnera spectabilis*, a new algal species for the hatchery culture of flat oyster (*Ostrea edulis*) larvae.**

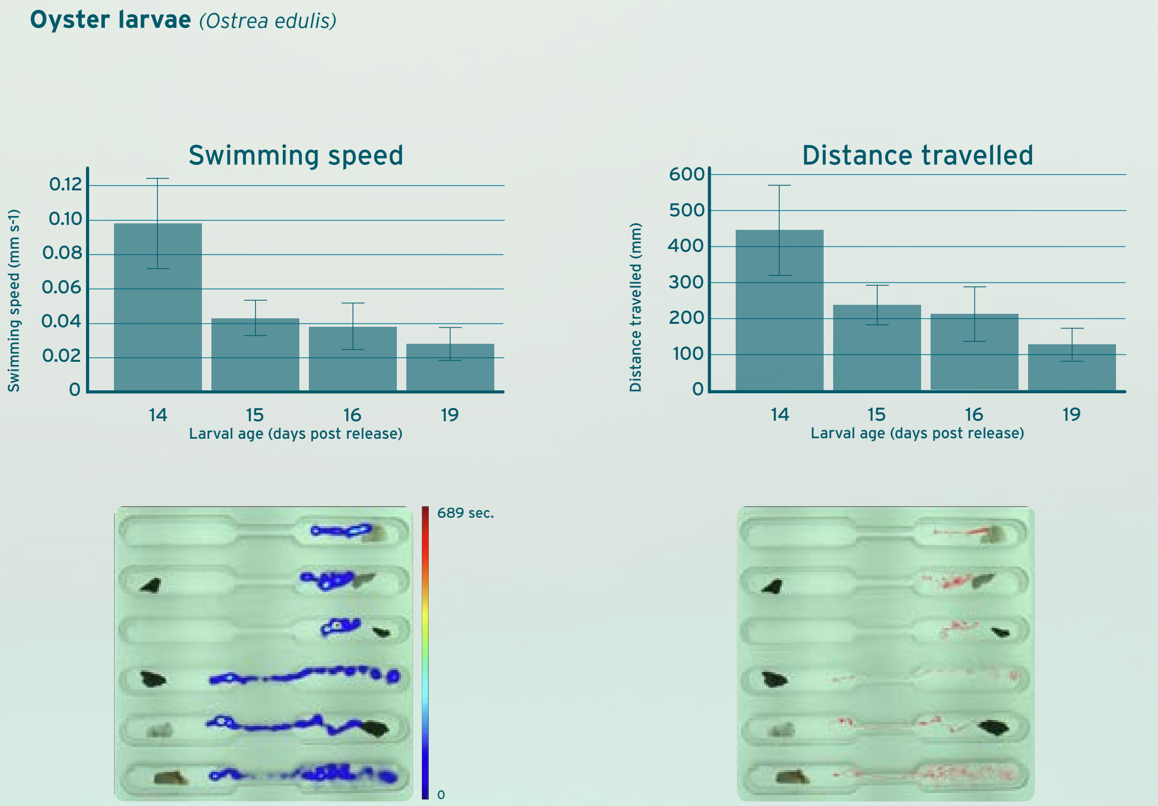
# European Oyster: Larvae Swimming Behaviour

**Towards oyster reef enhancement: tool to investigate oyster larvae swimming behaviour.**

**A method to study oyster larvae swimming behaviour in the laboratory is developed. With this method, swimming patterns and preference for specific habitats can be studied. This provides a valuable tool, for instance, to test which settlement substrates are preferred by larvae and therefore worthwhile to apply in the field. This study was performed on both oyster (*Ostrea edulis*) and coral larvae (*Favia fragum*).**




Laboratory set-up for tracking larvae swimming




**Implications for reef enhancement in wind farms**

From previous studies and field observations we know that oyster larvae can swim actively and settle more on specific types of substrates than on others. But how can we use this knowledge to enhance success of restoration measures in wind farms? How do we determine which settlement substrate they prefer most? And how do we know if they can reach the added substrates by active swimming and ambient currents?

In essence the analysis of swimming behaviour shows that oyster larvae cannot influence whether they settle inside or outside a wind farm. They can, however, choose whether they settle on a limestone or a shell. This confirms the importance of micro scale designs and providing adequate settlement substrate. The developed observation technique in this study can help to investigate oyster preference for settlement substrates.

## Laboratory setup for tracking larvae swimming

The setup consists of a chamber with swimming lanes and a high-resolution camera mounted above to film the larvae. The basic system is available through DanioVision, Noldus, The Netherlands. For filming tiny oyster larvae, a better high-resolution camera was included.

Different substrates are offered in the swimming lanes, for instance, substrate A left and substrate B right. Larvae are introduced in the middle and swimming behaviour is recorded for 90 minutes. The footage is processed to quantify swimming speeds, distance travelled and preference for specific substrates.

## Swimming experiments

Oysters prefer to settle on oyster shells and other shell material. Calcium is a known oyster settlement cue. In this experiment the oyster larvae can choose between oyster shell, limestone, or nothing. An oyster larva is introduced in the centre, and after a small period of rest the swimming behaviour is recorded.

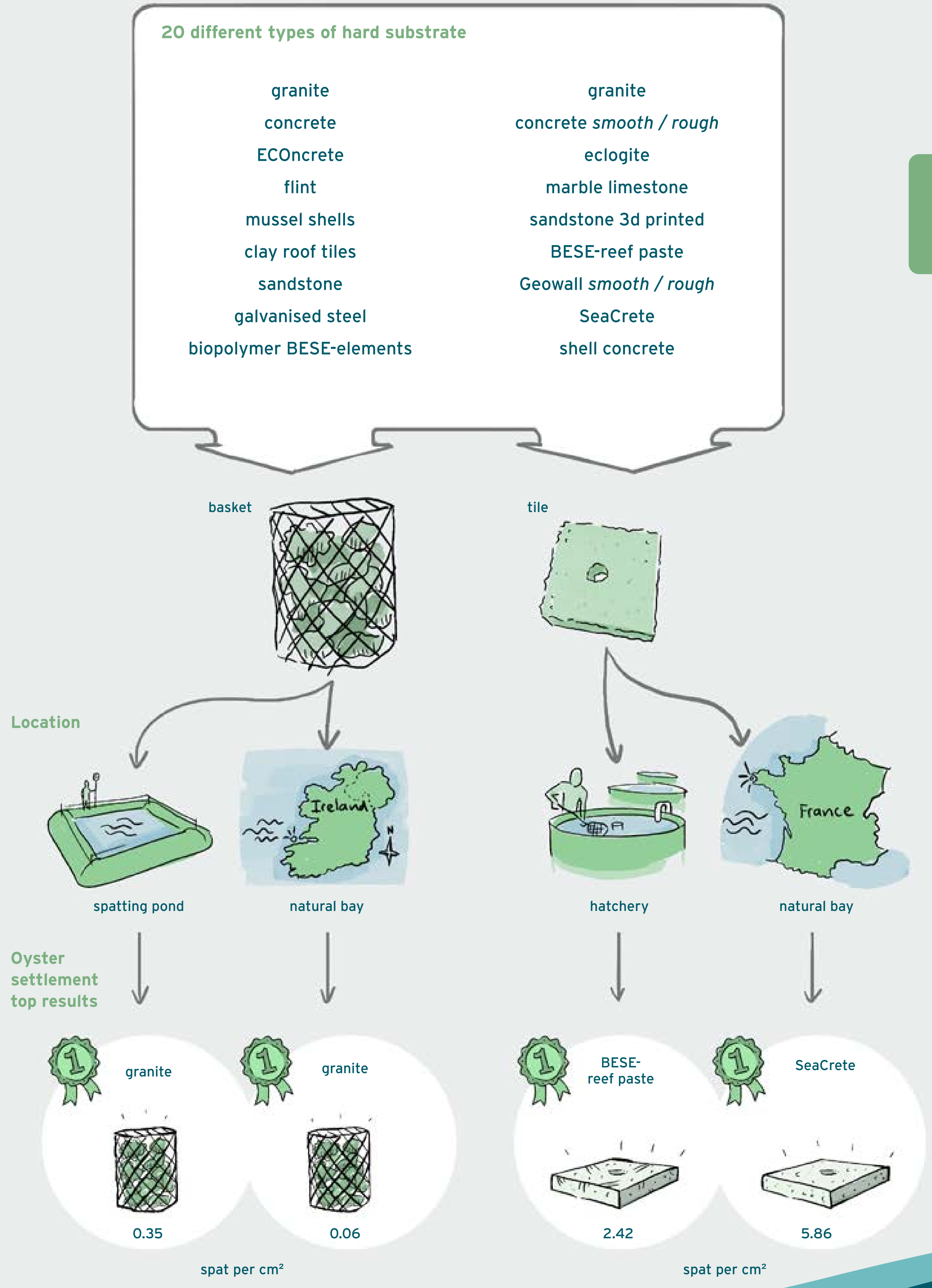
## Conclusions from oyster larvae swimming patterns

The method proved suitable to record behaviour, analyse swimming speed and direction, produce heat maps and analyse habitat preference for larvae. Younger oyster larvae swim faster and larger distances than older larvae. In contrast to coral larvae, oysters showed no clear substrate preference, although this lack of preference can be due to imperfections in the experimental setup which needs to be further optimized.

Recorded swimming speeds for both corals and oysters are much lower than ambient current speeds in the marine environment. This means that larval swimming cannot actively influence settlement on larger geographical scales. However, swimming behaviour at small scales is important for so called 'micro-siting', i.e. choosing which substrate to settle on if different substrates are in close proximity.

**Geertsema, R.C., P. Kamermans, A.J. Murk & T. Wijgerde (2023). Real-time high resolution tracking of coral and oyster larvae. *Journal of Experimental Marine Biology and Ecology.***

Source via QR code: doi.org/10.1016/j.jembe.2023.151910






# European Oyster: Substrate Preference of Larvae

**Towards oyster reef enhancement and the selection of the most suitable hard substrate for settlement: do oyster larvae have a preference?**

**In two separate studies, the settlement preference of European oyster larvae on 20 different types of substrates was tested with experiments under controlled and natural conditions. Clear evidence for substrate preference was found. This contributes to evidence-based substrate selection for interventions that focus on oyster reef restoration and enhancement in the North Sea.**

**Importance to reef enhancement in wind farms**
The development of offshore wind farms in the Southern North Sea results in large areas of undisturbed seabed. These areas could be suitable for active facilitation of oyster reef development. What type of hard substrate is most suitable for interventions aiming at reef restoration? How do you attract oyster larvae and stimulate them to settle locally on your reef development site? In this study settlement preference of flat oyster larvae was related to 20 types of substrates, including conventional scour protection materials, add-on materials known from shellfish restoration projects, spat collectors from aquaculture, and novel bioinspired materials. The knowledge contributes to selecting suitable hard substrate for enhancement of oyster reefs within offshore wind farms.

## Set-up

Two studies with four tests included 20 different substrate types. The first study included 9 substrate types tested in baskets under controlled conditions in a spatting pond (test 1) and under natural conditions in a natural bay in Ireland (test 2). The second study included testing of 12 substrate types in tile-shapes in two hatcheries (test 3) and a natural bay in France (test 4).

In total the studies tested 20 different substrate types for oyster larvae settlement, selection based on substrate application:

- As scour protection within the offshore wind industry (granite, sandstone, flint, eclogite, marble, limestone).
- In shellfish restoration projects (concrete, concrete smooth, concrete rough, ECOncrete, galvanized steel, sandstone).
- As spat collectors in the aquaculture industry (mussel shells, clay roof tiles, shell concrete).
- Bio-inspired materials purposely designed for oyster settlement (BESE-reef paste, Seacrete).
- Biobased or recycled add-on materials (BESE-elements, Geowall smooth and Geowall rough).

These substrate types range a wide variety in their original shape as well as their commercial availability. For substrates offered in tile-shape, rock-material lost part of its natural texture.
After each experiment, researchers transported the substrates to a laboratory to count oyster spat.

## Preferred substrate for oyster settlement

The results of the Ireland based study with baskets (test 1 and 2) showed that granite was the most suitable substrate for oyster larvae settlement, both in the spatting pond and the natural bay.
The second study in France (test 3 and 4) showed that some of the novel bioinspired materials performed most successful. Granite performed poorly in these tests. This can possibly be due to the tile-fabrication process including loss of natural rock texture.

**Study 1**

**Kamermans, P., F. Anteau, K Didderen, R ter Hofstede, Y Zhao, A Le Graet, D Maas, S Pouvreau, S Valk, T Wijgerde, A Zempleni, TE Kodger & T Murk (2025). Novel settlement substrates for European flat oyster (*Ostrea edulis*) restoration. *Ecological Engineering.***

Source via QR code: doi.org/10.1016/j.ecoleng.2025.107532

| Test | European oyster settlement | Substrate type |
|---|---|---|
| *Test 1* Spatting pond Ireland *(0 - 0,8 per cm²)* | Highest settlement | *Granite* |
| | Average settlement | *Concrete, ECOncrete, flint/silex, mussels, roof tile* |
| | Lowest settlement - unsuitable | *Sandstone, galvanised steel, BESE-elements (biopolymers)* |
| *Test 2* Natural bay Ireland *(0 - 0,08 per cm²)* | Highest settlement | *Granite, concrete* |
| | Average settlement | *ECOncrete, flint/silex, mussel shells,* |
| | Lowest settlement - unsuitable | *Sandstone, roof tile, galvanised steel, BESE-elements (biopolymers)* |
| *Test 3* Hatchery Netherlands *(0 - 2,5 per cm²)* | Highest settlement | *BESE-reef paste* |
| | Average settlement | *3D printed sandstone, concrete rough, limestone, marble* |
| | Lowest settlement - unsuitable | *Concrete smooth, eclogite, granite* |
| *Test 4* Natural Bay France *(0 - 6 per cm²)* | Highest settlement | *Seacrete* |
| | Average settlement | *Shell concrete, concrete rough, BESE-reef paste, 3d printed sandstone, marble, concrete smooth* |
| | Lowest settlement - unsuitable | *Eclogite, limestone, granite, Geowall smooth, Geowall rough* |

### Novel materials: bioinspiration, recycling

**SeaCrete** is a bioinspired material that uses tubeworm adhesives as inspiration. It is produced by combining a complex coacervate underwater adhesive and grinded *O. edulis* shells, but not yet commercially available.
**BESE-reef paste** is biodegradable, bioinspired and recycled, using 80% of grinded oyster shells as a base. BESE-reef paste is commercially available as an ecosystem restoration product.
**BESE-elements** is a biodegradable, bioinspired biopolymer- and recycled starch-based product, designed to mimic structural complexity of reefs and plant roots, used for various applications in ecosystem restoration.
**Geowall** recycles sludge from urbanised estuaries into concrete like material and is commercially available as a circular building product.

In the second study, BESE-reef paste yielded highest settlement rates in the hatchery and performed good in the natural bay. SeaCrete and reference tiles showed the highest settlement rates in the natural bay in France.
Substrate colour and rugosity showed to likely interact with the effect of material type on oyster settlement rates. However, material type was found to have a dominant effect on spat density.

### Settlement substrate selection for the offshore wind industry

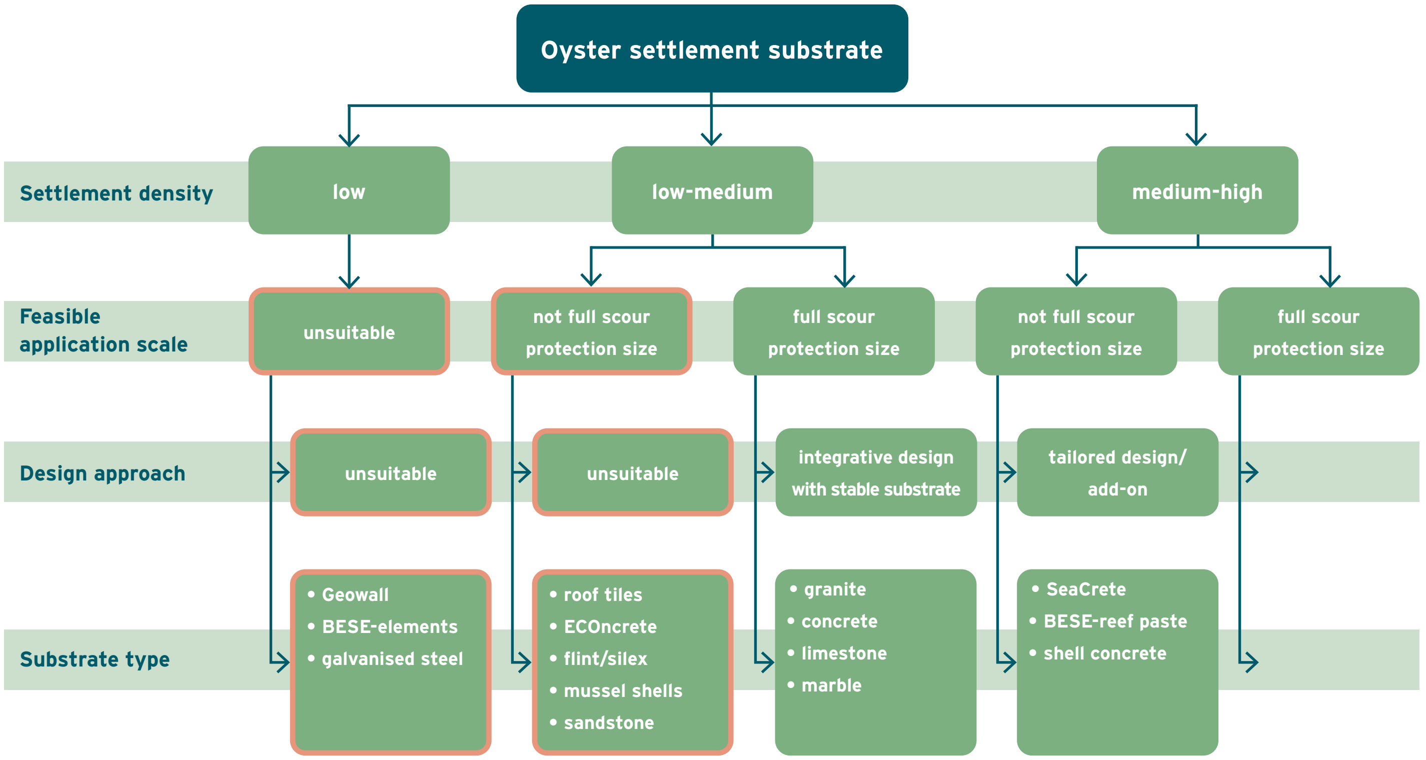
- **Bioinspired restoration materials** are novel materials. Seacrete and BESE-reef paste are purposely designed for oyster restoration, and the settlement density on these materials are high compared to the other tested materials
- **Rock material** such as granite can be used as oyster settlement substrate. The settlement density on these materials is low to medium. However, with the advantage of being a conventionally used material, for example used for scour protection, they can be used easily for integrative designs in offshore wind farms. Secondly, the substrate can easily be applied in large quantities generating large surface areas for oyster settlement.
- **Calcareous and shell-based materials** show good settlement performances with a biogenic origin of calcium carbonate (e.g. shells, shell concrete) and the use of lime.
- A fourth group of materials underperform for oyster settlement in the various tests. ECOncrete, Geowall, flint/silex, roof tile, BESE-elements and galvanized iron showed oyster spat densities of <1/cm² They are not listed as suitable settlement substrates for European oysters in field settings for offshore wind farms.
- Not only chemical composition, but also material roughness, rugosity, position and colour play a role in attractiveness for oyster settlement. At the same time, independent of type, the total surface area available influences oyster settlement potential, where larger surface areas allow more oysters to settle.

### What to choose in a wind farm? Focus versus scale

Special designed bioinspired materials are more successful in attracting oyster larvae than standard building materials such as granite. However, building materials, like granite as scour protection rock material, are applied in a much larger scale than an oyster-focussed add-on materials.
Small dense cores of oyster reefs may be most efficiently realised using specialized bioinspired materials that maximise oyster settlement densities when applied as add-ons to the wind farm infrastructure. To achieve large-scale oyster settlement across a wind farm, the use of integrative designs with standard scour protection material as additional oyster settlement substrate is likely important. For effective oyster colonization, scour protection rocks must remain stable and largely free of sediment. If the rocks move, they can crush the oysters, while excessive sedimentation can smother them.

### Kickstarting European flat oyster reefs in wind farms

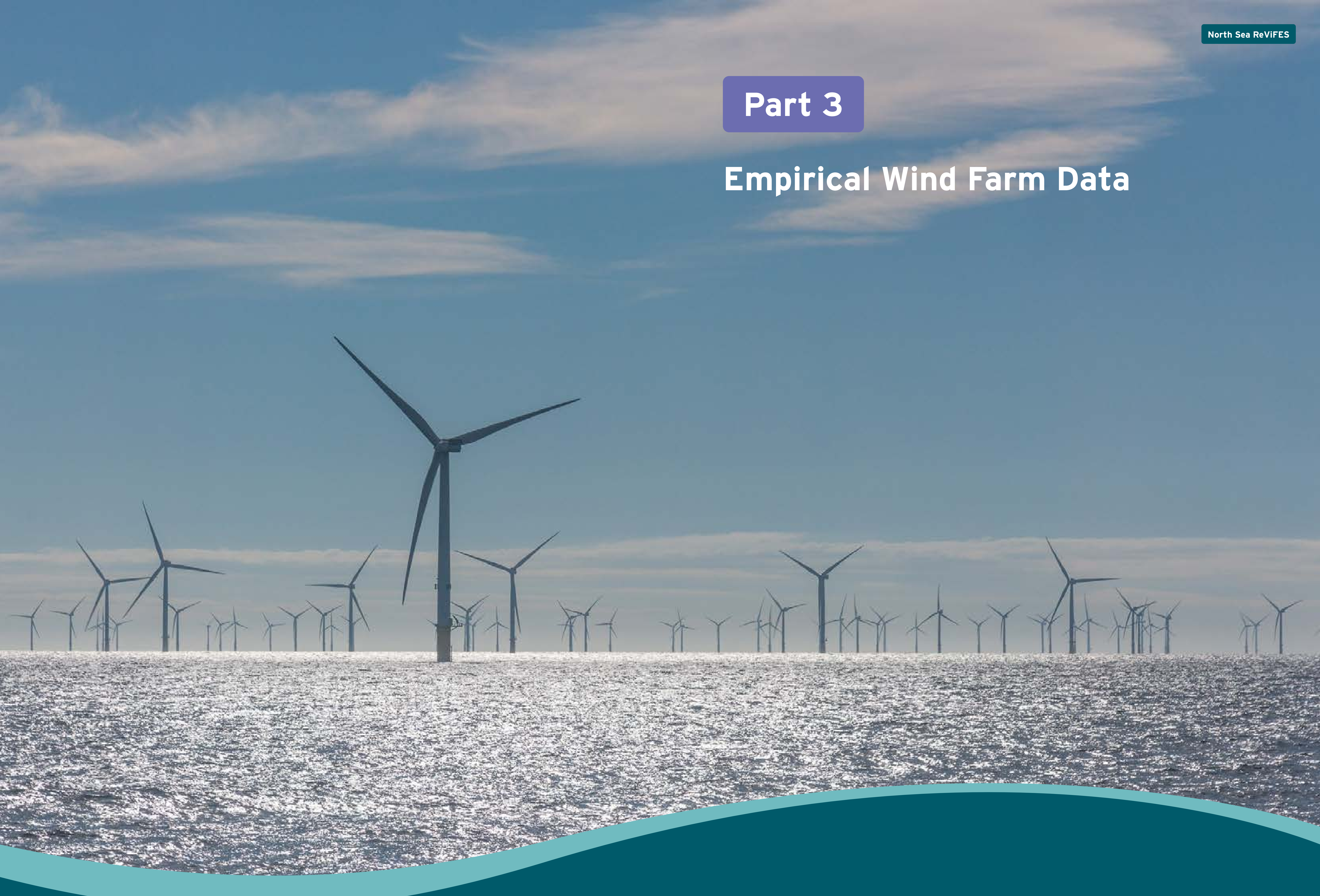
Using favourable substrate within wind farms is not enough to achieve oyster reef restoration due to the lack of natural oyster larvae supply and settlement in the North Sea. Therefore, pro-actively introducing live oysters is also necessary. Deploying suitable and stable substrate with oyster spat, as spat-on-substrate, or oyster broodstock on structures with settlement substrate nearby, seem efficient strategies to kickstart oyster reefs in the North Sea.




**Study 2**

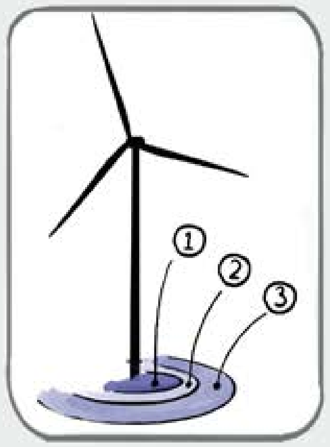
**ter Hofstede, R., S. Witte, P. Kamermans, L. Tonk (2024). Settlement success of European flat oyster (*Ostrea edulis*) on different types of hard substrate to support reef development in offshore wind farms. *Ecological Engineering.***

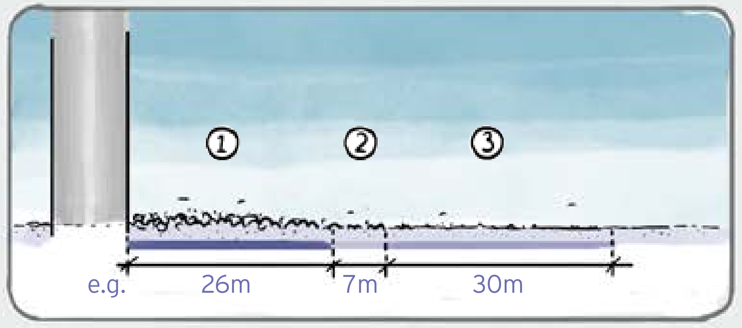
Source via QR code: doi.org/10.1016/j.ecoleng.2024.107189



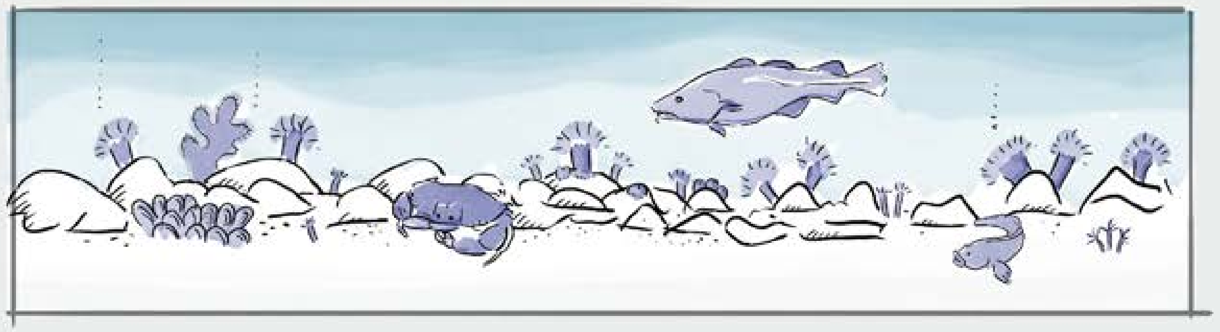
# Part 3

## Empirical Wind Farm Data

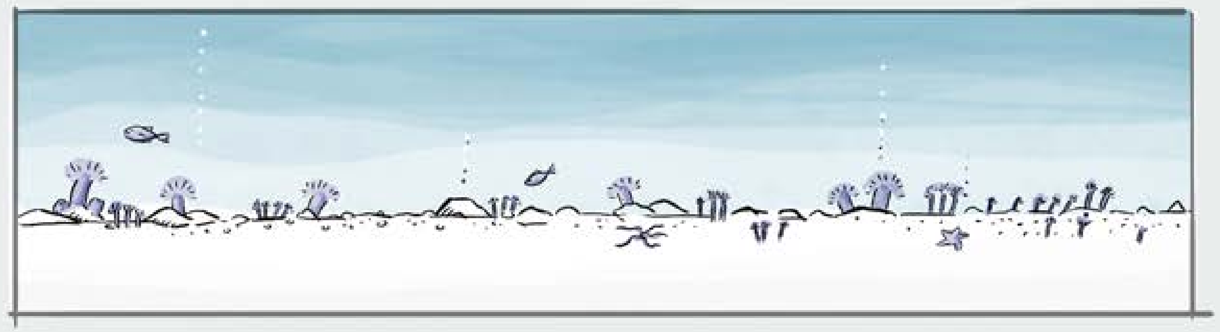


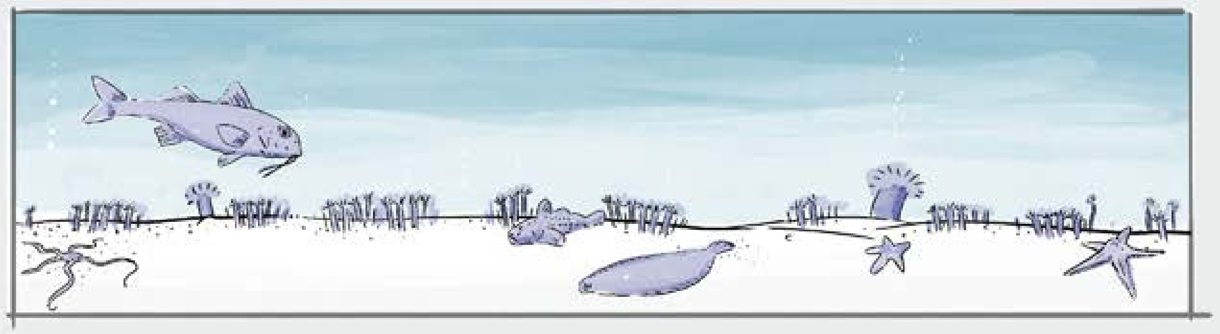

1 **The armour layer**



2 **The transition zone**



3 **The adjacent seabed**





# Epibenthic Biodiversity: Reef Communities on Scour Protections in Wind Farms

**Towards enhancement of a diverse reef community in offshore wind farms: do scour protections change epibenthic communities?**

**With a field study the epibenthic community structure on scour protections and it surrounding seabed was assessed. It identifies important explaining factors for community similarities and differences of scour protections in wind farms across the Southern North Sea.**

**Importance to reef enhancement in wind farms**

The installation of wind farms typically involves the addition of artificial hard substrates, such as patches of rock used for scour protection. How do benthic species communities on scour protection compare to the adjacent seabed? And what factors explain community differences? This study relates geographical distance and substrate type to epibenthic community differences in wind farms. This knowledge can be used in designs of future wind farms.

- Geographical distance and substrate type proved to be main explaining factors for epibenthic community differences.
- The communities at scour protections had a different species composition and a higher abundance compared to the surrounding seabed.
- Scour protection designs can be further heterogenized to enhance epibenthic species diversity. This is an important directive for nature-inclusive designs of future wind farms.

### Set-up

This study assesses video data collected with a Remotely Operated Vehicle at scour protections around foundations in four wind farms in the Southern North Sea. Footage along radial transects covered the scour protection and its surrounding seabed.

### Rich epibenthic species community

A diverse epibenthic community was observed, comprising 47 species from 7 different phyla, in the four offshore wind farms studied. Sponges, anemones, tube worms, crabs, molluscs, sea stars and fish are all part of the epibenthic communities on scour protections and their surrounding seabed.

### Zonation of rock layers: local scale differences

The area around a wind turbine foundation generally contains three different zones:

1. The armour layer of the scour protection. A stable rock layer mainly consisting of hard substrate, rock.
2. The transition zone. An area with a mixture between soft substrate (sand) and hard substrate (rock). Spanning from the armour layer to the adjacent seabed and often including the filter layer of the scour protection.
3. The adjacent seabed. The seabed adjacent to the scour protection, consisting of soft substrate, sand.

This local zonation is the main explaining factor of differences in epibenthic communities, with 80% dissimilarity between the armour layer (zone 1) and seabed (zone 3). The epibenthic community at the rocky armour layer of the scour protection had a different species composition and a higher species abundance than the community at the sandy seabed surrounding it.

**Ter Hofstede, R., F.M.F. Driessen, P.J. Elzinga, M. Van Koningsveld & M. Schutter (2022). Offshore wind farms contribute to epibenthic biodiversity in the North Sea. *Journal of Sea Research*.**

Source via QR code: doi.org/10.1016/j.seares.2022.102229

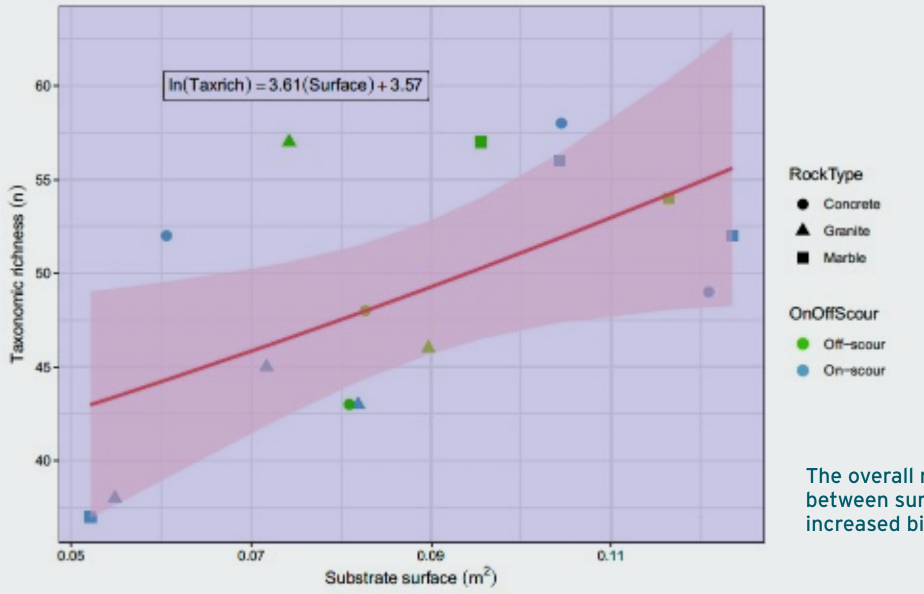
#### Geographic location: landscape scale similarities and differences

The studied wind farms overlap in age and in their scour protection designs. This leads to overlap between overall epibenthic communities with ~50% similarity between the wind farms. Nevertheless, differences between communities arise based on their geographic distance. Nearby located wind farms had a more similar epibenthic community compared to those further away.

#### Rocky islands as epibenthic refuge

In conclusion the study shows that offshore wind farms have a positive effect on diversity in epibenthic communities during their operational lifetime. The lack of bottom-disturbing activities and the presence of scour protection rock at the base of wind farm foundations create refuge and complex habitat for epibenthic species.






The overall relationship between surface area and increased biodiversity

One of the experimental cages after nine months on the seabed

ROV footage of the research cages on the seabed with associated marine life



# Benthic Biodiversity: Scour Protection Rock Type

**Towards nature inclusive design in offshore wind farms: enhancing benthic biodiversity with scour protection rock design.**

**Empirical evidence was collected to test if nature inclusive design options of scour protection in offshore wind farms can lead to enhanced benthic biodiversity. In a field experiment benthic biodiversity was related to different types of scour protection rock in a Dutch offshore wind farm.**

**Implications for biodiversity enhancement in wind farms**

From the earliest monitoring of the first offshore wind farms and onwards, it was clear that in the North Sea turbine foundations including scour protections can harbour rich reef communities in otherwise mostly soft bottom environments. Optimizing foundation and scour protection designs has long been hypothesized to enhance reef biodiversity, though these predictions lacked empirical evidence. Are different scour protection rock types yielding differences in benthic biodiversity?

Benthic biodiversity was investigated during an offshore field experiment with various types of scour protection rock. The main conclusion is that rock substrate types with increased surface area lead to increased biodiversity. A second conclusion is that the use of a mixture of different scour rock materials enhances the functional diversity[1] of the benthic community. This shows that nature inclusive designs can enhance the short-term biodiversity output of a scour protection. Empirical evidence is providing invaluable support for nature inclusive design activities in offshore wind farm development. Evidence of the effect of optimising scour protection designs for biodiversity justifies large investments in reef enhancement.

### Field experiment setup

Three different types of rock were tested in this study:

- Granite - standard scour protection material
- Concrete - rough surface
- Marble - calcareous rock

Quantities of each rock type were placed in research cages on scour protections in the Borssele offshore wind farm Lot V in the Dutch North Sea. Monitoring was performed after nine months by ROV footage and ultimately retrieving the cages for laboratory analysis of the rocks and its benthic fauna.

### Results

More than 17.000 animals from a benthic community of 131 different taxa were observed on the 3 rock types. Policy relevant species such as rossworm *Sabellaria spinulosa*, sand mason worm *Lanice conchilega*, and blue mussel *Mytilus edulis* where present in multiple samples. For some species groups differences were observed between rock types. However, independent of the rock type, the strongest detected pattern clearly shows that a larger surface area results in higher overall biodiversity. Additionally, functional diversity[1] of the benthic community differed depending on the type of rock used.

[1] *Functional diversity is a component of biodiversity related to things that organisms do in ecosystems or communities. Here it means diversity in species groups in how they use scour protection rocks. E.g. species that attach to, species that make a burrow in or species that use crevices around scour protection rocks.*

**Kingma, E.M., R. ter Hofstede, E. Kardinaal, R. Bakker, O. Bittner, B. van der Weide & J. W. P. Coolen (2024). Guardians of the seabed: Nature-inclusive design of scour protection in offshore wind farms enhances benthic diversity. *Journal of Sea Research*.**

Source via QR code: doi.org/10.1016/j.seares.2024.102502

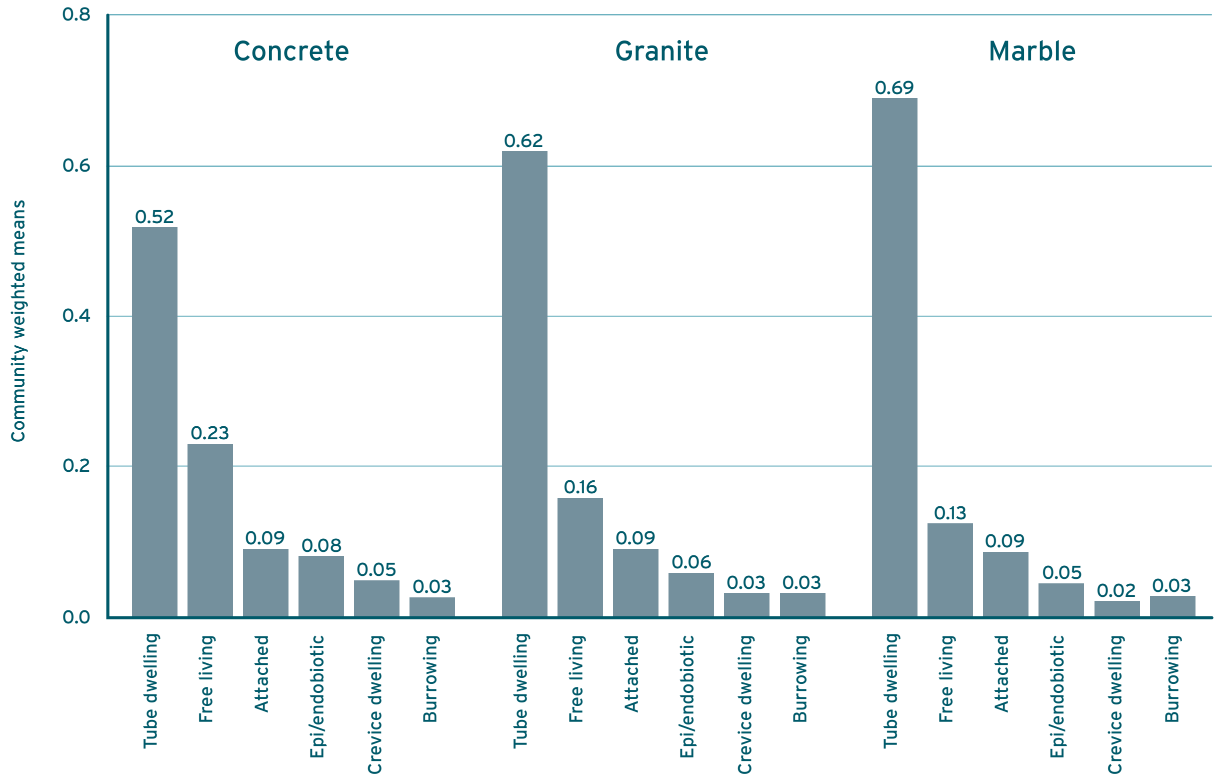


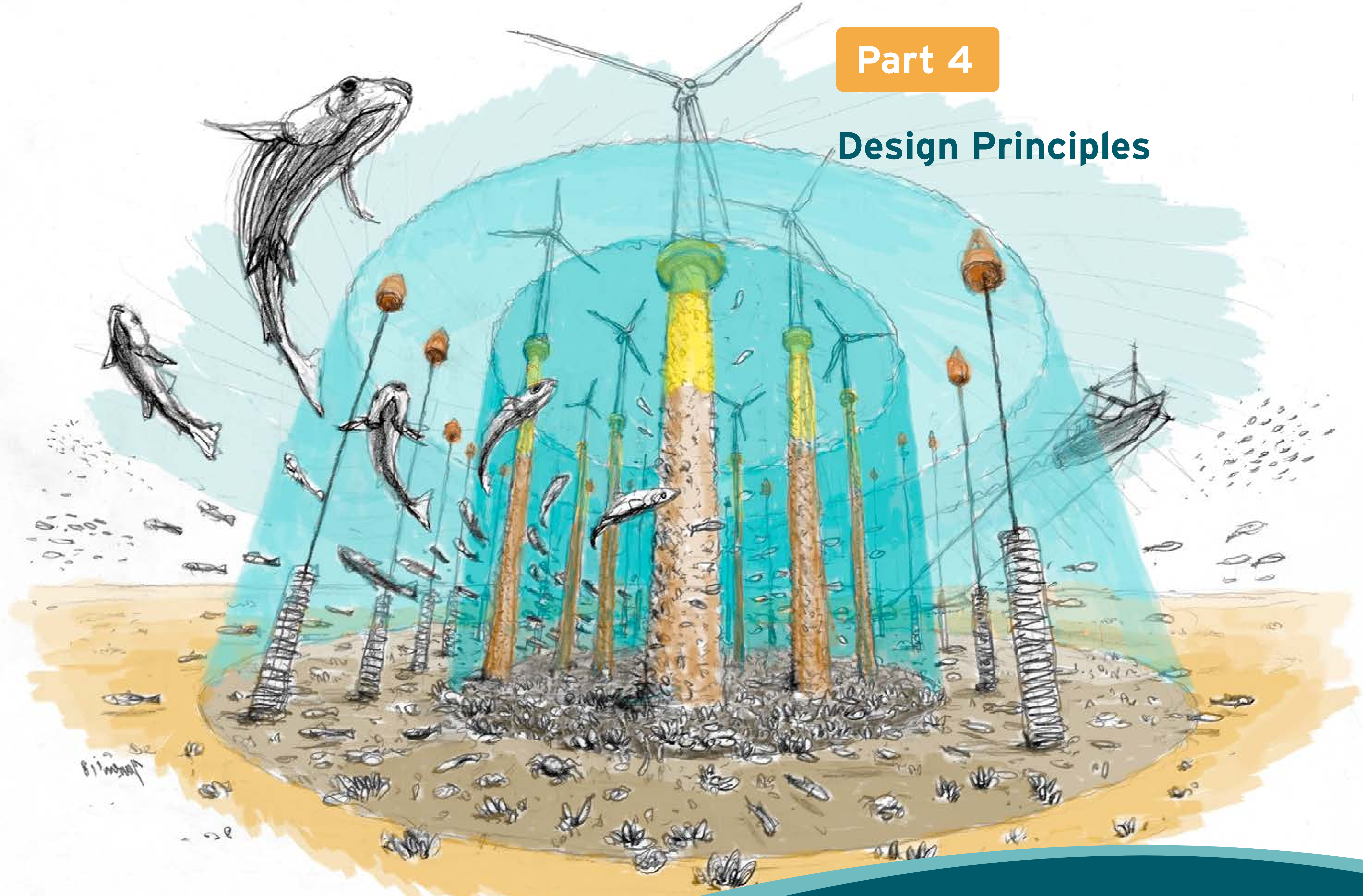
## Conclusions

Previous recommendations for enhancement of marine biodiversity in offshore wind farms include design options for the foundations themselves, add-on options such as artificial reef units and modifications to the scour protection rocks. Optimised scour protection rock designs have included more variation in size and shape to create more surface area and crevices, but also changing rock type for instance to create a calcium rich substrate to attract native oysters.

The results show that with optimizing scour protection designs, rock type can be used as a mean to create a larger surface area and in this way increase benthic biodiversity within the first year. Additionally, the combination of different rock materials in the scour protection promotes the functional diversity of benthic fauna. Overall, the study provides motivation for surface area maximisation and substrate variation of nature inclusive design of scour protections and encourages further investigation of other aspects of nature inclusive designs of wind farms.

**Functional diversity community weighted means for living habit trait across substrate and cage type.**

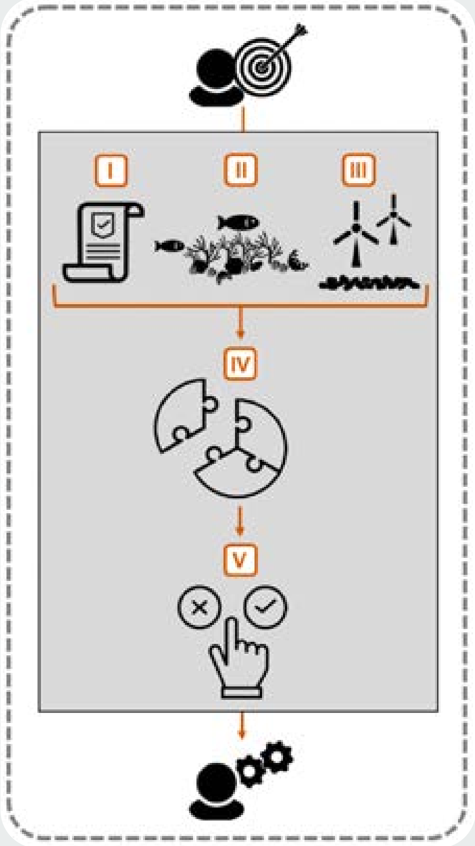


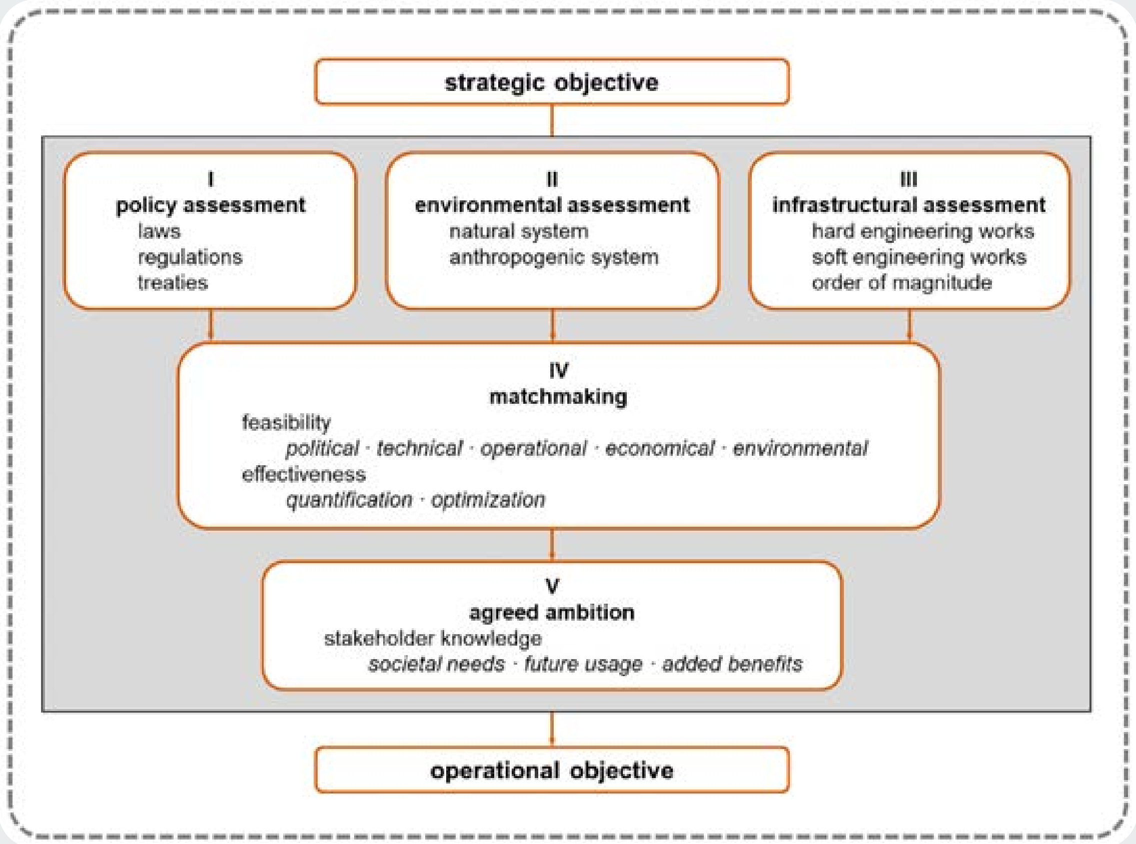


Jeroen Helmer

# Part 4

## Design Principles








# North Sea Reefs: Setting Objectives

**Towards successful reef enhancement in offshore wind farms: defining objectives for nature-inclusive infrastructure to achieve system-scale impact.**

**To achieve system-scale impact, it is important to set clear objectives for nature-inclusive infrastructure. This theoretical framework uses a stepwise approach that aligns policies, environmental conditions, and infrastructural development to define objectives to improve targeted ecosystem components. The framework is showcased by deriving objectives for nature-inclusive design in offshore wind farms in the North Sea.**

**Importance to reef enhancement in wind farms**
Clear objectives will guide project developers in designing nature-inclusive infrastructure and in establishing relevant monitoring programs. Stakeholder agreement requires the establishment of realistic and achievable targets and ambitions. This consensus can help align individual initiatives, enabling them to scale up collectively.

## The stepwise approach

The stepwise approach that is developed in this study facilitates the process to define operational objectives based on given strategic objectives.

*Step 1* is a policy assessment, that assesses laws, treaties and other regulations relevant for the project area and the wider marine ecosystem.

*Step 2* is an environmental assessment involving both the natural system and the anthropogenic system.

*Step 3* is an infrastructural assessment comprising both hard engineering works (e.g. foundations) and soft engineering works (e.g. dredged channels). This step also includes an assessment of the scale of actions, ensuring large enough scale to be both effective and cost-efficient.

*Step 4* is where step 1 to 3 meet and matchmaking between policy, environment and infrastructure takes place to determine the potential within an area for promoting selected ecosystem components by including nature-inclusive design.

Ultimately, in *Step 5* agreement is reached on achievable ambitions, involving knowledge of the system, stakeholder requirements, future usage of the area. Determining potential for additional side-effects or side-benefits from a measure or nature inclusive-design is an important part of this final step.

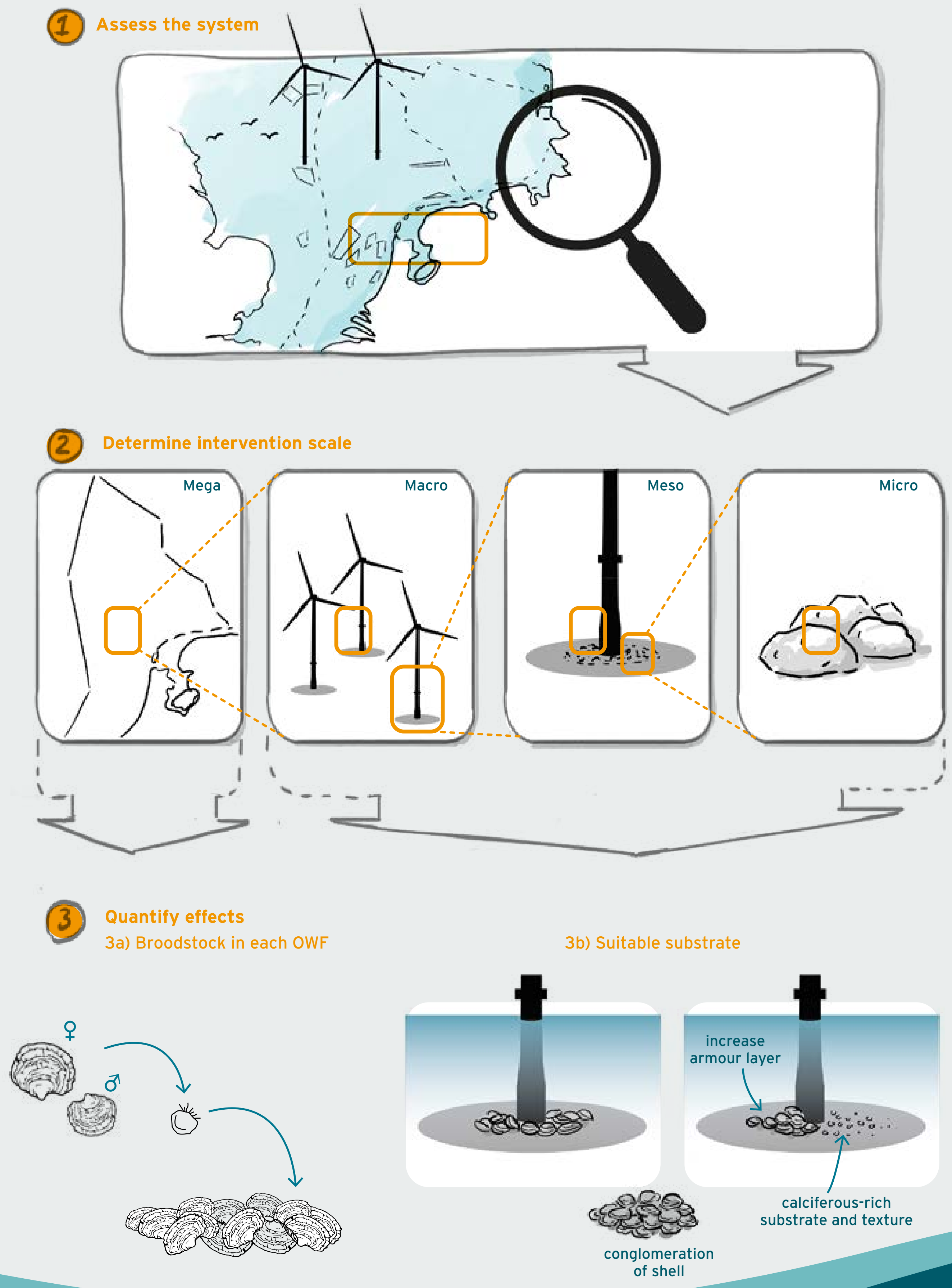
## Conclusions

Marine infrastructure has great potential to enhance ecological functioning of an area. Therefore, nature-inclusive design is increasingly applied in marine construction projects. In most cases, however, designs and measures are targeted at individual project requirements. This causes fragmentation and hampers the opportunity to make system scale impact. The stepwise approach presented in this study helps to define clear objectives for a wider area to reach project requirements and at the same time cease the opportunity to achieve system-scale impact.

**Ter Hofstede, R. & M. van Koningsveld (2024). Defining operational objectives for nature-inclusive marine infrastructure to achieve system-scale impact. *Frontiers in Marine Science.***

Source via QR code: 10.3389/fmars.2024.1358851

**Interventions at scale**
**How to select the right measures and determine the required scale?**






# European Oyster: Interventions at Scale

**Towards successful oyster reef enhancement in offshore wind farms:**
**How to select the right measures and determine their required scale?**

**A stepwise approach to select measures and determine their required scale is applied for oyster reef development in offshore wind farms in the southern North Sea. Different possible interventions are presented, and their potential effect is quantified.**

### Stepwise selection of measures and scale

**Step 1** Assess the system
**Step 2** Determine the scale of your interventions
**Step 3** Quantify effects

**Step 1**

### Assess the system

Presence of the target species
European oyster is the best indicator for environmental suitability. However, if oysters are not present in the current situation, a second good indicator is historical presence. Were oyster reefs present on you wind farm site? If the answer is no, this may not be a good location. If the answer is yes, one should further investigate if the environment could nowadays be suitable, e.g. being void of the stressors that caused the disappearance of oysters. From a Southern North Sea wide assessment, it is concluded that 21 of 62 existing wind farms are suitable for oyster reef development (d.d. 2020).

**Step 2**

### Determine the scale of your interventions

**Four different scales are distinguished:**

1. Mega scale is between wind farms and is about how populations in wind farms can be connected.
2. Macro scale is at the scale of 1 wind farm, including turbine foundations and in-between seabed, and is about how much space is available for the local population.
3. Meso scale is at the scale of 1 wind turbine foundation and is about how much reef enhancement can be achieved on one turbine foundation.
4. Micro scale is at the scale of material types and textures and is about what stimulates oyster larvae to settle locally.

**Four different interventions are discussed, as examples of the four scales:**

1. Providing live brood stock of oysters (high enough number, and varying sizes to ensure both sexes) (mega).
2. Stimulating oyster settlement on the soft substrate between wind turbines, by providing conglomerated shell (macro).
3. Increasing the size of the armour layer by 1 monopile diameter (meso).
4. Improving the ecological quality of the scour protection layer so it can serve as a optimal basis for oyster reef settlement, i.e. ensuring stability and immobility, adding calciferous-rich material to enhance settlement (micro).

**Ter Hofstede, R., G. Williams & M.van. Koningsveld (2023). The potential impact of human interventions at different scales in offshore wind farms to promote flat oyster (*Ostrea edulis*) reef development in the southern North Sea. *Aquatic Living Resources*.**

Source via QR code: doi.org/10.1051/alr/2023001

Step 3

## Quantify effects

If the stepwise approach is applied to the Southern North Sea, it leads to the following conclusions:

### 1. Mega scale

**Oyster broodstock for each wind farm.**

21 of 62 wind farms are considered suitable for oyster reefs. Oyster larvae don't naturally distribute far enough to connect between wind farms. Thus, each wind farm needs its own broodstock or population. Broodstock should contain varying oyster sizes to ensure both males and females. 1000 introduced oysters as a starting
population is estimated to yield 35000 adults after 10 years. Fully filling an average wind farm in 15 years would require an initial brood stock of 39.000 oysters.

### 2. Macro scale

**Small stable starting reefs, natural expansion.**

21 of the currently planned and installed wind farms are considered suitable for oysters. They hold a seabed area of 1614 $km^2$, which could hold ~200 million oysters. Oysters can be stimulated to settle on the seabed by providing shell material, preferable conglomerated shell material to create extra elevation, stability, and structure. It is assessed that oyster recruitment at stable reefs of shell material can be 8000 times higher than at soft sediment. Unrealistically large amounts of shell material would be needed to reach full potential in the 21 wind farms, hence strategic smaller populations should be actively stimulated, aiming for natural expansion over time. For instance, aiming at 1 % initial coverage with shell material of the wind farm area.

### 3. Meso scale

**Focus on armour layer.**

Wind turbine foundations typically have a scour protection at their base to prevent the surrounding seabed from erosion, which can be made suitable as a substrate for oyster reefs. Suitable means that scour protection rocks should remain above the sand, be stable and immobile. Typically, only the armour layer meets these conditions. The 21 suitable wind farms in the Southern North Sea provide ca 0,74$km^2$ of armour layer for reef development. Once broodstock has been introduced, the total of armour layer can host ~5 million oysters. Increasing the size of the armour layer is one possible intervention to increase the amount of potential oyster reefs.

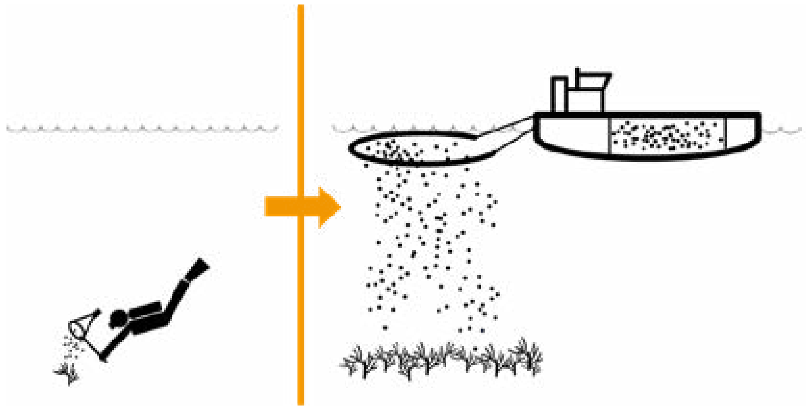
### 4. Micro scale

**Addition of calciferous rock and shell material.**

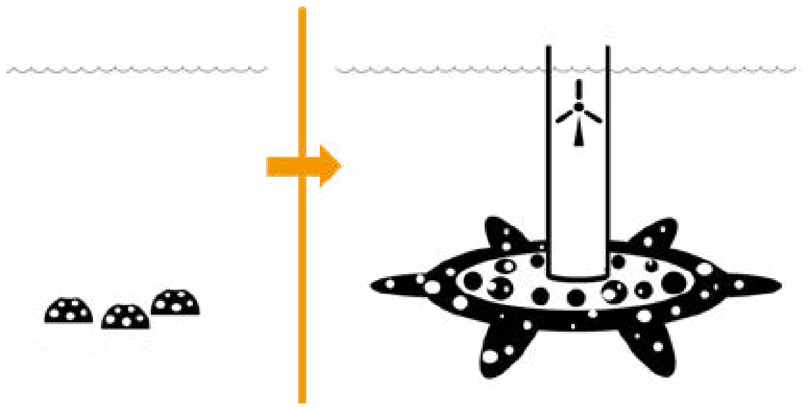
Interventions to promote oyster settlement Involves for example using calciferous-rich rocks instead of just granite scour protection rocks. In a previous study it was demonstrated that this could lead to 30% more local oyster settlement. Providing reefs of shell material can result even in 150 times more settlement.



1 **Pursue upscaling.**



2 **Landscape infrastructure**



# Reef Restoration: Five Golden Principles

**Towards successful reef enhancement in offshore wind farms: Advancing marine reef restoration by linking science and industry.**

**Building a wind farm at sea generates negative impacts that need mitigation strategies. On the other hand, nature-enhancement can be achieved during design and construction, especially for benthic marine life. How can construction works synergize with ecosystem restoration goals and nature-enhancing opportunities? Five general principles link the experience from marine contractors and knowledge from scientists to reef restoration.**

**5 Principles how marine contractors can support reef ecosystem restoration.**

1. Pursue upscaling: Use industrial techniques to achieve positive impact at scale.
2. Design siting of infrastructure to optimize habitat for targeted species.
3. Induce life to overcome connectivity bottlenecks and steer community composition.
4. Design nature development efforts to be self-sustainable.
5. Ensure continuity beyond project boundaries by early stakeholder engagement.

**Principle 1**

**Pursue upscaling.**

Current practices for restoration are often small at scale. There is a need to move to cost-effective solutions that can be implemented at a kilometer-scale. Innovative solutions can thereby be borrowed from industries, as they are already operating at economy of scale.

**Principle 2**

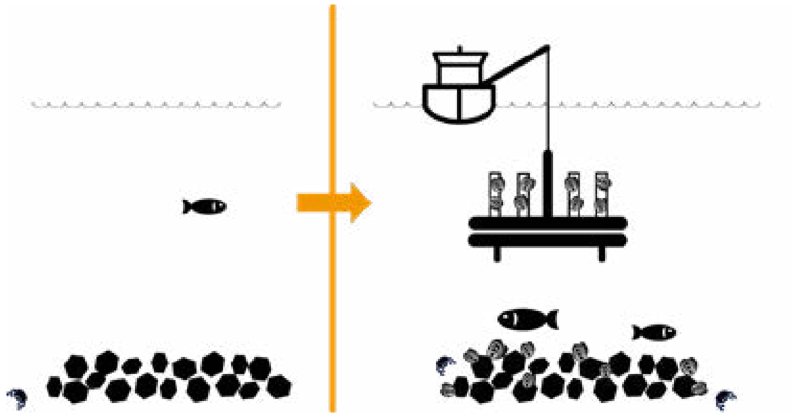
**Design siting of infrastructure to optimize habitat for targeted species.**

Restoring reef ecosystems often involves installing artificial reef structures designed with customized and optimized three-dimensional features. Scaling up to large quantities of these tailor-made add-ons, however, is costly and has a large carbon footprint. To create optimized habitats on a large scale, it is more efficient to integrate habitat designs into marine infrastructure built for other purposes, such as energy production and coastal protection. For example, optimizing scour protection designs in offshore wind farms to enhance ecological value on a large scale is more efficient and cost-effective than installing separate artificial structures.

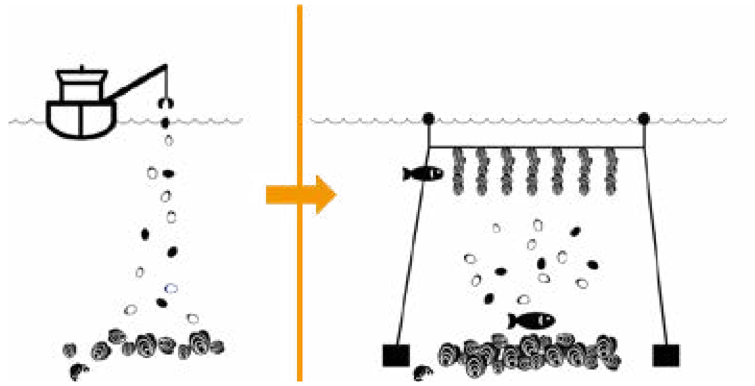
**ter Hofstede, R., T.J. Bouma, & M. van Koningsveld (2023).**
**Five golden principles to advance marine reef restoration by linking science and industry.**
***Frontiers in Marine Science*.**

Source via QR code: doi.org/10.3389/fmars.2023.1143242

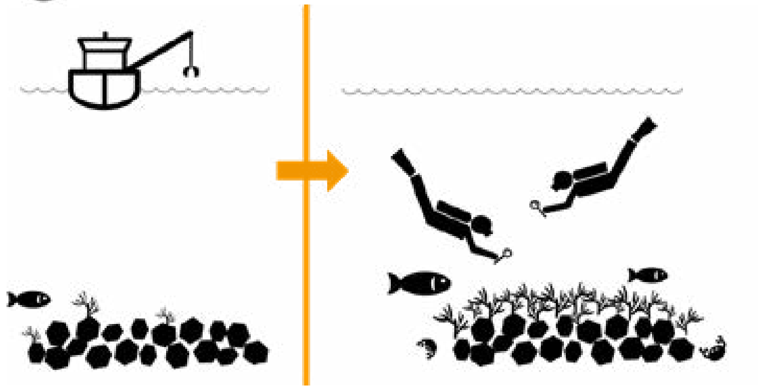
### 3 Induce life



### 4 Support self-sustainment



### 5 Continue by stakeholder engagement



**Principle 3**

**Induce life to overcome connectivity bottlenecks and steer community composition.**

New marine structures create hard substrates that are rapidly colonized by organisms with larvae present in the local seawater. However, lack of local larvae makes it hard for new organisms to settle and grow. Introducing broodstock of target species can help address this limitation and guide community composition in a desired direction. While this approach can be costly and risky, expertise from the marine industry has led to the development of reliable and cost-effective methods.

**Principle 4**

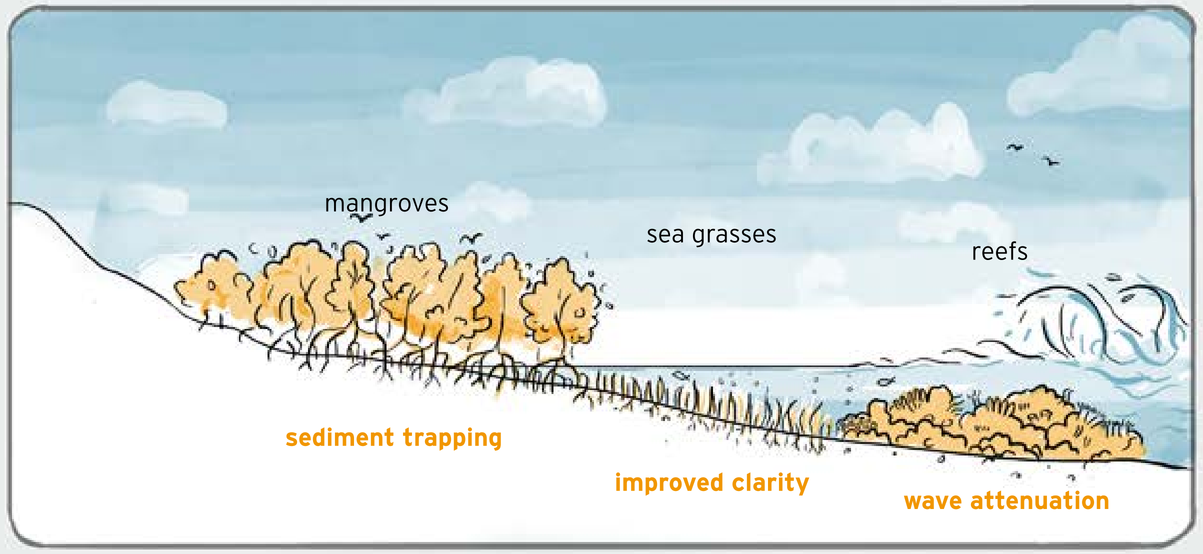
**Design nature development efforts to be self-sustainable**

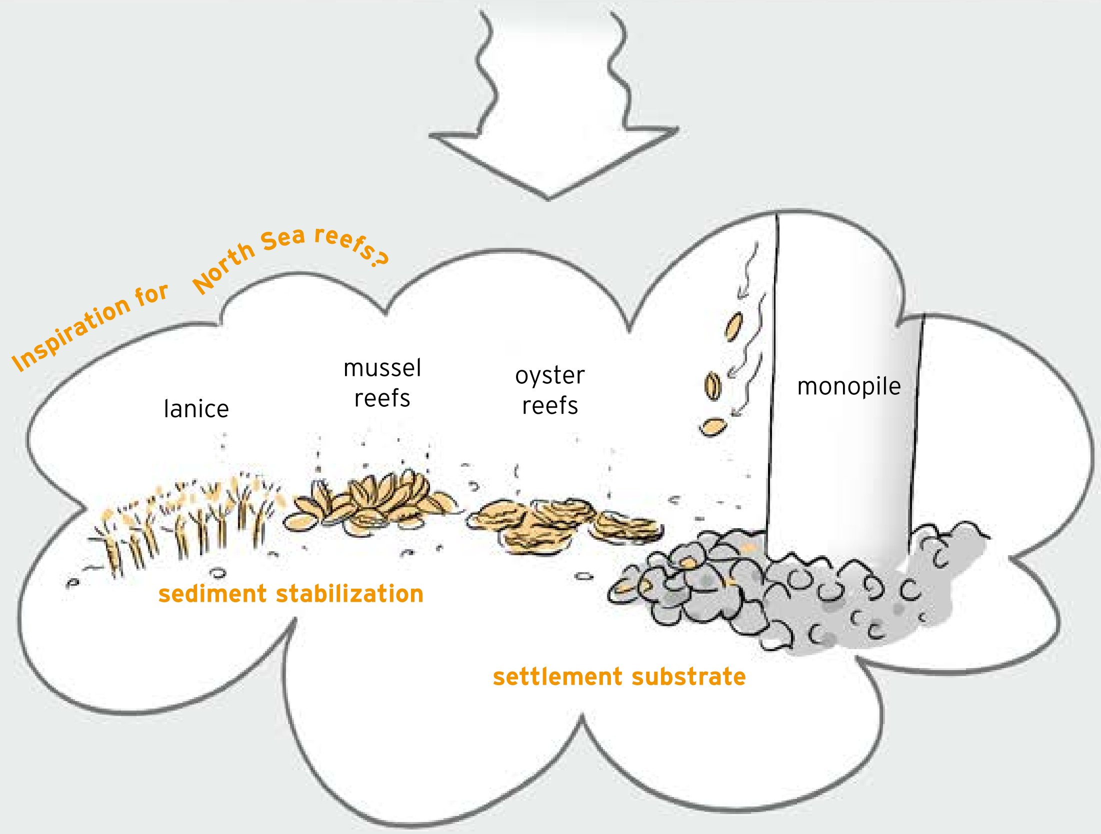
The ultimate goal of any restoration effort should be to recreate a self-sustaining ecosystem. Self-sustainment indicates good health, the ecosystem being able to maintain its structure and function over time without further need of (costly) human interventions. Examples of successful restoration of self-sustaining reefs however, are rare. To succeed, interactions between biota and abiotic features should be taken into account as well as connectivity with other restored or remnant ecosystems.

**Principle 5**

**Ensure continuity beyond project boundaries by early stakeholder engagement**

Ecological restoration timelines often extend beyond those of marine infrastructure and active ecosystem restoration projects. These projects typically span only a few years from design to construction. Monitoring, evaluation and maintenance of a restoration effort to ensure long-term success take much longer. To bridge the gap between initiation and continuation, local partners should be engaged from the outset, ensuring their commitment to take responsibility after the initial phase and prolong the efforts.






# Success in Coastal Ecosystem Restoration: Address Multiple Habitats Simultaneously

**Towards successful restoration of coastal marine ecosystems: work across multiple habitats simultaneously.**

**With a motivational literature review the benefits of working on multiple habitats simultaneously are highlighted within the context of coastal ecosystem restoration. Recognising positive interactions between different habitats is an important step to improve ecosystem restoration success.**

**Importance to offshore wind farm development**

Offshore wind infrastructure can interact with coastal marine habitats, for instance in case of a nearshore wind farm or cable landings. Reef, saltmarsh, seagrass or mangrove restoration can support environmental goals or mitigation efforts within offshore wind developments. Coastal wetland restoration as well as mitigation mostly focusses on single habitats. Shifting from single habitat practices to rebuilding multiple, connected habitats across seascapes presents a new angle to marine ecosystem restoration motivated in this study.

## Facilitating roles of connected habitats

Physical, chemical and biological parameters determine whether and where habitats can occur in marine coastal areas. Seagrasses, mangroves and salt marshes need relatively calm conditions to start and thrive, often created by coral or oyster reefs that attenuate wave action and reduce currents. In turn, the seagrasses, mangroves or salt marshes trap sediment and land-runoff and thereby create favourable clear water conditions for reefs to thrive. These positive interactions are referred to as cross-habitat facilitation. When multiple types of habitats are destroyed, restoration with a focus on a single habitat will not bring back the essential facilitating mechanisms, hampering a successful outcome.

## Cross-habitat facilitation occurs at different scales

Essential cross-habitat facilitation for increased restoration success has been documented within scales of metres to a few kilometres, for instance with restoring oysters and mangroves just 20 meters apart. However, facilitation may work at much larger scales too, up to seascapes. Filtration by oysters and sediment stabilisation by seagrass can result in increased water clarity that stretches for tens of kilometres throughout entire estuaries. Ecological modelling may be required to determine in advance such potential effects.

## A new angle to marine ecosystem restoration and seascaping

Research indicates that restoring multiple habitats together improves success rates. However, only a tiny fragment of thousands of marine coastal restoration case studies took a multi-habitat approach. Advancing ecosystem restoration policies, innovations, and technologies requires greater awareness of the benefits of multi-habitat interconnections.

**Vozzo, M.L., C. Doropoulos, B.R. Silliman, A. Steven, S.E. Reeves, R. ter Hofstede, M. van Koningsveld, J. van de Koppel, T. McPherson, M. Ronan & M.I. Saunders (2023). To restore coastal marine areas, we need to work across multiple habitats simultaneously. *PNAS*.**

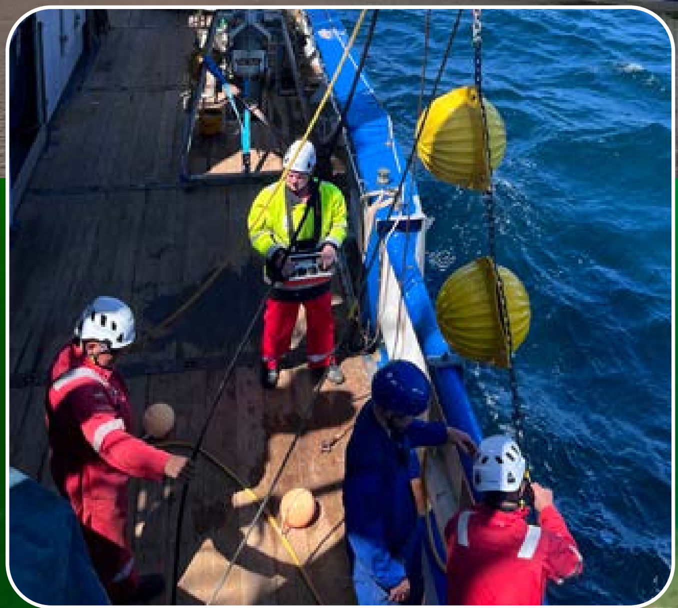
Source via QR code: doi.org/10.1073/pnas.2300546120

# Thesis Spotlight

# North Sea Reefs: Ecosystem Services of Wild Reefs

**Towards self-sustaining reefs: lessons learnt from field data of wild reefs in the North Sea.**

**By comparing near shore and offshore temperate reefs to no-reef areas this North Sea ReViFES dissertation highlights ecosystem services of wild reefs in the North Sea. The thesis is based on field observations as a foundation with extensive sets of empirical data from North Sea reefs collected during multiple scientific expeditions.**

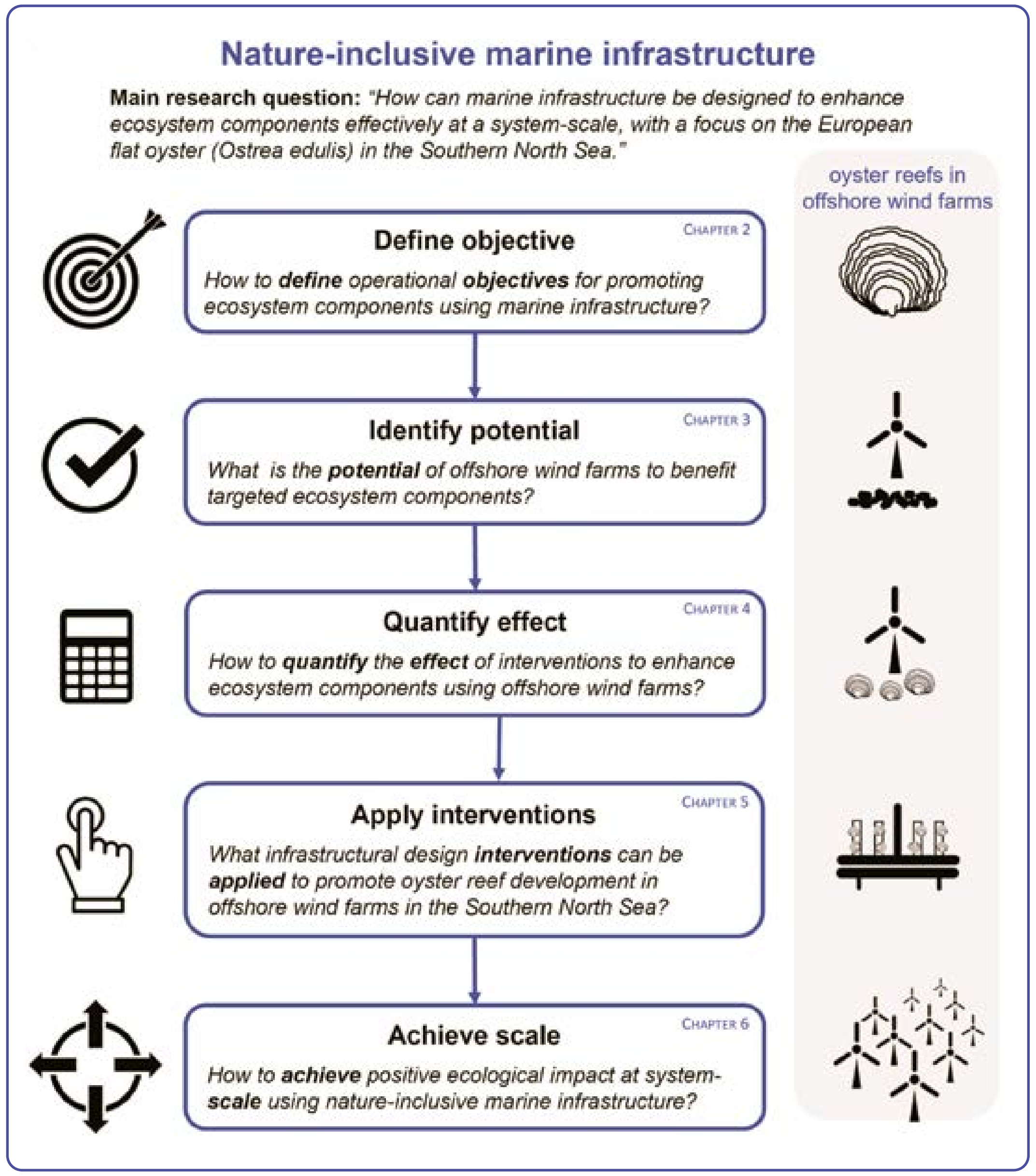
**Coral, C. *(in preparation)*. A walk on the wild side. Temperate reefs and their ecosystems services: lessons learnt from wild reefs in the North Sea. Dissertation University of Groningen, later available at rug.nl/library**

Source via QR code: www.youtube.com/watch?v=SbF32TYtvwk

# European Oyster: Engineering Nature-inclusive Marine Infrastructure

**Towards successful oyster reef enhancement in offshore wind farms: the process to identify, select and implement measures for marine infrastructure.**

**With a step by step approach from objective setting to achieving scale this North Sea ReViFES dissertation focusses on implementing nature-inclusive marine infrastructure with an emphasis on flat oyster reef development in offshore wind farms in the Southern North Sea.**




**ter Hofstede, R. (2024). Engineering nature-inclusive marine infrastructure with an emphasis on flat oyster reef development in offshore wind farms in the Southern North Sea. Dissertation TU Delft *Delft University of Technology*.**

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