Reef-building species and biogenic reef enhancement in the Dutch North Sea

Background documents

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Contents

Samenvatting

Opdracht, doelstelling en bereik

Dit rapport is opgesteld in opdracht van het ministerie van Landbouw, Natuur en Voedselkwaliteit. Het is bedoeld als onderdeel van de basis voor het algeheel natuurverbeteringsprogramma (incl. soortenbescherming) in het Nederlandse deel van de Noordzee.

Bereik van het rapport is de beschrijving van biogene riffen vormende soorten en het potentieel voor biogene rifvorming of- herstel in het Nederlandse deel van de open Noordzee (het niet-kustgebied van de 'Exclusieve Economische Zone', of EEZ, van Nederland). De volgende soorten en hun relevantie als 'rifbouwers' in de EEZ worden besproken:

1. De tweekleppige schelpdieren platte oester (*Ostrea edulis*), paardenmossel (*Modiolus modiolus*) en mossel (*Mytilus edulis*).
2. De soorten schelpkokerworm (*Lanice conchilega*) en gestekelde zandkokerworm (*Sabellaria spinulosa*), behorend tot het fylum van de ringwormen en tot de klasse van de mariene borstelwormen.

Achtergrond

Biogene riffen vormen habitats die qua structuur en soortensamenstelling verschillen van de open zeebodem, waardoor de algehele biodiversiteit en mogelijk ook de productiviteit van het Noordzee-ecosysteem toenemen.

Het Noordzee-ecosysteem heeft een breed scala aan menselijke drukfactoren ondergaan en ondergaat dat nog steeds. Dit heeft geleid tot afname van de meeste biogene riffen, terwijl de Habitatrichtlijn vereist dat natuurlijke habitats en soorten van Europees belang in hun hele biogeografische verspreidingsgebied in een gunstige staat van instandhouding worden gehouden. Bovendien verplicht de Kaderrichtlijn Mariene Strategie lidstaten om voor hun mariene wateren een goede milieutoestand te bereiken en/of te behouden, waaronder biogene riffen. Ook de mogelijk toekomstige EU-Natuurherstelwet en OSPAR richten zich op tot herstel van mariene habitats.

Herstelfilosofie

In dit rapport wordt ervan uitgegaan dat herstelinspanningen gericht moeten zijn op het minimaliseren van menselijk ingrijpen en in wezen de natuur zoveel mogelijk zijn gang moeten laten gaan. D.w.z. hoe minder ingrepen nodig zijn om de gewenste rifverbetering te bereiken, des te beter. Alleen als spontane rifvorming niet binnen een tijdsbestek van minimaal 5 jaar succesvol kan worden verwacht, worden ingrepen zoals het verstrekken van natuurlijk of kunstmatig substraat of het introduceren van levende organismen in het gebied als een optie beschouwd.

Verschillen in relevantie en rifvormend potentieel

De in dit rapport beschreven kenmerken van bovengenoemde soorten laten zien dat een belangrijk onderscheid kan worden gemaakt in hun relevantie en rifvormend vermogen in de EEZ:

1 Gestekelde zandkokerwormen (*Sabellaria spinulosa*), schelpkokerwormen (*Lanice conchilega*) en mosselen (*Mytilus edulis*) zijn al zodanig aanwezig dat actief herstel voor deze soorten niet nodig zal zijn.

2 Platte oesters (*Ostrea edulis*) zullen hoogstwaarschijnlijk niet (binnen afzienbare tijd) op eigen kracht riffen vormen, maar zullen een beginpopulatie en een serie van andere maatregelen nodig hebben.

3 De omgevingscondities voor paardenmosselen (*Modiolus modiolus*) zijn beperkt en zullen door de gevolgen van klimaatverandering nog beperkter worden. Daarom wordt rifherstel in de EEZ niet relevant geacht voor deze soort.

Sabellaria spinulosa en *Lanice conchilega* zullen waarschijnlijk in grotere mate terugkeren en kunnen zelfs riffen vormen op de Noordzeebodem in die gebieden waar menselijke bodemverstoring wordt uitgesloten en waar het leefgebied geschikt is. Voor *Sabellaria* zullen de meest geschikte omstandigheden in de EEZ waarschijnlijk in de Natura 2000-gebied Bruine Bank, het KRM-gebied Borkumse Stenen en mogelijk het Natura 2000-gebied Friese Front en een aangrenzend gebied liggen. Ook zal de bouw van windparken waarschijnlijk kansen bieden voor kleine *Sabellaria*-rifaggregaties, met name in of nabij erosiebeschermende bestorting (*scour protection*). Voor *Lanice* kan de omvang van het geschikte gebied groter zijn, omdat de soort beter is aangepast aan de algemene omstandigheden van de EEZ, misschien zelfs met inbegrip van bodemberoerende visserij.

Platte oesters (*Ostrea edulis*) zullen hoogstwaarschijnlijk niet (of niet binnen afzienbare tijd) zelfstandig riffen vormen, doordat zich geen riffen van deze soort meer in de open Noordzee bevinden. Rifherstel of -nieuwvorming vergt daarom introductie van een beginpopulatie en andere maatregelen , zoals het uitbrengen van schoon substraat in de periode dat de larven in het water zijn. Uit een overzicht van diverse herstelprojecten, met platte oesters die uit zeer verschillende gebieden worden geïmporteerd, blijkt dat de algemene milieuomstandigheden in de Noordzee, ook buiten de grenzen van de EEZ, nog steeds geschikt zijn voor de oesters om te overleven, te groeien en zich voort te planten. Het opnieuw creëren van zelfvoorzienende of autonoom groeiende riffen op de Noordzeebodem, wat het uiteindelijke hersteldoel is, vereist echter een stabiele startpopulatie op de zeebodem met lokale vestiging van oesterlarven (rekrutering) en aan deze vereisten wordt nog niet voldaan.

Kennislacunes

Er zijn verschillende kennislacunes over de twee kokerwormsoorten, in het bijzonder met betrekking tot hun rifvormend potentieel: het is nog steeds niet erg goed bekend wat de exacte voorwaarden zijn voor deze riffen om te kunnen ontstaan, dus het valt nog te bezien of de gebieden waar menselijke bodemverstoring is of wordt opgeheven voor rifvorming geschikt. Ook is niet geheel duidelijk of sommige interventies (zoals het leveren van substraat) de rifvorming aanzienlijk kunnen versnellen (*Sabellaria spinulosa*) of belemmeren (*Lanice conchilega*).

Waarom sublittorale mosselbanken wel op offshorehardsubstraat aanwezig zijn, maar niet op de open zeebodem, is een vraag die meer onderzoek vergt. Ook om te achterhalen of het kweken van mosselen in bepaalde gebieden lokaal kan helpen bij de vorming van mosselbanken.

Voor platte oesters zijn er belangrijke kennislacunes over een breed scala aan rifherstelaspecten:

- Hoe de rekrutering tijdens populatie-initiatie in EEZ offshore-omstandigheden (met sterke stromingen en turbulentie) kan worden verbeterd.

- De minimale grootte van een platte-oesterrif die nodig is om in offshore-omstandigheden aanzienlijke rekrutering binnen het rifgebied te veroorzaken, en het effect van stimuleringsmaatregelen op de rekrutering en dus ook op de minimale rifgrootte.
- Hoe te voorkomen dat een startpopulatie bedolven raakt in de zeebodem, of wijd verspreid, opnieuw gezien de stromingen en turbulentie in een substantieel deel van de EEZ, met de losse (zand/siltige) zeebodem als extra negatieve factor.
- Het algemene begrip van de condities die geschikt zijn voor offshore platte-oesterrifherstel (of nieuwvorming) is nog altijd beperkt, omdat de huidige kennis gebaseerd is op het historische voorkomen van deze riffen. De aanwezigheid van oesterriffen beïnvloedt de lokale omstandigheden, ten gunste van overleving en nieuwvorming van die riffen. Daardoor is het nog altijd weinig duidelijk waar in de huidige situatie (zonder die riffen dus) de beste condities voor praktisch rifherstel/nieuwvorming voorkomen.
- Detectie van platte-oesterrekrutering in het turbulente, donkere en vaak troebele water bij de Noordzeebodem is lastig, zodat het monitoren van het potentiële succes van rifherstelpogingen wordt belemmerd.
- Specifiek gerelateerd aan de productie in *hatcheries* (op zich de meest geschikte methode voor grootschalige zaadoesterproductie): de betrouwbaarheid daarvan is nog steeds laag, als gevolg van plotselinge larvensterfte, terwijl de oorzaken hiervan grotendeels onbekend zijn.

Aanbevelingen

Geen van de soorten, of de riffen die daaruit kunnen worden gevormd, zoals in dit rapport beschreven, is rechtstreeks beschermd onder de Nederlandse implementatie van de Natura2000/Habitatrichtlijn. Anderzijds zijn deze wel vervat in de Nederlandse uitvoering van de Kaderrichtlijn Mariene Strategie. Daarom wordt aanbevolen om deze soorten en hun riffen/bedden consistenter in deze regelgevingskaders op te nemen.

Een survey van biogene riffen (met name *Sabellaria*) is gepland in het MONS-programma. Het wordt aanbevolen om specifieke gebieden te selecteren waar de natuurlijke omstandigheden voor deze riffen waarschijnlijk geschikt zijn, zoals de Bruine Bank, en om het effect van het beperken van bodemverstoring daar te monitoren. Mogelijk kunnen ook reeds bestaande SONAR-surveygegevens (door Rijkswaterstaat, windparkexploitanten of anderen) worden geanalyseerd op aanwezigheid van riffen. Het wordt verder aanbevolen om habitatgeschiktheidsmodellen te verbeteren op basis van dergelijke monitoringgegevens.

Voor het herstel van platte-oesterriffen wordt een geïntegreerd onderzoeks- en ontwikkelingsprogramma voor de offshore-situatie in de Noordzee aanbevolen, dat voortbouwt op de huidige, zowel op leren-door-doen als op fundamenteel onderzoek gebaseerde projecten en programma's (zoals het overkoepelende programma van de Rijke Noordzee), maar dat een grotere schaal en een sterkere algehele coördinatie heeft. Met ten minste de volgende elementen:

- Ontwikkeling van adequate restoratietechnieken, toepasbaar op zodanig grote schaal dat zelfstandig voortbestaande riffen kunnen ontstaan.

- Verbeterde habitatgeschiktheidsmodellering, om de omstandigheden die nodig zijn voor de vorming van platte-oesterriffen in de huidige situatie beter te begrijpen.
- In geselecteerde gebieden met een sterke ruimtelijke heterogeniteit, zoals de Borkumse Stenen: beter in kaart brengen van de zeebodem, om te onderzoeken waar lokaal geschikte omstandigheden voor rifherstel kunnen bestaan.
- Ontwikkeling van monitoringtechnieken die het mogelijk maken rekrutering te detecteren.
- Onderzoek en ontwikkeling om de betrouwbaarheid van de productie van platte oesters in broederijen te verbeteren.

Een dergelijk programma is ook nodig voor de uitvoering van de in het Noordzee Overleg gemaakte afspraak, om 100 km^2 platte oesterrif in het Friese Front aan te leggen.

Er kunnen andere soorten of soortgroepen zijn die riffen vormen of rifvorming ondersteunen, zoals hydroïdpoliepen, maar dit is grotendeels onbekend. Het is van belang om meer onderzoek naar dergelijke soorten te doen, opdat hun potentiële rol in biogene rifvorming in de Noordzee beter wordt begrepen.

Voor de hierboven beschreven monitoring-, onderzoeks- en ontwikkelingsacties wordt ook aanbevolen om intensiever samen te werken met andere Noordzeelanden, omdat het ecosysteem niet stopt bij de grenzen en omdat er verschillende gerelateerde projecten en programma's worden ondernomen in de andere Noordzeelanden. Daarnaast is er een gemeenschappelijke beleidscontext met de meeste Noordzeelanden, zoals de Habitatrichtlijn, de Kaderrichtlijn Marine Strategie en de toekomstige EU-natuurherstelwet.

Summary

Commission, objective and scope

This report is commissioned by the Dutch Ministry of Agriculture, Nature and Food Quality, as basis component of its North Sea ecosystem improvement program (incl. species protection). Scope of the report is the description of biogenic reef species and the potential for biogenic reef enhancement or restoration in the Dutch part of the open North Sea (the non-coastal area of the 'Exclusive Economic Zone', or EEZ, of The Netherlands).

The following species and their relevance as 'reef-builders' in the EEZ are discussed:

- The bivalve shellfish European flat oyster (*Ostrea edulis*), horse mussel (*Modiolus modiolus*) and blue mussel (*Mytilus edulis*).
- The annelids sand mason worm (*Lanice conchilega*) and Ross worm (*Sabellaria spinulosa*).

Background

Biogenic reefs form habitats which are different from the open sea floor in structure and species composition, thereby increasing the overall biodiversity and possibly also the productivity of the North Sea ecosystem.

The North Sea ecosystem has undergone and still undergoes a wide range of human pressure factors. This has resulted in negative influence on most biogenic reefs, whereas the Habitats Directive requires the maintenance of natural habitats and species of European interest at favourable conservation status across their biogeographical range. Furthermore, the Marine Strategy Framework Directive requires EU-member states to keep or achieve a good environmental status, which includes biogenic reefs. The draft EU Nature Restoration Law (currently under debate) and OSPAR also call for restoration of marine habitats.

Restoration philosophy

This report adopts the philosophy that restoration efforts should aim at minimising human intervention and essentially let nature run its course as much as possible. i.e. the fewer interventions required to achieve the desired reef enhancement, the better. Only if spontaneous reef formation cannot be expected to be successful within the scope of minimally 5 years, interventions such as providing natural or artificial substrate, or introducing living organisms into the area are considered to be an option.

Differences in relevance and reef-forming potential

The species characteristics described in this report show that an important distinction can be made concerning their relevance and reef-forming potential in the EEZ:

- The annelid worms (*Sabellaria spinulosa* and *Lanice conchilega*) and blue mussels (*Mytilus edulis*) are already present to such extent that active restoration will not be required for these species.
- European flat oysters (*Ostrea edulis*) will most probably not (within a foreseeable timespan) form reefs on their own account but will need a starting population and further enhancement.

- The environmental conditions for horse mussels (*Modiolus modiolus*) are limited and will become even more limited due to the consequences of climate change. Hence, reef restoration in the EEZ is not considered to be relevant for this species.

Sabellaria spinulosa and *Lanice conchilega* will probably return to a greater extent and may even form reefs on the North Sea bottom in those areas where human disturbance is removed and where the habitat it suitable. For *Sabellaria*, the best conditions in the EEZ will probably be in the N2000 area Brown Bank, the MSFD area Borkum Reef Ground and possibly the N2000 area Frisian Front and a neighbouring area. Also, the construction of wind farms will probably constitute opportunities for small *Sabellaria* reef aggregations, in particular in or near scour protection. For *Lanice*, the extent of suitable area may be larger, since it is better adapted to the overall conditions of the EEZ, possibly even including bottom trawling.

Flat oysters (*Ostrea edulis*) will most probably not (within a foreseeable timespan) form reefs on their own account, because the reefs of the open North Sea have disappeared. Restoration or creation of reefs therefor requires the introduction of a starting population and further enhancement measures, such as the deployment of clean substrate in the period when larvae are in the water. A survey of the projects undertaken with flat oysters starting populations imported from very different areas shows that the general environmental conditions in the North Sea, also beyond the borders of the EEZ, are still suited for the oysters to survive, grow, and reproduce. However, the re-creation of self-sustaining or autonomously growing reefs on the North Sea bottom, which is the ultimate restoration objective, requires a stable start population on the sea floor with local recruitment and these requirements are not yet fulfilled.

Knowledge gaps

There are various knowledge gaps concerning the annelid worms, in particular concerning their reef-forming potential: it is still not very well known which are the exact conditions for these reefs to become re-established, so it remains to be seen whether the areas where human bottom disturbance is or will become abolished are adequate for reef formation. Also, it is not certain whether some interventions (such as supplying substrate) may significantly speed up (*Sabellaria spinulosa*) or hamper (*Lanice conchilega*) reef formation.

Why sublittoral blue mussel beds are present on offshore hard substrate, but not on the open sea floor, is a question that deserves more investigation. Also to find out whether cultivation of mussels in particular areas may locally assist mussel bed formation.

For flat oysters, there are key knowledge gaps on a wide range of reef restoration aspects:

- How to enhance recruitment during population initiation, given the strong currents and turbulence in a substantial part of the EEZ.
- The minimum size of a flat oyster reef which is required to cause substantial recruitment within the reef area in offshore conditions, and the effect of settling stimulation measures on recruitment and therefore also on minimum reef size.
- How to avoid a start population becoming buried in the sea floor, or widely spread, again given currents and turbulence in a substantial part of the EEZ, with the loose (sandy/silty) sea floor as extra negative factor.

- The overall understanding of the conditions suitable for offshore flat oyster reef formation/restoration is still limited, since it is largely derived from historical information (when the reefs were still present). The presence of oyster reefs influences local conditions, conducive to survival and/or growth of these reefs. Hence, it is understood only roughly where the best reef formation/restoration conditions are located in the present situation (being without the reefs).
- Detection of flat oyster recruitment in the turbulent, dark and often turbid North Sea bottom region is very hard, so that monitoring the potential success of reef restoration attempts is handicapped.
- Specifically related to production in hatcheries (as such being the most appropriate method for large-scale seed oyster production): the reliability is still low, due to sudden larval mortality incidents, whereas the causes for this phenomenon are largely unknown.

Recommendations

None of the species, or their reefs/beds, described in this report are currently directly protected within the Dutch implementation of the Natura 2000/Habitats Directive. Yet, the Dutch implementation of the Marine Strategy Framework Directive does include biogenic reefs. Hence, it is recommended to include these species and their reefs/beds more consistently in these regulatory frameworks.

A biogenic reef survey is planned in the MONS program, aiming at *Sabellaria* occurrence. It is recommended to select specific areas where the natural conditions for these reefs are probably suited (such as the Brown Bank) and to monitor the effect of curtailing bottom disturbance there. Possibly, already existing bottom survey SONAR data (by Rijkswaterstaat, wind farm operators or others) can be analysed for reef presence too. It is also recommended to improve habitat suitability models on the basis of such monitoring data.

For flat oyster reef restoration, an integrated research and development program for the North Sea offshore situation is recommended, which builds on the current projects and programmes which are characterized by learning-by-doing as well as fundamental research (such as the overarching The Rich North Sea program) but which has a larger scale and a stronger overall coordination. At least, it should contain the following elements:

- Development of adequate restoration techniques, applicable on a sufficiently large scale to create self-sustaining flat oyster reefs.
- Improved habitat suitability modelling, to better understand the conditions required for the formation of these reefs in the current situation.
- In selected areas with strong spatial heterogeneity, such as the Borkum Reef Grounds: better mapping of the sea floor habitat, to investigate where locally appropriate conditions for reef restorations may exist.
- Development of monitoring techniques which allow detection of recruitment.
- Research and development to improve the reliability of flat oyster production in hatcheries.

This programme should also lead to the operationalisation of the agreement by the North Sea Platform ('Noordzee Overleg'), to create 100 km^2 of flat oyster reef in the Frisian Front.

There may be other species or species groups which form reefs or support reef formation, such as hydroids, but this is largely unknown. More research into such species will lead to a better understanding and description of their potential role in biogenic reef formation in the North Sea.

For the comprehensive monitoring, research & development actions described above, it is also recommended to cooperate more intensively with other North Sea countries, since the ecosystem does not stop at borders and since there are various related projects and programmes being undertaken in the other North Sea countries. Besides, there is a common policy context with most North Sea countries, such as the Habitats Directive, the Marine Framework Strategy Directive and the prospective EU Nature Restoration Law.

1 Introduction

1.1 Commission, objective and scope

This report is commissioned by the Dutch Ministry of Agriculture, Nature and Food Quality, as basis component of its North Sea ecosystem improvement program. Scope of the report is the description of biogenic benthic reefs and their potential enhancement in the Dutch part of the open North Sea (the non-coastal area of the 'Exclusive Economic Zone', or EEZ, of The Netherlands).

1.2 Background

Biogenic reefs are among the most important marine natural habitats in the waters of Northern Europe, enhancing biodiversity (Holt et al., 1998) and probably also productivity (Peterson et al. 2003). These are formed if the reef-building benthic species are present in sufficient densities. The threshold density differs per species. Such reefs give rise to habitats which are different from the open sea floor in structure and species composition, thereby increasing the overall biodiversity and possibly also the productivity of the North Sea ecosystem.

The North Sea is a relatively shallow continental shelf sea, surrounded by highly developed Western European countries. It is one of the busiest marine systems in the world and has for centuries been exploited for human use, which puts intense pressure on the marine ecosystem (IenW et al., 2022). Since the first International Conference on the Protection of the North Sea, the surrounding countries have achieved good results in reducing pollution (International Conferences on the Protection of the North Sea, 1999). For example, there is a ban in place for discharging and incinerating waste at sea, countries in its drainage basin have agreed to reduce nutrient inputs by 50%, there is a ban on dumping offshore installations and the application of TBT is prohibited.

However, damage to biogenic reefs has already been done in the past. In particular, flat oyster reefs have disappeared in the open North Sea, due to overexploitation for consumption in the end of the 19th and the beginning of the 20th century (Bennema et al., 2020; Gercken & Schmidt, 2014). Nearshore, oysters remained in culture, which has resulted in the species remaining locally existent, although not in the form of natural reefs (Engelsma et al., 2010). After the Second World war, bottom trawling fishery for crustaceans and demersal fish increased strongly and still occurs with high intensity in the EEZ (Philippart, 1998). The beam and otter trawls disturb the upper sediment layers, so that other biogenic reefs are also diminished (Holt et al., 1998). The vast majority of the area of the Dutch Continental shelf is trawled more than once per year (https://www.eea.europa.eu/data-and-maps/figures/bottom-trawl-fishing-intensity-in).

The Habitats Directive requires the maintenance of natural habitats and species of European interest at favourable conservation status across their biogeographical range. Furthermore, the Marine Strategy Framework Directive requires a good environmental status, which includes biogenic reefs and the prospective EU Nature Restoration Law calls for restoration of marine habitats.

The Dutch government is therefore planning to enhance and/or restore biogenic reefs in the open EEZ where feasible. Removing the major threat (i.e., seabed disturbance, by bottom trawling or other means) is the first prerequisite. A number of areas are already protected by law from bottom-trawling (mostly since March 8, 2023, together with several zones in the German North Sea; see https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R0340). This accounts to 5% of the EEZ area, to be extended to 15% by 2030 according to (OFL, 2020). In addition, the installation of offshore wind farms will lead to less disturbance of the seafloor by activities such as bottom trawling is, due to operational and safety considerations). In the future this area will increase substantially, due to the planned governmental extension of nature protection zones and the scaling up of offshore wind energy in the EEZ. Figure 1.1 gives an impression of the location of actual and planned areas in the EEZ.

This document details background information on several reef-building species in this part of the North Sea. In addition, prerequisites and options for the enhancement of the reefs constituted by these species are discussed.

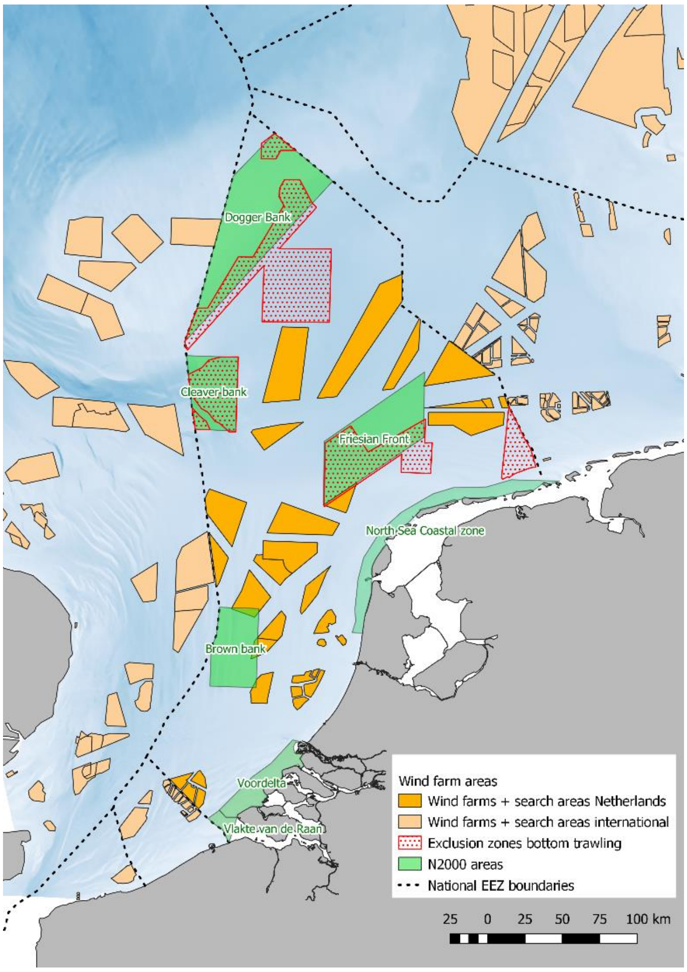

FIGURE 1.1: IMPRESSION OF DESIGNATED OFFSHORE WIND FARM AREAS AND MARINE PROTECTED AREAS IN THE EEZ.

1.3 Relevant species

There are several species of marine bivalves and annelid worms which may be relevant for biogenic reef formation in the North Sea and therefore within the scope of this report.

Reef building marine bivalves include the European flat oyster (*Ostrea edulis*), horse mussel (*Modiolus modiolus*) and blue mussel (*Mytilus edulis*) are included. The flat oyster currently is the main focus of reef restoration projects in the North Sea, as it formerly occurred in large areas and was an important ecosystem engineer until early last century (Bennema et al., 2020; Houziaux et al., 2011; Olsen, 1883). Actual horse mussel reefs are generally not observed in the EEZ, but they do occur in neighbouring deeper parts of the North Sea (Dinesen & Morton, 2014). Blue mussel is generally seen as an intertidal reef builder, but the species is found throughout the North Sea, mostly in the upper water layers on vertical artificial structures. However, there may also be opportunities for this species to form reef structures on or near the seabed (Baden et al., 2021).

Reef building annelid worms are the sand mason worm (*Lanice conchilega*) and the Ross worm (*Sabellaria spinulosa*) (OSPAR, 2013; Rabaut et al., 2009). A close relative of *Sabellaria spinulosa*, the Honeycomb worm (*Sabellaria alveolata*) does occur in shallow and intertidal areas along the south and west coast of the UK and the Atlantic coasts of France but does not occur in deeper waters (Maddock, 2008a). Hence, this species is not included, although some information regarding the habitat requirements of *S. spinulosa* have been taken from literature from *S. alveolata*, as some requirements seem to be fairly similar.

There may be other species or species groups which form reefs or support reef formation, such as hydroids, but this is largely unknown. More research into such species will lead to a better understanding and description of their potential role in biogenic reef formation in the North Sea.

1.4 Criteria regarding restoration

This report adopts the philosophy that restoration efforts should aim at minimising human intervention and essentially let nature run its course as much as possible. For any reef restoration effort to be successful, the main threats of reef formation and expansion need to have been removed, which mainly pertains to human bottom disturbance, such as by trawling and construction of infrastructure. The basis of the adopted philosophy is explained in more detail in (Van Duren, 2017).

1.4.1 Conforming with natural habitat conditions

Enhancement of biogenic reefs should conform to the original habitat conditions of the target area and, vice versa, it should be substantiated that the target reef type belongs to this habitat, in its natural condition. For example, adding hard substrate to a naturally soft sediment area may induce reef formation, but it would essentially change the original habitat conditions. It may be the case that the seabed has been disturbed by human activities for so long that patches of hard substrate that may have been present once (e.g., in the form of shell material or stones), are no longer present in sufficient amounts. In such cases introducing settlement substrate is considered warranted in this report.

In line with the central philosophy of this report, the less interventions required to achieve the desired reef enhancement, the better. For example, if according to the best available information, only protecting the seabed from disturbance is sufficient for the desired enhancement (possibly to be substantiated by monitoring), other interventions can best be left out.

This also implies that, only if spontaneous reef formation cannot be expected to be successful within the scope of at least 5 years, interventions such as providing natural or artificial substrate, or importing living organisms into the area are considered to be an option.

1.4.2 Choice of materials to be deployed or to be avoided

If hard substrate needs to be supplied this ought to be either in keeping with the environment (e.g., natural shell material, or rocks of a composition similar to what could be found in historical times) or of a temporary nature (e.g., structures that are biodegradable over a few years' time). This would also be in line with current decommissioning guidelines for human infrastructure.

Any hazardous or non-natural material (such as plastic, metal, composites) are to be avoided for reef enhancement, even if such materials are used in wind farms as essential components of infrastructure. In addition, such artificial materials are an additional risk for the settlement of invasive species (Bracewell et al., 2012, 2013).

1.4.3 Deployment of live material

In line with the above, active reef enhancement using the introduction of live animals to 'seed' a population will be considered as a last resort. Firstly, importing living organisms from other areas always yields a risk of invasive species (Lee & Gordon, 2006). Secondly, importing organisms from elsewhere creates a risk of introducing animals with a different genetic make-up from those that are, or were, naturally occurring in the target environment (Grant et al., 2017). Therefore, restoration using live animals will only be considered under the following conditions: (1) if natural colonisation is deemed impossible, due to the fact that the species is functionally extinct in the ecosystem, (2) there is a reasonable chance that the seed population will constitute the start of a new reef in the target area or (3) it is necessary to test the survival/growing chances of a seed population in the target area.

If active restoration with live material cannot be avoided, all international rules and associated protocols regarding animal husbandry, genetic diversity and veterinary hygiene should obviously be followed. This comprises not using any source material that is known to carry diseases, even if the disease is likely to enter the ecosystem via independent transport from neighbouring areas. If infectious diseases may be transported to offshore restoration sites via other vectors than via restoration projects (a scenario that can almost never be excluded), it is worthwhile putting effort into finding stocks with a natural immunity for disease(s).

1.5 Structure of this report

The basic structure of this report is as follows:

- The information on the annelid worms and marine bivalves is grouped in two chapters, with separate paragraphs per species.
- These species paragraphs have the same overall structure of subparagraphs, to provide the required standard information basis. Only the paragraph on *Ostrea edulis* contains an extra subparagraph about the production of start populations.
- In the final chapter, a general discussion of main elements of the described species is provided and recommendations are given to overcome current barriers regarding enhancing biogenic reefs, including the knowledge gaps that are identified in this report.

2 Shellfish

2.1 *Ostrea edulis*

2.1.1 General description

Ostrea edulis, the European flat oyster (see fig. 2.1), is an endemic species of the European marine environment.

FIGURE 2.1: IMAGE OF A NEARSHORE FLAT OYSTER REEF (PHOTO: STEPHANE POUVREAU, IFREMER)

O. edulis is a 'protandrous hermaphroditic species', i.e. it first develops as a male and changes sex several times later in life. Depending on the size, a female individual can produce up to 1-3 million eggs. The eggs are fertilized in the mantle of the mother oyster's shell where the larvae will reside a up to ten days before they swarm into the water column. After a larva has reached a sufficient size, settlement on hard substrate follows (de Bruyne & van Leeuwen, 2013). The estimated period the larvae spend in the water is 8-10 days by (FAO, 2009), but may be somewhat longer, i.e., up to 14 days (Gardner & Elliott, 2002). Given average currents and assuming that larvae drift as inert particles modelling by (Van Duren et al., 2022) leads to maximum dispersal distances of circa 50 km in the EEZ.

The young flat oysters that develop are vulnerable for predation by crabs, starfish and predatory snails such as oyster drills (Smaal et al., 2017). Individuals can live for more than 30 years and grow to a maximum size of ca. 20 cm.

Oysters pump large volumes of seawater (several litres per hour per individual, see (Wijsman & Smaal, 2017)) through their gills, thereby absorbing various nutrients, such as algae and other suspended organic and inorganic particles. All particles that they are unable to ingest, or digest are expelled as faeces and pseudofaeces (de Bruyne & van Leeuwen, 2013).

2.1.2 Legislative and policy context

Table 2.1 lists relevant legal and policy instruments for the protection of oysters and oyster beds in the Netherlands.

TABLE 2.1 (INTER)NATIONAL LEGAL AND POLICY INSTRUMENTS AND THEIR APPLICABILITY FOR THE EUROPEAN FLAT OYSTER ("YES" = RELEVANT; "NO" = NOT RELEVANT)

Instrument	Description	European flat oyster
International		
Habitats Directive (HD) Annex 1	In the Netherlands, contrary to other North Sea countries such as Germany, biogenic reefs are not yet considered to be part of HD habitat type H1170 reefs, as described in the H1170 profile document (Ministerie LNV, 2014). Hence, flat oyster reefs are also not part of H1170. To change this, the Dutch definition of the habitat type H1170 (Ministerie LNV, 2014) should be changed fundamentally. In 2020, Dutch parliament adopted a motion by member Futselaar (Futselaar, 2020) to protect flat oyster reefs: ".... calls on the government to grant protected status to existing and future flat oyster reefs by adding them as "typical species" for protected areas in habitat type profile documents 1110 and 1140, and as a biogenic structure in habitat type 1170" (Futselaar, 2020)	Not yet
HD Typical species	In contrast to e.g., mussel beds, oyster beds are not yet considered typical species for Natura 2000 habitat types (see above).	Not yet
OSPAR List of Threatened and/or Declining Species and Habitats	In order to protect biodiversity, OSPAR has defined a list of 'threatened and declining species and habitats' that are in need of protection (OSPAR, 2008). Oysters and oyster reefs are part of this list. See review in Bos & Tamis (2020)	Yes
The EU Common Fisheries Policy (CFP)	Offshore fishery measures in MSFD and N2000 areas are established under the Art 11 of the CFP. These zones offer protection for future oyster reefs; see EUR-Lex - L:2023:048:TOC - NL - EUR-Lex (europa.eu)	Yes
National		
Dutch Fisheries act (Visserijwet)	The flat oyster is a commercial species as meant in article 1.2, Staatscourant 1982, 253	Yes
Uitvoeringsregeling Visserij	Uitvoeringsregeling Visserij 1 June 2021: the oyster reef in the Voordelta is closed to fisheries (Ministerie van LNV, 2021)	Yes
Dutch Nature Conservation Act (Wet Natuurbescherming)	The oyster is not protected under the Nature Conservation act.	No
Marine Strategy Framework Directive	D6T5: Return and recovery of biogenic reefs including flat oyster reefs (Marine Strategy Part 1, 2018) (IenW & LNV, 2018)	Yes
Red List	A Red List is an overview of species that have disappeared or are in danger of disappearing from the Netherlands. Red lists do not have a legal status. There is no Dutch Red List for marine benthic species such as the flat oyster.	No
North Sea Agreement	The North Sea Agreement (OFL, 2020) includes the agreements between central government and stakeholder parties about choices and policy aimed at the balance in activities in the North Sea up to and including 2030 and beyond. As part of the North Sea Agreement, species protection plans will be developed and implemented. Specifically for flat oysters, a total area of 100km^2 will be reserved for oyster reef restoration within the Frisian Front no-fishery zone (Noordzee Overleg, 2022).	Yes

In summary, related to the EEZ:

- Natura 2000/ Habitats Directive: Flat oysters are not yet included as separate conservation goal within this regulatory framework for Dutch waters.
- Marine Strategy Framework Directive: D6T5: Return and recovery of biogenic reefs including flat oyster reefs is mentioned as an objective for Dutch waters.

- OSPAR: No targets, but protection recommendations are provided.
- Dutch North Sea Agreement: Within the no-fisheries zone at the Frisian Front, two sites of 50 km^2 will be reserved for flat oyster reef restoration.

2.1.3 Distribution

Previously (until the 19th century), large offshore and coastal beds of *O. edulis* were present along all European sea shores, ranging from the coast of Scandinavia to even the Black Sea, and also in deeper offshore waters (see Thurstan and zu Ermgassen, submitted; cf). https://www.google.com/maps/d/u/0/edit?mid=1Pq_gYXjM9ZrddSc5bmYu36pIqX5IcGU&usp=sharing for the historical flat oyster occurrence map reported in the article). Flat oyster reefs also used to comprise large parts of the North Sea and Wadden Sea ecosystems in the 19th century (Olsen, 1883). Nowadays, the species and its habitat have disappeared in many of these regions (Bennema et al., 2020; Smaal et al., 2017; Van der Have & Van der Zee, 2016). Overfishing, bottom disturbance and pollution, but also natural factors such as diseases have played a role in this (OSPAR, 2020b).

Nowadays, oyster reefs only occur in estuarine environments between 0 and 6 meters deep, where hard substrate is accessible for larval settlement.

In Dutch marine waters, flat oyster reefs were numerous in the Dutch Wadden Sea, northern parts of the former Zuiderzee and offshore in the North Sea, until the first half of the 20th century (Bennema et al., 2020; Gercken & Schmidt, 2014). After the construction of the Afsluitdijk (1932), the oyster beds in the Zuiderzee (now IJsselmeer) quickly disappeared. Also in the Wadden Sea, the flat oyster population has almost completely disappeared as a result of overfishing, severe winters and the disease *Bonamiosis* (de Bruyne & van Leeuwen, 2013) (van der Have & van der Zee, 2016). In the North Sea, flat oyster beds occurred over a large area, mostly in the Oyster Grounds, the Dover Strait and Southern North Sea (Bennema et al., 2020; Olsen, 1883, de Bruyne & van Leeuwen, 2013).

To date, mixed reefs (with *Magellana gigas*) of *O. edulis* can be found in the Voordelta (Christianen et al., 2018) and the Rotterdam outer harbour (Kardinaal et al., 2021). More and more individuals are found in the wild in Oosterschelde and Grevelingen Meer, as offspring from aquaculture. In addition, (Van der Have et al., 2017) discovered a total of 51 flat oysters at 9 different locations in the Wadden Sea (Eijerlandse Gat). These oysters can be offspring from a Texel breeding experiment conducted in the 1970s. Additionally, a few flat oysters have recently been discovered on shipwrecks (R. Olie, pers. comm., 2023). An overview of the current findings and restoration pilot projects is given in (Bos et al., 2023, in prep.). See Figure 2.2 below, also for the individual findings mentioned above. It shows that despite sampling large areas in the North Sea and Wadden Sea, among others during fish surveys, flat oysters are still rarely detected.

There may still be some small populations which are not yet discovered, since in the Ecofriend project (Bos et al., 2023b, in prep.), flat oyster larvae were detected at a location north of the Wadden Sea, which is far from any restoration pilot and also outside the general current directions from those pilots.

The recent observation that flat oysters are spreading in the wild in Dutch coastal waters is probably caused by the population becoming less sensitive to the effects of infection by *Bonamia ostreae*, an important oyster disease (Smaal et al., 2015).

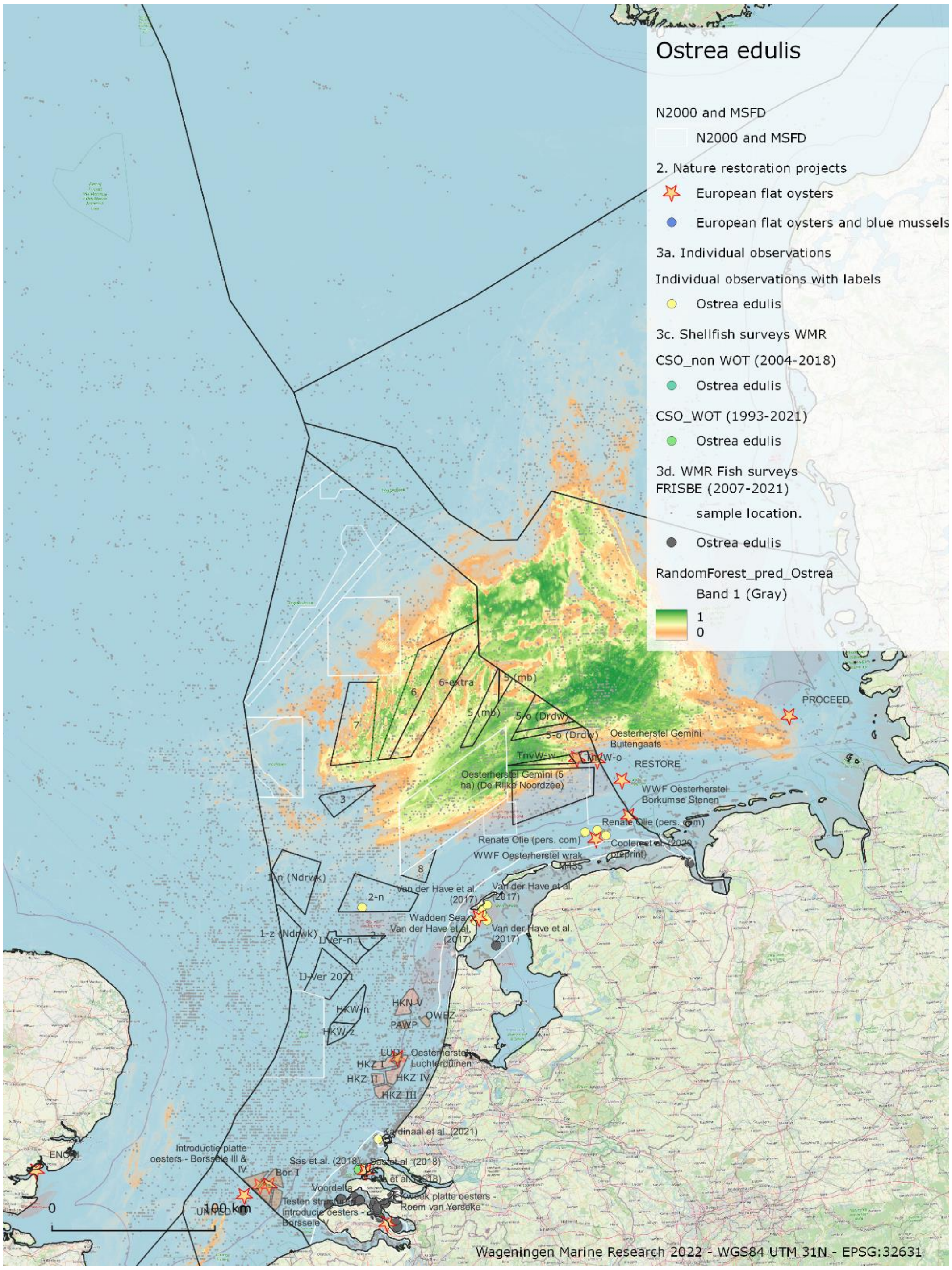

Figure 2.2 *Ostrea edulis*, predicted habitat suitability (Herman & Van Rees, 2022) and recordings of observations. Most recordings in the EEZ are on artificial hard substrates, in restoration projects or on shipwrecks (Bos et al., 2023, in prep).

In the coastal zones of UK, Ireland, France, the Netherlands, Denmark, Portugal, and Spain, there are still some reduced populations of *O. edulis*, but mostly due to aquaculture (Kennedy & Roberts, 2009, Smyth et al., 2009, 2016, 2018). In the Belgian and German North Sea coastal zones, oyster reefs have disappeared completely and are now considered extinct (OSPAR, 2020), but individual flat oysters are still found (Kerckhof et al., 2018). Extensive natural populations of *O. edulis* are still present along the coasts of southern Norway and the west coast of Sweden (OSPAR, 2020).

But overall, flat oysterreefs have disappeared to such an extent in the open North Sea that active restoration measures, including supplying a start population, are necessary for reef recovery in this area (OSPAR, 2020).

2.1.4 Habitat requirements

The OSPAR Background Document for *O. edulis* (OSPAR Commission, 2009) indicates that flat oysters live attached to rocks, loose stones and shells on sandy and muddy bottoms, from the low water mark to several tens of meters deep.

Smaal et al. (2017), Van Duren et al. (2022) and (Van Duren et al., 2023), considering a range of variables, assessed the relative suitability of (potential) offshore wind energy locations in the Dutch EEZ as well as of the nature conservation area Borkum Reef Ground and search areas for oyster restoration in the Natura 2000 area Frisian Front. Additionally, Herman & Van Rees (2022) assessed the probability of occurrence of flat oysters in the Dutch EEZ using logistic and random forest analysis, involving historical data of oyster occurrence as well as current variables: water depth, bathymetric positions, bottom shear stress from currents, mean salinity, mean temperature, temperature difference over the year and gravel, mud and sand fractions in the sediment. The results of Herman & Van Rees were also incorporated in the studies of (Bos et al., 2023, in prep.), (Van Duren et al.,2022) and (Van Duren et al., 2023). In addition, (Stechele et al., 2023) consider habitat suitability in the larger North Sea on the basis of dynamic energy budget modelling. The latter largely agrees with the results of (Herman & Van Rees, 2022), which gives confidence in the results of both studies.

The study of Herman & Van Rees shows the overall flat oyster habitat suitability in the highest detail for the EEZ, so its result is depicted in fig. 2.2 (previous paragraph). (Herman & Van Rees, 2022) concludes the following about the habitat requirements of flat oyster reefs: "*The sediment should not be composed of mobile sand but has a high proportion of either gravel or mud. It is also likely that substrate plays a key role in oyster settlement. Where hard substrate is provided, populations may develop also outside of the areas where they were present on natural substrate. The populations in Voordelta and Rotterdam harbour are examples of this possibility. Probably, there are no physiological limitations for flat oysters in the North Sea, so this study cannot provide information on habitat suitability when artificial substrate is offered, but it seems likely that in that case most of the North Sea will allow oyster growth.*"

However, this does not imply that reefs will develop or can easily be restored in the areas where these once existed, since the local environmental conditions greatly change once the reefs are absent, which is the case in the present situation (see below).

As will be discussed in par. 2.1.6.2, hydrodynamic conditions near the sea floor are critical for flat oyster recruitment and subsequent reef restoration: currents and wave-induced turbulence in the North Sea may cause such dispersal of the start population and the larvae produced by it that no reef is formed. Besides, large parts of the North Sea bottom are characterized by sandy and silty sediments, which may be loosened by bottom trawling or where sand waves occur naturally. These conditions do not provide proper settling substrate for flat oysters and may also cause the oysters to be overturned or buried, given the turbulent environment, so that the current circumstances may not be conducive to reef formation, even in those areas where the oyster reefs originally occurred (see par. 2.1.6.2).

There may exist sheltered pockets (such as throughs between sand ridges or other types of depressions), with more stable sediments and/or more appropriate settling substrate on the bottom of the EEZ, but these are not mapped in sufficient level of detail.

2.1.5 Habitat formation, ecosystem function and commercial value

Flat oysters can form extended biogenic reefs (EUNIS code: A5.435), which are dense clusters of oysters that from a large colonial community with a large influence on the ecosystem. Therefore, the flat oyster is an ecosystem engineer (Smaal et al., 2015).

The flat oyster is recognized as an ecological keystone species because of its significance as habitat (OSPAR, 2009). Oyster reefs (like any other biogenic reef) influence the local environmental conditions, with decreased turbulence and increased sediment stabilisation compared to an open sandy/silty sea floor. Additionally, the presence of oyster reefs may improve the water quality by filtering and sequestering suspended organic and inorganic particles in (pseudo)faeces (Zu Ermgassen et al., 2021, OSPAR Commission, 2009), but this effect will be relatively small in offshore conditions. Because of these factors and since they provide a complex hard substrate structure, they offer settling ground, food, shelter, and spawning/nursery ground for many associated species (OSPAR, 2020a). All in all, they form a habitat which is a hotspot for biodiversity.

The extent to which oyster beds entrap organic suspended particles and thereby carbon is described in (Zu Ermgassen et al., 2021 and Lee et al., 2020). There are two different mechanisms: (1) Stabilizing the seafloor and trapping of organic material and suspended particles in the sediment under the oyster bed and (2) Sequestering CO_2 in the shell, as calcium carbonate ($CaCO_3$), but there are also various CO_2 release mechanisms, so the overall balance is uncertain (Lee et al., 2020, Zu Ermgassen et al., 2021).

As a species with commercial value, flat oysters are nowadays much less important than Pacific oysters, almost everywhere in Europe. For example, in the Netherlands, approximately 1.9 million European flat oysters (value 0.6 M Euros) were brought to the market in 2020, compared with 22.1 million Pacific oysters (2.2 M Euros) in that same year (CBS, 2020) (https://www.agrimatie.nl/PublicatiePage.aspx?subpubID=2526&themaID=2857&indicatorID=2881&sectorID=2864).

2.1.6 Monitoring and research on current reef locations and restoration projects

2.1.6.1 National research and data collection

There is no current regular monitoring targeting European flat oyster in the EEZ. However, the species is recorded when encountered in annual governmental shellfish or fish (WOT) and benthos (MWTL/MSFD) surveys (see Bos et al., 2023, in prep) and extended monitoring in planned in (I&W et al., 2022).

In the Voordelta, a targeted survey of the oyster reef (size of oysters and reef area, oyster reproduction, associated biodiversity) is taking place in the period 2021-2024 (Kamermans et al. 2022). In the Rotterdam harbour, an inventory of flat oysters at quay walls was performed in 2021

(Kardinaal et al., 2021). In both locations, flat oysters appear to be mixed with a denser Pacific oyster population. The Rotterdam harbour survey revealed that flat oyster density increased relative to Pacific oyster density with greater depth (beyond 10 m), which demonstrates the capacity of flat oysters to thrive in relatively deep waters.

2.1.6.2 Restoration pilots

Since 2016 several offshore native oyster restoration pilots have been started in Germany (e.g. Pogoda et al., 2023), Belgium (https://www.h2020united.eu/) and the Netherlands (Didderen et al., 2019a,b; Didderen et al., 2020; Sas et al., 2019). All projects in the Netherlands and the current Belgian project are financed and undertaken by private parties, mostly in wind farms, whereas in Germany (via the RESTORE project) flat oyster restoration is undertaken by government (financed by various ministries and executed by AWI Bremerhaven) and outside wind farms. The results of the Helgoland pilot of RESTORE are published and could therefore be included in this report. A large new project is being undertaken in the Borkum Reef Ground, also as part of RESTORE, but results are not published yet. A new Belgian project is being planned by the Belgian Federal Government (see https://www.health.belgium.be/nl/herstel-van-oesterbanken).

In the Netherlands, coordination of initiatives and the related knowledge dissemination is largely taken up by the overarching The Rich North Sea program (funded by the National Postal Code Lottery, see www.derijkenoordzee.nl). The added value of such coordination is high, given the wide range of projects and related research questions. This program is now in its last year.

Project characteristics are summarized in Table 2.2 and results in Table 2.3 below, which use the monitoring metrics provided by the Native Oyster Restoration Alliance (NORA) as basis (Zu Ermgassen et al., 2021). The environmental factors as described by the NORA-metrics are indicated in the first column. Three factors included in the NORA-metrics are not relevant for offshore projects, hence not included (i.e. 23. Shoreline loss/gain; 24. Shoreline profile; 25. Density and cover salt marsh/sea grass beds). The data in the tables below are taken from (van Onselen et al., 2021).

The offshore areas where the reported pilots were carried out are moderately deep (25-36 m) and characterized by a seabed which is either mostly sandy (in Borssele III/IV/V and Luchterduinen wind farms), sand with loose shells (in Gemini wind farm and Borkum Reef Ground), or sand with stones (Helgoland). Most pilot sites (Borssele III/IV/V, Luchterduinen, Gemini, Borkum Reef Ground) were characterized by dynamic conditions, in particular induced by waves during the winter period. In both the Borssele III/IV/V and Luchterduinen projects, moving sand waves were observed.

Various deployment methods were used, with young and/or adult oysters: in baskets in larger racks or cages positioned on the sea floor or on the scour protection of wind turbines, or adult native oysters deployed directly on the sea floor. The adult oysters deployed in the Dutch North Sea originated from Tralee Bay (Ireland) and Hafrsfjord (Norway). The young oysters in the Helgoland study originated from a hatchery in France.

TABLE 2.2 CHARACTERISTICS OF OFFSHORE FLAT OYSTER PROJECTS IN THE NORTH SEA (VAN ONSELEN ET AL., 2021). RESULTS ARE PRESENTED ACCORDING TO THE UNIVERSAL MONITORING METRICS IN THE NORA-HANDBOOK (ZU ERMGASSEN ET AL., 2021).

NORA-metric	Data	Borssele III/IV/V OWF	Luchterduinen OWF	Gemini OWF	Borkum Reef (NL)	Heligoland (D)
-	Deployment date	2018	2018	2018	May 2018	2016
-	End of project	2028	2019	2020	2028 (intended)	2020
-	Deployment methods	baskets (8) on tables (4) on scour protection	tables (3) with baskets (4)	cages (6) with 120 oysters, loose oysters	tables (4) with baskets, incl. 560 oysters, loose oysters	cages (3) in 3 locations
1	Water depth (m)	30	20-30	31	25	26
1	Surface area (ha)	ND	ND	ND	1	ND
2	Sediment	Sand	Sand	Sand with loose shells	Sand with loose shells	Sand with stones
3	Number of oysters deployed	2.400	480	28.000	80.000	24.000
3	Oyster density (ind/m^2)	ND	ND	ND	1,6	ND
3	Change in density of deployed oysters	ND	ND	Yes	Yes	ND
3	Size range (mm)	78 (mean)	45-110	45-110	45-110	2
3	Sources of deployed oysters	Tralee Bay Hatchery, Ireland	wild, Hafrsfjord, Norway	wild, Hafrsfjord, Norway	wild, Hafrsfjord, Norway	Hatchery, France

Most pilot studies aimed to test the factors survival, growth and reproduction, since these are the most critical success factors once a pilot is started in an area where reefs have disappeared, such as the offshore North Sea. Two projects (Borkum Reef Ground and Gemini) aimed to kick-start a self-sustaining population, by deploying individual oysters on the sea floor, in combination with oysters in baskets for monitoring. The results are presented in Table 2.3 below.

Table 2.3 Results of offshore flat oyster projects in the North Sea (Van Onselen et al., 2021). Results are presented according to the monitoring metrics in the NORA-handbook (zu Ermgassen et al., 2021).

NORA-metric	Data	Borssele III/IV/V OWF	Luchterduinen OWF	Gemini OWF	Borkum Reef (NL)	Heligoland (D)
7	% showing growth	Yes, though not quantified before (Van Onselen et al, 2012) was published	26,5%	67% (July 2018) 100% (April 2019)	100% (July 2018) 10-30% weight increase 100% (Sept 2018) 20-50% weight increase	100%, 10x weight increase in 1 year
8	Survival (% in first months)	96,3% (July 2021)	80% (July 2018) in cages above sand	100% (n=21) in cage, July 2018	37,5-92,5%, July 2018 in cages 92% on sea floor, July 2018	10-60%, in cages
8	Survival (% after first months)	ND	ND	ND	20-73%, in cages, Sept 2018	100%, in cages
9	Condition index (dry meat/shell weight in g) range	ND	ND	1 - 4,7 (July 2018)	1-4,8 (Sept 2018)	Good
9	Gonad development (%)	0% (n=32) July 2021	6% (n=17) July 2018	Near 100% (n=21) end of July 2018	50% (n=20) July 2018	
11	Sex ratio	ND	7 ♀♀, 1 ♂, 9 indet. (n=17)	ND	ND	?
	Larval abundance (N/100L)	low	90-125	6-12 (Gemini) 6-7 (half way Gemini - coast)	5-43	Yes
14	Recruitment	ND	ND	ND	Yes, 4 (on cage) 1 (sea floor)	ND
15	*Bonamia* prevalence (n)	0 (32)	0 (17)	0 (35)	0 (36)	0 (100)
17	Sand waves (moving) observed?	Yes, but no impact on the pilot	Yes, strongly negative.	Not observed	No. Minor scouring around reef structure	ND
17	Sedimentation rate	Probably low	Probably low	Probably low	Probably low	Probably low
18	Nearby oyster reef density	Absent	Absent	Absent	Absent	Absent
19	Biodiversity increased in pilot?	Possibly, no quantitative data	Possibly, no quantitative data	Unclear	Possibly, no quantitative data yet	Possibly, no quantitative data yet
22	Predators observed, with freely scattered oysters? (qualitative)	ND	ND	Yes, starfish	2.5/m2 (starfish and crabs. Sept 2018	ND
	Sources	T0 scientific report and T1 field report, Eurofins AquaSense 2021	Didderen et al., 2019a; Sas et al., 2018	Didderen et al., 2018, Bos et al., 2023 in prep.	Didderen et al., 2019a, Bos et al., 2023 in prep.	Pogoda et al., 2020

All pilots in which the oysters were appropriately contained show that the survival of adult oysters is high in the first three months after deployment. The survival of young oysters is somewhat lower during the first months, but very high after a year. All studies show that flat oysters, even when introduced from a completely different habitat (i.e., Irish bays or Norwegian fjords) or straight from a hatchery, grow very well in the wide variety of offshore locations in the Dutch North Sea. Most pilot studies showed that gonads developed in the oysters and also larvae were shown to be present in July, although in relatively low concentrations (5-125 ind/100L) compared to the larval abundance near or above native oyster reefs (several hundreds of larvae/100L; Maathuis et al., 2020). Recruitment was observed several months after deployment in the Borkum Reef Ground pilot, but to a very low extent. Some more recruitment was observed near the UNITED project location, but it is not fully clear where these recruits originated (the Borssele II/IV project is close and individual flat oysters are also still found in this area; T. Kerkhove, pers. comm., 2022).

Eight potentially important parameters (Zu Ermgassen et al., 2021) appear to be data-deficient:

- **Shell cover** is important because oyster spat requires a suitable habitat for settlement. Generally, the native oyster shells form the best settlement substrate, but other molluscan shells are suitable as well.
- **Sex ratio** is important because skewed or unbalanced sex ratios may lead to a lower reproductive output.
- **Recruitment index.** Successful recruitment is critical for the long-term persistence of oyster populations. It can be measured by estimating the density of recruits (oyster spat) on the reef or on clean settlement substrate, such as empty shells.
- **Fecundity** is a measure of the number of larvae a female oyster produces and provides information if oysters are contributing to a self-sustaining population.
- High **sedimentation rate** can negatively affect survival, growth and recruitment but can also indicate a low current velocity and high retention rate of larvae.
- **Light penetration** depends on the light absorption by suspended particles, including phytoplankton and particulate organic and inorganic matter. Light penetration may be a limiting factor for phytoplankton and thereby food availability for oysters, but this is less relevant in non-stratified offshore conditions.
- **Blue carbon** (carbon stock and carbon sink) is widely acknowledged as an ecosystem service. Oyster reefs can entrap organic rich sediment and therefore function as a carbon sink, but this effect will probably be relatively small compared to other sinks of CO_2.

Overall, the native oyster restoration pilots show that the measured parameter values of growth rates, survival rates, condition indices and reproduction are sufficient for the first three components of the native oyster life cycle (Figure 2.3). In other words: flat oysters from very different habitats are still adapted to the offshore North Sea growing conditions, even in very different locations. In this aspect, the pilots appear to be successful.

Very limited information is available on the fourth essential life-cycle component, recruitment. Some recruitment was observed in only two pilots (Borkum Reef Ground and UNITED), but to a very low extent. There may be more recruitment (although this is not probable, given the wide dispersal and burial of many of the oysters, see below), but its detection in the dark and often turbid and turbulent North Sea bottom region is extremely difficult.

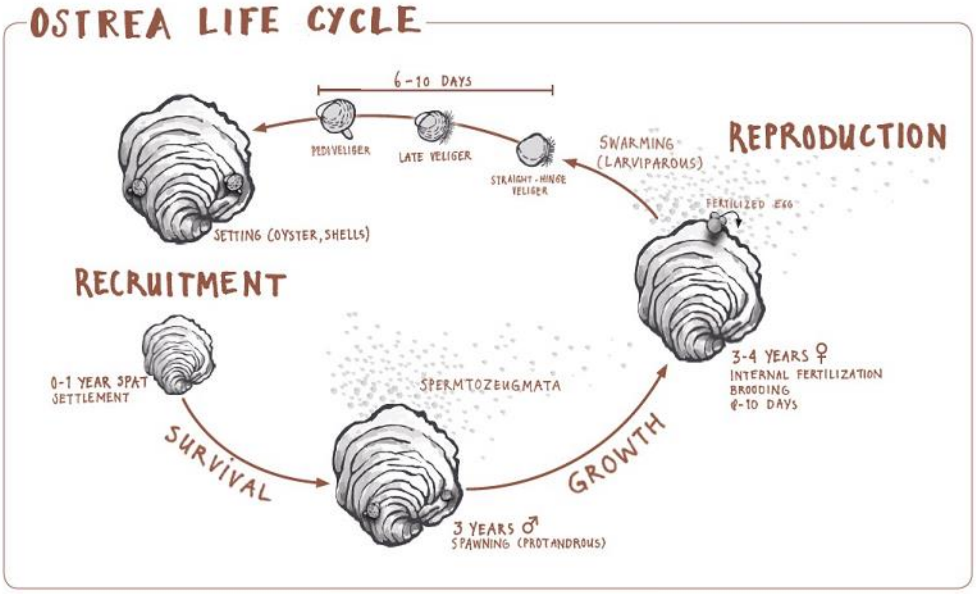

FIGURE 2.3 DETAILED LIFE CYCLE OF *OSTREA EDULIS* WITH CRITICAL SUCCESS FACTORS: SURVIVAL, GROWTH, REPRODUCTION AND RECRUITMENT (SAS ET AL., 2019).

In addition, the dynamic North Sea conditions appeared to cause the loss of the lightly constructed oyster deployment cages in Gemini, the partial burial of heavy deployment cages in Luchterduinen and the probable burial and scattering oysters over a large area in Borkum Reef Ground. In a second Luchterduinen project (started in 2022), much more robust oyster platforms were deployed on the scour protection of wind monopiles, but this attempt is too recent to be able to report results yet.

In the Ecofriend project (Bos et al., 2023, in prep.) the scattering of loosely deployed oysters was investigated, and it indeed appears that oysters become displaced and/or turned over at turbulence levels that occur during storm events to depths up to ca. 40 meter, whereas pilots are usually in lower water depths. An additional problem is that the upper level of the North Sea bottom, particularly in the EEZ, is dominated by sandy and silty sediments, which are loose as such (causing oysters to be buried in turbulent conditions) and may also be loosened further by the frequently occurring bottom trawling. Also, this type of sediment does not provide proper settling substrate for flat oysters. Hence, probably, the loose deployment of oysters on the sea floor, in its current condition, will not be appropriate to start a reef in the open North Sea. Methods to track loosely deployed flat oysters on the sea floor (in the Gemini wind park) and to model their movements, in order to better understand the dispersal process, are currently being investigated in the WINOR-project (pers. comm. T. Bouma, 2022).

It may be that small rocks of various sizes, such as employed as scour protection in wind farms, provide an appropriate combination of shelter and settling substrate (especially if deployed in the period when there are larvae in the water, see par. 2.1.7.5), but this has not yet been sufficiently tested in offshore conditions and neither have alternative deployment, sheltering and/or substrate deployment methods. In the innovative TreeReef project, a method is tried out to introduce both settling substrate and shelter by means of small disused pear trees. A Treereef pilot in the Dutch

Wadden Sea showed promising potential, but the concept still needs to be tried out in an offshore situation too (pers. comm. T. Bouma, 2022). Another promising concept is the use of substances, such as biofilms, glycoproteins and fresh shells that stimulate larvae to settle (Rodriguez-Perez et al., 2019, 2020, Vasquez et al. 2014), but these also need to be tested in (offshore) practice. The effect of shell deployment timing on larval settling will be tested in the WINOR project in the Gemini wind farm (P. Kamermans, pers. comm. 2023).

Since reef-forming annelid worms may stabilize the sediment, reduce shear stress at sea floor level and may also provide recruitment substrate, flat oyster reef formation may be stimulated where these species form reefs (or reef clumps). Hence, it has been suggested that there may be facilitation or synergistic effects between those species groups and flat oyster reefs (Christianen et al., 2018). However, the possibilities for such interactions seem low. Environmental requirements for *Lanice* and *Ostrea* are very different, resulting in little co-occurrence in distribution maps predicted by (Herman and Van Rees, 2022); compare figs. 2.2 and 2.3. Environmental requirements for *Sabellaria*, especially the high bottom shear stress and high amounts of sand moving over the substrate, do not correspond to the requirements for *Ostrea* either.

Overall, it is not well known where the best conditions for flat oyster reef restoration are, in the EEZ in its current condition (largely characterized by high turbulence and loose sediment). Habitat suitability models are based on historical information of reef presence, but once the reefs have disappeared, the conditions may not necessarily be suited for a new reef to start en grow. There may exist natural pockets of relative shelter (such as throughs between ridges and other types of depressions in the sea floor (e.g., Van der Reijden et al., 2019) and/or better settling substrate in the bare EEZ sea floor (areas with many loose shells or high shelliness), so that these locations would be better suited for flat oyster reef formation/restoration. Possibly concomitant even with already existing reef pockets by other species. Such pockets are probably to be expected mostly in areas with strong sea floor heterogeneity, such as between (stable) sand ridges (as in the Brown Bank) and in stony areas (as in the Borkum Reef Ground). To locate these requires more extensive EEZ sea floor mapping in those areas. Such mapping is currently being planned as part of the MONS-program, to start in July 2023.

The principal flat oyster reef restoration objective is to re-establish populations which can sustain themselves, or even better, grow autonomously. Otherwise, human intervention would remain necessary, which is contrary to true ecosystem restoration goals, such as set out in Chapter 1 and in (Zu Ermgassen et al, 2021). To create self-sustaining populations or growing reefs, substantial recruitment in or near the seed population is a prerequisite. Therefore, the first knowledge gap with respect to reef restoration is the recruitment phase and in particular how to enhance recruitment during population initiation in North Sea offshore conditions. These conditions are characterized by frequent, wave-induced turbulence (also near the sea floor during storm events) and strong currents. The second knowledge gap is the minimum size of a flat oyster reef which is required to cause substantial recruitment within the reef area in offshore conditions, again given currents and turbulence, possibly in combination with the effect of settling stimulation measures. The third knowledge gap is how to avoid a start population becoming buried in the sea floor, or widely spread, again given currents and turbulence, with the loose (sandy/silty) sea floor as extra negative factor in the open North Sea. A related, practical knowledge gap is how to practically create new sea floor conditions (with substrate, or otherwise), allowing a seed population to remain in place and also promoting larval settling, in areas with a silty/sandy sediment (as is mostly the case in the EEZ).

2.1.6.3 International research and data collection

There is no harmonised international research and data collection on the European flat oyster. However, OSPAR area assessments are made for the oyster (OSPAR, 2020a) and individual national datasets are combined by OSPAR to create distribution maps (https://jncc.gov.uk/our-work/marine-habitat-data-product-ospar-threatened-andor-declining-habitats/).

As referred to above, recommendations for monitoring of restoration pilots are described in the NORA Handbook on oyster restoration (zu Ermgassen et al., 2021), but very often data collection is still incomplete, due to various reasons.

2.1.7 Seed populations: production and bioveterinary considerations

2.1.7.1 Introduction

For active restoration flat oysters are available as adults or as juveniles (called spat). These are either fished as adults from natural beds or culture plots, or produced as spat with collectors in the field, in spatting ponds, or in hatcheries.

The source material should be:

- disease free;
- tolerant or resistant against diseases when possible;
- free of non-native species;
- in good condition, so that it has maximum opportunities for survival, growth and reproduction in the target area;
- adapted to the local environment and to climate change;
- as genetically diverse as possible.

In the following paragraphs the requirements will be outlined in more detail. In addition, possibilities for import and production are discussed.

2.1.7.2 Diseases

There are two main pathogens for *O. edulis*: *Marteilia refringens* and *Bonamia ostrea* (Haenen et al., 2011). Both species are unicellular parasites and infection can cause death of the host. *Bonamia*, causing bonamiosis, occurs in the Netherlands, France, Ireland, United Kingdom and Spain, but some bays are pathogen free (Sas et al., 2020). *Marteilia* occurs in flat oysters along the Atlantic coasts of France, Spain and Portugal and in the Mediterranean and Adriatic Sea, but not in the Netherlands.

EU regulations permit transfer of oysters and mussels between water bodies provided they are either disease free, or the donating and receiving water bodies have the same disease status (EU Regulation 2016/429). Most European countries have a disease monitoring program in place when fishing and culture of oysters and mussels takes place (Haenen & Engelsma, 2020). Since there is no production of flat oysters in the North Sea the disease status is considered disease free. This means that the animals that are introduced for restoration purposes must be disease free too. They can be collected in areas where the disease does not occur. (Sas et al. 2020) give an overview of the distribution of *Bonamia* in flat oysters in Western Europe. Alternatively, flat oysters can be purchased from companies that produce spat. Kamermans et al. (2020) gives an overview of disease-free hatchery and pond producers in Atlantic Europe. To be recognised as a disease-free area or a disease-free company it is compulsory to comply with EU Regulations 2016/429 EUR-Lex - 32016R0429 - EN - EUR-Lex (europa.eu) and 2020/689 EUR-Lex - 32020R0689 - EN - EUR-Lex (europa.eu). These regulations describe the necessary registration, notification and monitoring procedures.

Bonamia-free oysters come from areas where the parasite has never been detected. These oysters are susceptible to the disease, as they have never been exposed to it. Oysters that come from areas where the parasite occurs may be tolerant (infected, but not affected by the parasite) or resistant (not infected even though exposed to the parasite). Significant gains for disease resistance could be obtained using selective breeding programs. Several studies showed that spat produced with parents that survived in *Bonamia*-infected areas resulted in offspring that also showed better survival (Culloty et al. 2004; OYSTERECOVER, 2013). Ongoing efforts to supply oysters for Dutch restoration projects focus on hatchery production of disease-free spat that may also have developed tolerance to the disease (Kamermans et al., 2023).

2.1.7.3 Avoidance of non-native species

Oysters and mussels can contain other organisms either growing on the shells, or in the mantle cavity. Brenner et al (2014) reviewed risks associated with shellfish translocation, such as introduction of non-native species including pathogens like protists, bacteria and viruses. Many examples of severe ecological impacts have been documented worldwide owing to the intentional or unintentional translocation of animals (Brenner et al., 2014). It is therefore important to develop risk reduction methods to be incorporated into current fish health or environmental legislation. The flat oysters for the pilots described in (Didderen et al. 2018, 2019a,b) and (Schutter et al. 2022) came from *Bonamia*-free areas in Norway and Ireland and were treated to avoid introduction of non-native species following a protocol developed by (Van der Have et al., 2018) and (Van den Brink & Magnesen, 2018).

2.1.7.4 Adaptation capacity

Flat oysters will be sourced from other locations than the restoration location. Because of this adaptation to the local environmental conditions may not be optimal. It is therefore recommended to monitor survival, growth, reproduction and recruitment of the shellfish once they have been deployed (Sas et al., 2019).

Genetic diversity is of great importance for the long-term survival of populations. The broader the genetic base, the better the chance of survival when environmental conditions change. Information on genetic diversity is needed to avoid potential maladaptation when transplantation and/or a too low diversity could impair the sustainability of the program. In addition, genetic characterization can assist in the choice of the origin of the shellfish for restoration. Ideally, genetic monitoring of the recruited spat through time is also included in order to follow the evolution of the genetic diversity and the effect of restoration efforts. A recent study on *O. edulis* confirmed the existence of four genetic clusters of populations: 1. North Sea, 2. Atlantic Ocean, 3. western part of the Mediterranean Sea, 4. eastern part of Mediterranean Sea and Black Sea (Lapègue et al. 2022).

Laboratory experiments indicate that flat oysters are relatively well adapted to climate change: (Kamermans & Saurel, 2022) showed that *O. edulis* still grows at 30 ^{0}C.

2.1.7.5 Production

The first step for hatchery production is to collect the parents (broodstock) from natural or cultured populations. These oysters can either be ready to spawn, or not ready to spawn. When they are ready to spawn, the oysters can be used directly for spawning. Alternatively, they can be stored in tanks at low temperatures without food where they can be kept in spawning condition up to a few months. When they are not ready to spawn, they are conditioned in tanks, with a gradual temperature increase while providing food over a period of 4 to 6 weeks. Fertilisation takes place during conditioning. Release of larvae is detected by directing the outflow of the conditioning tank over a sieve which is checked daily for the presence of larvae. Development to larvae occurs within 48 h. During this phase the larvae are reared in static or flow-through systems and fed live microalgae. Generally, the hatchery cultures these microalgae on site. The larval phase lasts around 2 weeks. After this period, they undergo metamorphosis by settling onto a substrate. In commercial hatcheries this is cultch, shells grinded to sand grain size. This is done because the end product should be single oysters. Selecting the best settlement substrate for restoration projects is under development, but shells seem a good choice. Bottlenecks still remain in flat oyster seed production in hatcheries compared to other shellfish species. This concerns relatively little control over broodstock conditioning, sudden mortality of larvae during the rearing process and high mortality during metamorphosis.

Spat rearing is carried out in a nursery where the oysters are kept on sieves with running seawater. The small oysters (spat) are usually reared indoors and fed microalgae that are cultured indoors. Larger oysters (seed) are reared outdoors with algae that are cultured in open ponds. The final product of a hatchery is seed. Different sizes of seed are produced. This is indicated by the size of the mesh that retains the seed, e.g., T8 is seed that stays on an 8-mm sieve. The larger the seed size, the higher the price. The process from broodstock conditioning to T8 seed takes around 5-6 months.

In spatting ponds, ready tospawn-broodstock is introduced in land-based basins of around 2 m deep filled with seawater. Presence of larvae is monitored daily. As soon as larvae are present water exchange with the nearby estuary is stopped. To monitor settlement of spat unglazed ceramic tiles are used. When 25 % of the larvae are larger than 250 µm settlement substrate is introduced. This used to be tiles, but nowadays empty mussel shells in oyster bags are more commonly used. Around 7-14 days after settlement the water can be exchanged again. Natural seawater is used; therefore, production of algae is not needed. However, natural fluctuations in food supply can occur, reducing the success rate compared to hatchery production. In addition, production is only possible in the summer months.

Culture in the field starts with collecting spat, from clean substrate that is provided at the time when oyster larvae are settling. Shells with spat are harvested the following spring. There are more species that like to settle on hard substrate and fouling can be a major problem especially in submerged collectors. Therefore, best practice is to present the collector shortly before settlement, which is two weeks after the peak in oyster larvae (Van den Brink et al., 2013). A recent analysis of long-term data series indicates that the timing of larval release can be predicted based on the development of the temperature (Maathuis et al., 2020). Flat oyster spat is cultured up to market size in off-bottom structures such as bags on trestles or baskets on long-lines, or on bottom plots.

In a number of European countries flat oysters are harvested from wild beds. In Denmark, France and Spain this is done with dredges, while in Sweden and Norway the oysters are hand-picked, either from areas that emerge at low tide, or with divers from permanently submerged areas.

2.1.7.6 Import

When shellfish are imported from outside the Netherlands the supplier needs to register the animals in a system called TRACES (TRAde Control and Expert System). TRACES is the European Commission's online platform for sanitary and phytosanitary certification required for the importation of animals, animal products, food and feed of non-animal origin and plants into the European Union, and the intra-EU trade and EU exports of animals and certain animal products (TRACES (europa.eu)). EU law requires consignments of animals to be accompanied by official certificates, attesting compliance with the applicable requirements. National competent authorities and economic operators complete official certificates, such as health certificates, online in TRACES and the control authorities at EU border or at the final destination check the consignments and their accompanying documents to allow them to enter and/or move through the EU. The receiving party must also be registered in the TRACES system. In the case of shellfish for restoration this needs to be an organisation registered as aquaculture holding facility.

2.1.7.7 Key points

Flat oysters can be obtained for restoration purposes. Since the species is endangered, production is preferred over harvesting from natural beds. Hatchery production has the additional advantage that there are no fouling organisms and that selective breeding for disease-free and disease-tolerant strains is an option. However, for large scale hatchery production the process needs to become more reliable. Genetic characterization of the released shellfish is recommended but has to date not been incorporated in restoration programs.

2.1.8 Knowledge gaps

The restoration pilots which have been undertaken until so far, have shown that survival, growth and reproduction of (well-contained) flat oysters in the open North Sea are generally good, even with oysters from completely different origins and habitats. So, the primary requirements to reef restoration are fulfilled.

However, it is still unclear how to reach the real restoration objective, namely the formation of self-sustaining or autonomously growing reefs. It was attempted to start reef formation by deploying individual adult oysters on the sea floor, but this method has not been successful, since typical turbulence and currents in the North Sea cause dispersal and/or burial of the oysters. Most probably this process also causes wide dispersal of the larvae produced by a seed population. Besides, large parts of the sea floor are characterized by sandy and silty sediments, which do not constitute proper settling substrate for flat oysters. There may exist pockets of relative shelter and/or better settling substrate on the bottom of the EEZ (such as gravelly material and/or shells in throughs between ridges), but these are not mapped in sufficient detail. Furthermore, methods to create structures which cause shelter and seabed stability, in combination with adequate settling substrate and applicable on a sufficiently large scale, need to be developed and tested.

Hence, the key knowledge gaps are:

- The overall understanding of the conditions suitable for offshore flat oyster reef formation/restoration is still limited, since it is largely derived from historical information (when the reefs were still present). Hence, it is understood only roughly where the best reef formation/restoration conditions are located in the present situation.
- In order to establish reefs, which sustain themselves, or grow independently:
    - The physical characteristics of North Sea floor (relief, sediment composition) are not known in insufficient detail to detect possibly existing pockets of sufficient shelter and/or adequate settling substrate.
    - Methods to deploy adequate shelter and substrate, to keep the start population together and also to stimulate local settlement need to be further developed and tested in the offshore practice.
    - The minimum extension of a flat oyster reef which is required to keep the recruitment inside the reef, again given currents and turbulence, is not known and neither is the effect of settlement stimulation measures on the required minimum extension.
- Detection of flat oyster recruitment in the turbulent, dark and often turbid North Sea bottom area is very hard, so that monitoring the potential success of reef restoration attempts is difficult.

A knowledge gap which also hampers flat oyster restoration initiatives is related to production in hatcheries (being the most appropriate method for large-scale seed oyster production): the production reliability is still low, due to sudden larval mortality incidents, and the causes for this phenomenon are still largely unknown.

2.1.9 Threats, impacts and opportunities

The main historical threat to flat oyster reefs is seabed disturbance by humans, and of course, extensive overharvesting as occurred more than a century ago. Governmental regulation and wind farm development cause more and more areas in the North Sea to be closed to human seabed disturbance. In addition, harmful pollution has strongly decreased so that the primary conditions for reef formation are being fulfilled. The fact that current projects have shown flat oysters to do well in several, widely separated North Sea locations testifies to this.

However, the protection of flat oyster reefs is not implemented in the Dutch Natura 2000/Habitats Directive framework, so that these have no formal protection status in the EEZ. Hence, an important opportunity is to include flat oyster reefs in this regulatory framework.

The other opportunities lie in closing the knowledge gaps, as described in par. 2.1.8. In the MONS program (MONS, 2023), a start of the required research and monitoring (by its actions ID8, ID51 and ID57) is foreseen. An important opportunity also lies in international cooperation, between The Netherlands, Belgium and Germany, since offshore flat oyster restoration projects are taking place, and are being extended, in all three countries.

2.1.10 Potential success of measures

Again referring to par. 2.1.8, there are important knowledge gaps concerning effective flat oyster reef restoration. The success of restoration measures, hence, is dependent on the speed with which these knowledge gaps can be closed. This requires an integrated flat oyster restoration reef development program for the North Sea offshore situation, which builds on the current projects and programmes, which are characterized by learning-by-doing as well as fundamental research, but on a larger scale and internationally based. This program should at least contain the following elements:

- Development of adequate restoration techniques, applicable on a sufficiently large scale to create self-sustaining flat oyster reefs.
- Improved habitat suitability modelling, to better understand the conditions required for the formation of these reefs.
- In selected areas with strong spatial heterogeneity, such as the Borkum Reef Grounds: better mapping of the sea floor habitat, to investigate where appropriate conditions for reef restorations may exist.
- Development of monitoring techniques which allow detection of recruitment.
- Research and development to improve the reliability of flat oyster production in hatcheries.

This programme should also lead to the operationalisation of the agreement by the North Sea Platform ('Noordzee Overleg'), to create 100 km^2 of flat oyster reef in the Frisian Front.

2.2 Modiolus modiolus

2.2.1 General description

Modiolus modiolus (or horse mussel) is a large mussel species with a maximum length up to around 220 mm. See fig. 2.4 below.

FIGURE 2.4 ***HORSE MUSSEL (MODIOLUS MODIOLUS) (PHOTO: OSCAR BOS, WAGENINGEN MARINE RESEARCH).***

The species has a small reddish foot and short syphons. The two valves are roughly triangular with a blunt head and a lower edge that is often curved slightly inwards. The shell is greyish white to light purple with a brown/black scaly periostracum and a white glossy inner nacre layer. On the shell surface also growth lines are visible. The non-fused mantle edges are orange-yellow coloured and are not clearly wavy or serrated but do have fine fringed tentacles (de Bruyne & van Leeuwen, 2013).

Horse mussels are attached to each other by byssus threads, hence we adopt the term ‘beds’ for aggregates, instead of ‘reefs’ (just as with blue mussels, see par. 2.3.1).

Reproduction can take place year-round depending on the location and depth, but peaks occur in late spring - summer. Female individuals can produce more than a million eggs, which can be fertilized in the water column. The following larval stage is relatively long-lasting and may take several months. After settlement initial growth is rapid which later slows down. The species matures late and is capable of reproduction after 3 to 4 years. The normal lifespan usually lasts between 25-30 years, but individuals even over 50 years can be found (de Bruyne & van Leeuwen, 2013).

Horse mussels filter vast amounts of seston particles from the seawater column, thereby strengthening the benthic-pelagic coupling and increasing the benthic production. Moreover, the high filtering activity leads to the production of large amounts of (pseudo)faeces, which can locally enrich the seabed sediment with organic matter (OSPAR, 2008, 2009).

The sediment underlying horse mussel beds is stabilized by the byssus threads, which bind living and dead shells and sediment together. Eventually this will change the local morphology/topography, acoustic reflectance and roughness of the sea floor. This change in roughness over often extensive areas can locally alter hydrodynamic conditions which stabilizes the sediment even more by reducing the erosion potential (OSPAR, 2009).

2.2.2 Legislative and policy context

Given the low relevance of horse mussels for the southern part of the North Sea (see par. 2.2.5), its protection status is not regulated in Dutch waters.

2.2.3 Distribution

The horse mussel is a cold-water species which typically inhabits deeper marine areas with a strong bottom current, saline conditions, and with mostly a coarse sand or gravel seafloor. Regularly, they are also observed on other substrates, such as bedrock and the foundations of offshore structures (Anwar et al., 1990; OSPAR, 2009). Using their byssus threads, younger/juvenile horse mussels attach onto stones, shells, and other hard substrate objects. M. modiolus beds or reefs are observed at a depth between 25 and 40 meters. However, the species also thrives up to around 200 m deep (de Bruyne & van Leeuwen, 2013).

When the conditions allow, denser clumps can develop to become a mussel bed (EINIS classification: A5.621, A5.622, A5.623 and A5.624) which are often long-lasting biogenic reefs that build up from the accumulation of faecal pellets, shell material, and trapped sand. Over time this will separate them from the substrate on which they first established (OSPAR, 2009). The beds significantly impact the nearby environment by changing local conditions and increasing the biodiversity (see par. 2.2.4).

2.2.4 Habitat formation and ecosystem function

M. modiolus beds provide a habitat for a diverse sublittoral community. The beds bring nursery refuge for many species by offering shelter between the shells and byssus threads (de Bruyne & van Leeuwen, 2013). Additionally, settling area for other bivalve spat is provided by biota growing on the mussels (such as dense growth of bushy hydroids and bryozoans). Overall, numerous species, such as sponges, hydroids, bryozoans, soft corals, brittle stars, snails, bivalves, and sea squirts, can be observed in these beds (de Bruyne & van Leeuwen, 2013). The increased structural heterogeneity related to these biogenic reefs thus locally enhances the biodiversity which will even attract other species in the nearby environment such as fish or seabirds (OSPAR 2008, 2009). The rich community of free living and sessile (epi)fauna together with predators makes it a dynamic system with a higher biodiversity compared to the surrounding seabed (OSPAR 2008, 2009).

2.2.5 Current status of reef distribution

Beds of *M. modiolus* are mostly found in patchy form in cold-temporal coastal regions on the north-east Atlantic shelf (see fig. 2.5).

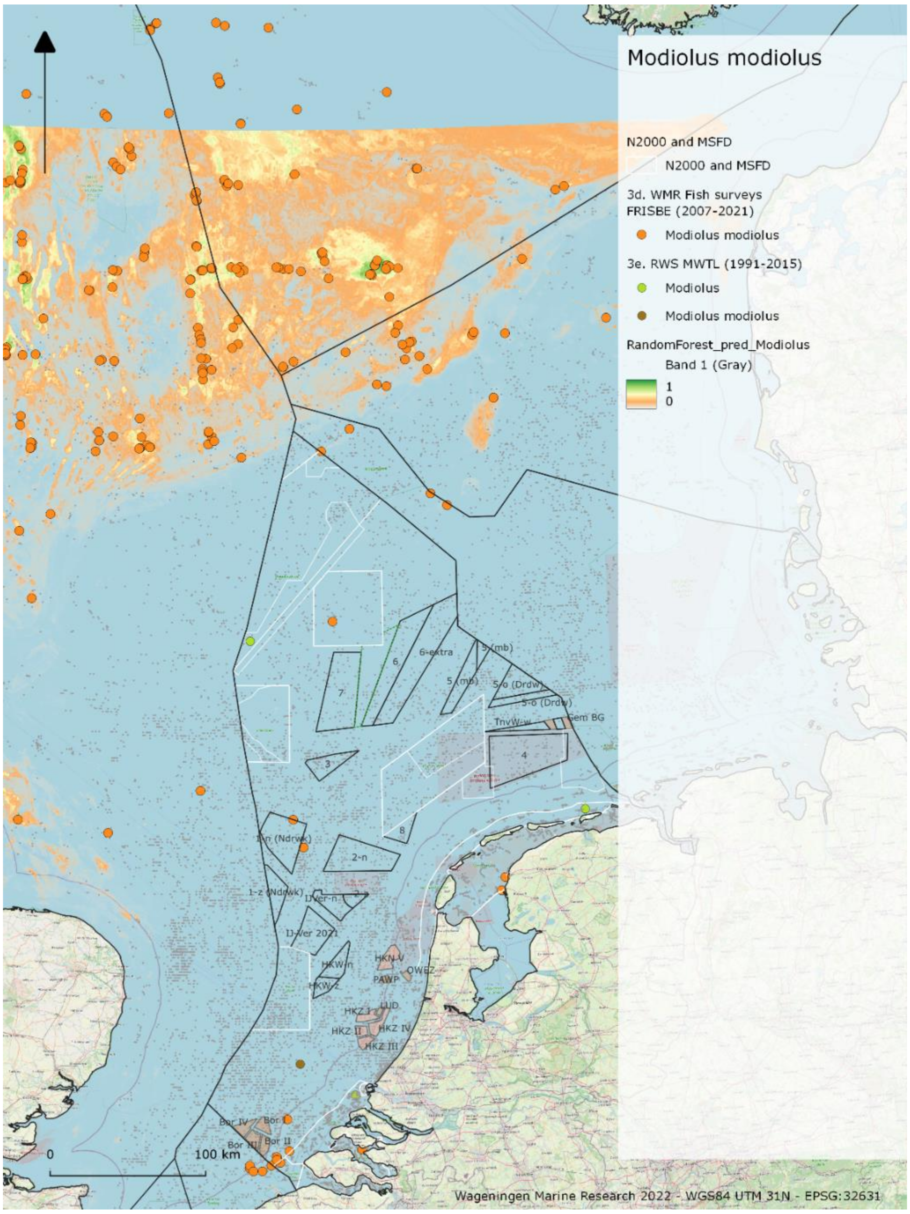

FIGURE 2.5 *MODIOLUS MODIOLUS*, PREDICTED HABITAT SUITABILITY (HERMAN & VAN REES, 2022) AND RECORDINGS OF OBSERVATIONS (BOS ET AL., 2023, IN PREP).

These beds have been observed at a variety of locations, from the lower coast to approximately 200 meters deep, on both natural and artificial (offshore foundations) substrates. The beds are distributed from the southern part of the Barents Sea and White Sea to the North Sea and Irish Sea. Some beds were also found around the Arctic islands of Iceland and the Faeroes (OSPAR, 2009). The southern limit of its current distribution ends at the Bay of Biscay (in deeper waters) (OSPAR, 2009).

Modiolus is a cold-water species, hence beds mostly occur in the Northern part of the North Sea, although they are occasionally found in the southern part too. See (Herman and van Rees, 2022) and fig. 2.5. A main threat to horse mussels is global warming, leading to higher North Sea water temperatures. This will most probably lead to movement of the overall population to the North, i.e. also further out of the EEZ.

2.2.6 Monitoring and research on current reef locations

2.2.6.1 National research and data collection

Since the horse mussel is a more deep-water species and is assumed to be infrequent in the southern North Sea, little attention is paid to active recovery. While (Bos et al., 2019) showed incidental occurrence of this mussel species in the Dutch North Sea, no efforts have been made in Dutch waters for the monitoring or conservation of the species (Van Onselen et al., 2021).

2.2.6.2 Project monitoring

No project monitoring on horse mussels is taking place in Dutch waters.

2.2.6.3 Restoration pilots

Restoration of horse mussel beds is still in its infancy. (Fariñas-Franco et al., 2013) and (Fariñas-Franco & Roberts, 2014) carried out restoration experiments within the historic range of *M. modiolus* in a coastal area in Northern Ireland. They successfully transplanted adult horse mussels from remnant natural reefs to a nearby experimental location. Based on the translocation experiments, results of larval dispersal models and determination of the physiological condition and age distribution of the remnant population, (Elsäßer et al., 2013) and (Fariñas-Franco & Roberts, 2018) recommend a combined approach of strict protection of the remaining larval sources and active restoration through stock supplementation to address recruitment limitations and increase connectivity between remnant subpopulations. However, restoration in the Dutch North Sea is not considered as opportune, since it is not a typical species in this area and will probably become even less so, given global warming, which leads to an increase in North Sea water temperatures.

2.2.6.4 International research and data collection

Detailed information regarding the distribution of current *M. modiolus* beds is missing due to its patchy occurrence and the uncertainty whether current data refer to beds or individuals. OSPAR encourages the agreement partners to undertake habitat assessments and surveys in their respective maritime zones with the use of for example multibeam surveys or targeted SONAR mapping. This would entail more information about the extent of this habitat which is required to set up conservation measures and for the fishery management (OSPAR, 2009).

2.2.7 Production of seed populations

Production of horse mussels in hatcheries is still in its infancy. At DTU Aqua in Denmark, a breeding project has recently started (C. Saurel, pers. comm. 2023).

2.2.8 Knowledge gaps

There are various knowledge gaps on how to enhance horse mussel reefs, but these are not relevant to the Dutch situation, given that the species is not typical for the Dutch part of the North Sea.

2.2.9 Threats, impacts and opportunities

Being a cold-water species, a main threat to horse mussels is global warming, leading to higher North Sea water temperatures. This is another reason why horse mussel reef protection or restoration are not considered appropriate in the Dutch North Sea. However, since the species appears to occur occasionally (see par. 2.2.4), it is recommended to keep an eye on potential horse mussel occurrences in ongoing and new monitoring programmes. By doing so, the hypothesis that it is not a naturally occurring species will be tested without much effort.

2.2.10 Potential success of measures

See par. 2.2.8: on the basis of current knowledge, conservation or restoration measures in Dutch waters are not considered relevant.

2.3 Mytilus edulis

2.3.1 General description

Mytilus edulis (common mussel or blue mussel) is a medium sized mussel species with an average adult size of 50-70 mm (see fig. 2.6).

FIGURE 2.6 SUBLITTORAL BLUE MUSSEL (*MYTILUS EDULIS*) BED ON A BOULDER IN THE VOORDELTA (PHOTO: OSCAR BOS, WAGENINGEN MARINE RESEARCH).

The animal has a creamy white to light orange body colour with yellow-brown mantle edges. The double, loose mantle margins run at the back of the shell to an orange inflow siphon with small white tentacles. The white outflow siphon is smaller and more conical in shape. The shell is elongated and triangular in shape, and rather thin. The rear edge of the shell is rounded, and the lower edge is almost straight. The outside of the shell has a purple-blue color. Lighter colors (yellow-brown-greenish) also occur, with often dark purple lines present. The shells of juveniles are more yellow and slightly translucent. Adult shells have a black periostracum and a glossy inner nacre layer (de Bruyne & van Leeuwen, 2013). Byssus threads, made of a sticky protein substance produced in the foot gland, are used to attach the shells to the substrate. The strong anchoring provided by the byssus threads allow the mussels to remain attached even in extremely turbulent waters. Furthermore, the streamlined shell ensures that fast flowing water can easily pass without dragging the mussels along. When mussels die, the byssus threads are loosened. Hence, a decaying mussel cluster falls apart (de Bruyne & van Leeuwen, 2013), contrary to e.g. oysters. As with *Modiolus*, we adopt the term 'bed' for a blue mussel aggregate.

Mussels are filter feeders, drawing in water through the inflow siphon. The gills take up the oxygen and filter out the food particles. Everything ingestible is processed from the gills through the digestive system, and what is left over is expelled as pseudofaeces, ejected directly from the gills. This allows mussels to remove large volumes of suspended sediments from the water column, which accumulates under and around the mussel beds (de Bruyne & van Leeuwen, 2013).

During the fertilization period, millions of eggs and sperm cells from the adult mussels are released more or less simultaneously. Fertilization takes place in the water column. Larvae develop with a planktonic stage of 3 to 6 weeks and will be carried along with the water flow, until spatfall starts. A critical phase then begins, since the larvae depend on suitable substrate for attachment and in order to survive. In addition, many predators eat mussel seed. If the mussel can develop properly, the animals can become 18 to 24 years old (https://www.marlin.ac.uk/species/detail/1421).

The species is considered relatively tolerant to environmental variables (e.g. temperature, salinity, and oxygen) and can deal with changes in conditions such as food quality/quantity. The mussel is quite adaptable in responding to fluctuations, and can respond with changes in terms of morphology, behavior, and physiology (OSPAR Commission, 2015).

2.3.2 Legislative and policy context

In the Netherlands, *Mytilus edulis* production and harvesting is regulated by the Fisheries Act. Offshore sublittoral mussel beds in the Dutch part of the North Sea have not been considered for conservation yet, since they have been considered absent.

Intertidal and subtidal mussel beds are mainly found in the Wadden Sea and in the Delta area and are an important part of the good structure and function of habitat type H1140 under the Habitats Directive. In addition, conservation objectives have been set within the Dutch Nature Conservation act for various bird species for which shellfish are an important source of food, such as oystercatchers. Mussels and mussel beds are thus legally protected as important components in the ecosystem. Furthermore, there is an environmental target to restore biogenic reef building species under the MSFD.

Table 2.4 below lists relevant legal and policy instruments for the protection of mussel beds in the marine environment.

TABLE 2.4 (INTER)NATIONAL LEGAL AND POLICY INSTRUMENTS AND THEIR APPLICABILITY FOR SUBLITTORAL BLUE MUSSEL BEDS ("YES" = RELEVANT; "NO" = NOT RELEVANT).

Instrument	Description	Blue mussel bed (sublittoral North Sea)
International		
Habitats Directive (HD) Annex 1	In the Netherlands, mussel beds are not considered to be part of HD habitat type H1170 reefs (only geogenic reefs are considered).	No
HD Typical species	Intertidal mussel beds are an important part of the good structure and function of habitat type H1140 under the HD. In addition, conservation objectives have been set within the Dutch Nature Conservation act for various bird species for which shellfish are an important source of food, such as oystercatchers. Mussels and mussel beds are thus legally protected as important components in the ecosystem. This probably does not apply to sublittoral mussel beds in the North Sea	No
OSPAR List of Threatened and/or Declining Species and Habitats	In order to protect biodiversity, OSPAR has defined a list of 'threatened and declining species and habitats' that are in need of protection (OSPAR, 2008). Intertidal mussel beds are on this list (but not sublittoral/offshore mussel beds).	No
The EU Common Fisheries Policy (CFP)	Offshore fishery measures in MSFD and N2000 areas are established under the Art 11 of the CFP. These zones offer protection from bottom contacting fisheries for future mussel beds. EUR-Lex - L:2023:048:TOC - NL - EUR-Lex (europa.eu)	Yes
Trilateral	A larger area and a more natural development and distribution of mussel beds is also an important goal in the Trilateral Wadden Sea Plan (but there are no targets for sublittoral beds)	No
National		
Dutch Fisheries act (Visserijwet)	The blue mussel is a commercial species as defined in article 1.2, Staatscourant 1982, 253	Yes
Dutch Nature Conservation Act (Wet Natuurbescherming)	Blue mussels are not protected under the Nature Conservation act, though included as typical species for intertidal areas.	No
Marine Strategy Framework Directive	Return and recovery of biogenic reefs (D6T5), so possibly also mussel beds (Marine Strategy Part 1, 2018) (IenW & LNV, 2018).	Yes
Red List	A Red List is an overview of species that have disappeared or are in danger of disappearing from the Netherlands. Red list do not have a legal status. Sublittoral mussel beds are not listed.	No
North Sea Agreement	The North Sea Agreement (OFL, 2020) includes the agreements between central government and stakeholder parties about choices and policy aimed at the balance in activities in the North Sea up to and including 2030 and beyond. As part of the North Sea Agreement, species protection plans will be developed and implemented, but mussel beds are not specifically mentioned.	Yes

In summary, related to the EEZ:

- Natura 2000/Habitats Directive: Mussel beds are not included within this regulatory framework for offshore Dutch waters.
- Marine Strategy Framework Directive: D6T5: Return and recovery of biogenic reefs is a target, hence also mussel beds.
- OSPAR: No targets or recommendations to protect or enhance offshore mussel beds.

2.3.3 Distribution

M. edulis is currently primarily found in coastal regions and estuaries, in both tidal areas and shallow waters, up to a few meters below the low water mark. But mussels are also present on various types of structures (monopiles, platforms, buoys) in the upper parts of the water column of the offshore North Sea at many different locations (Bos et al., 2021; Coolen et al., 2020), as well as on hard substrate objects on the sea floor, such as shipwrecks (K. Bartelink, pers. comm. 2022) and the scour protection of monopiles (W. van Broekhoven, pers. comm. 2023; Hutchison et al., 2020). Apparently, mussel beds are physiologically adapted to the overall environmental conditions of the open North Sea. See fig. 2.7 for mussel findings in the EEZ.

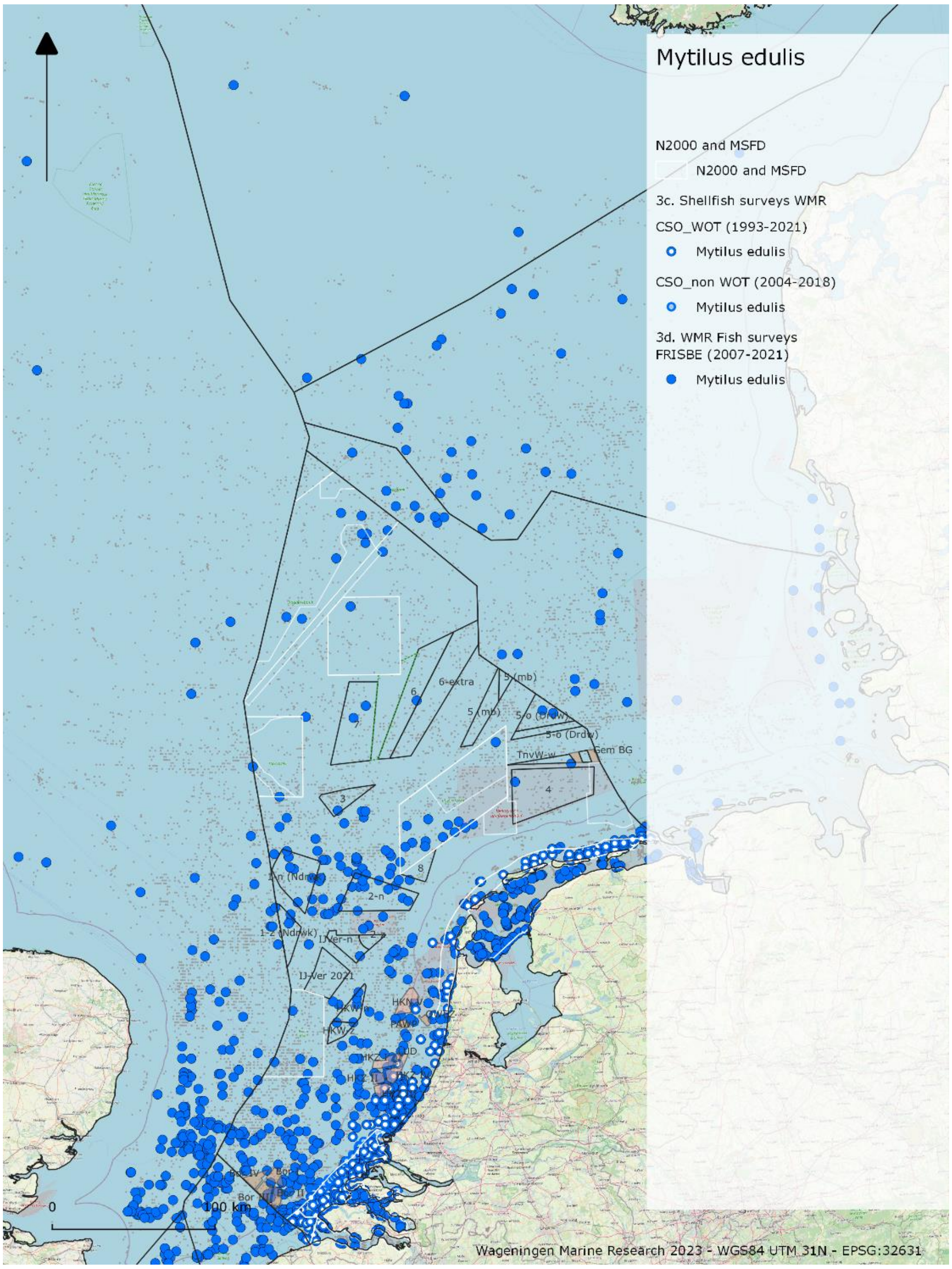

FIGURE 2.7 *MYTILUS EDULIS* RECORDINGS OF OBSERVATIONS (BOS ET AL., 2023, IN PREP).

Mussel beds also occur on the sea floor at some North Sea locations with strong relief and/or rocky substrate, such as the Swedish and UK North Sea coast, up to a depth of ca. 20 m (Baden et al., 2019, Tillin & Mainwaring, 2016).

2.3.4 Habitat requirements

Mussels can survive at salinities of 18 to 40‰ and water temperatures up to 29˚C (de Bruyne & van Leeuwen, 2013). They can occur in both hard and soft substrate environments, as long as there is some settling substrate (e.g., shell debris, or live cockles/oysters and even hydroids; M. van Stralen, pers. comm. 2015) present for the initial settlement of the larvae. In soft substrate environments however, clustering of the mussels is more frequently observed and can lead to the formation of extensive mussel beds (de Bruyne & van Leeuwen, 2013).

However, mussel beds are historically rare on the EEZ North Sea floor, which is mostly characterized by soft sediments. See fig. 2.8.

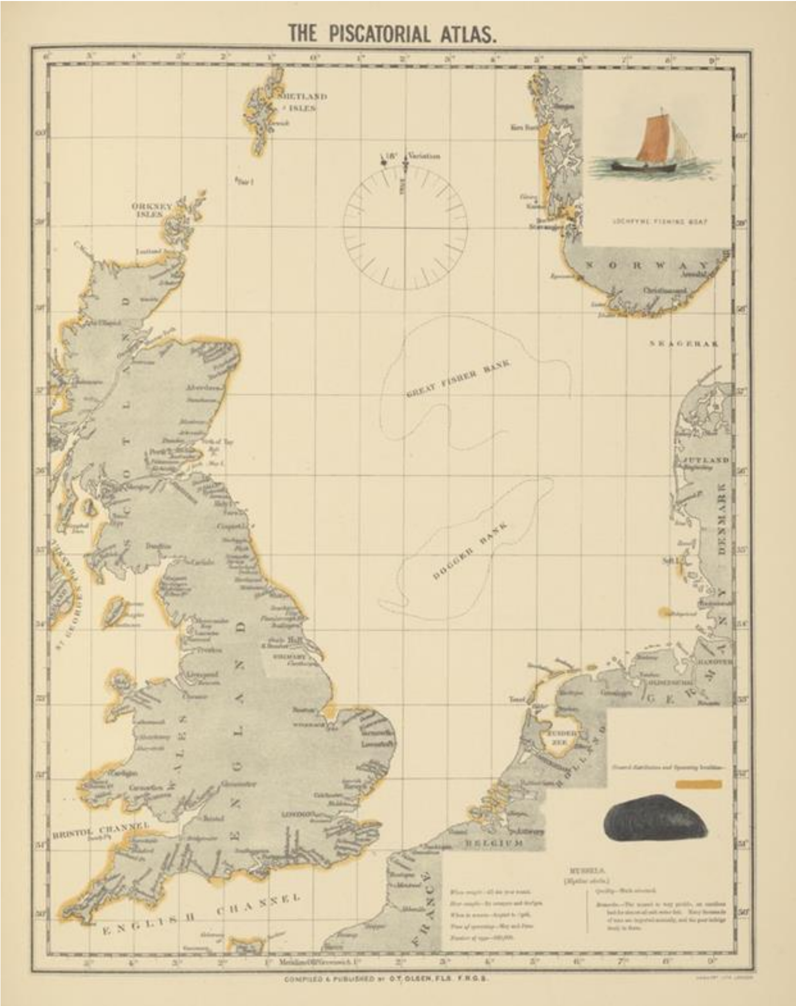

FIGURE 2.8 HISTORICAL DISTRIBUTION (19TH CENTURY) OF BLUE MUSSELS IN AND AROUND THE NORTH SEA. PAGE 108 IN OLSEN (1883). NOTE THE ABSENCE OF MUSSEL BEDS IN THE OFFSHORE SOFT-SEDIMENT PART OF THE NORTH SEA.

The main factors restricting subtidal mussel bed formation and long-term persistence on the EEZ sea floor are physical stability and predation. For example, in the Wadden Sea, where mussel beds in the sublittoral have been closely monitored for decades (see e.g. Troost et al., 2022), freshly settled mussel beds are frequently removed by storms. In areas which are relatively protected against storms, strong predation, especially by starfish, is often limiting. Hence, the existence of a sublittoral mussel bed in the Voordelta is still unexplained, since predators such as starfish and crabs are present there, as is the case in the Wadden Sea.

Possibly, an explanation of the occurrence of mussel beds on hard substrate objects on or near the EEZ sea floor are the high currents and turbulence occurring around these objects, causing their predators to be swept away, whereas the mussels remain attached (P. Herman, pers. comm.), but this merits further investigation. In general, why sublittoral blue mussel beds are present on offshore hard substrate, but not on the open sea floor, is a question that deserves more investigation. Also, to find out whether cultivation of mussels in particular areas may locally assist mussel bed formation (see par. 2.3.5).

2.3.5 Habitat formation, ecosystem function and commercial value

According to the OSPAR Commission (2015), *M. edulis* beds on mixed or sandy sediments are defined by a cover of at least 30%. The mussels bind the substratum and numerous infaunal and epibiota organisms are associated with these beds. Following the EUNIS classifications, mussel beds can be categorized into distinct habitat subgroups according to their sedimentologic surroundings. For example, mussel beds can be found on either littoral sand (EUNIS code: A2.7211) or mixed substrata (EUNIS code: A2.7212). EUNIS 2008: A5.625 Mytilus edulis beds on sublittoral sediment (Tillin & Mainwaring, 2016).

The presence of sometimes extensive beds together with the high filtering capacity leads to the accumulation of large amounts of silt/mud/sand and allows intertidal beds to keep up with sea level rise induced by climate change (OSPAR Commission, 2015). This trapping of sediment particles also improves the water quality significantly. Furthermore, the beds may reduce coastal erosion by stabilizing the sediment with the byssus threads and locally altering the flow conditions.

Mussel beds provide a habitat for a diverse sublittoral community. Numerous species find refuge in these beds or seek for food by for example benefitting from the organic material deposited by the mussels. (Dittmann, 1990) and (Asmus, 1987) recorded 41 and 96 related species in beds of M. edulis, respectively. Seaweeds, such as *Fucus vesiculosus*, can attach to the mussels and the mussels themselves are typically encrusted with epifauna organisms such as barnacles (*Semibalanus balanoides, Elminius modestus or Chtamalus spp*). The mussels themselves also serve as important food sources for several species of higher trophic level, such as seabirds (Sukhotin et al., 2008).

M. edulis has been harvested for human consumption for centuries and to date the species has a substantial contribution to the global bivalve aquaculture production. In new offshore integrated farming strategies, offshore mussel cultivation in marine coastal zones and wind farms is a promising prospect, from a production perspective but also from a nature enhancement perspective. (Bridger et al., 2022) argue that an offshore mussel farm in a UK bay has positive effects on neighbouring marine nature. Among others, the sea floor in the cultivation area appears to be enriched by mussel clumps which fall down from the growing lines in the upper water column. Possibly, such mussel clumps could function as reef starting points for other species, such as flat oysters. Obviously, location, design and management of the mussel farm should be such that it will not have a negative impact (such as anoxia near the sea floor due to local eutrophication) on the local ecosystem .

2.3.6 Current status of mussel bed distribution

A sublittoral mussel bed was recently found in the Voordelta (Kamermans et al., 2022), in an area which is relatively sheltered and without bottom trawling activity. It is unclear why this mussel has not (yet?) disappeared due to predation. In any case, circumstances are less harsh there than in the offshore EEZ, so it cannot be expected that this occurrence can be extrapolated to the open EEZ sea floor. Mussel presence on the scour protection in a wind farm may contribute to local biodiversity enhancement, but will most probably remain restricted to these hard-substrate locations.

2.3.7 Monitoring and research on current reef locations

2.3.7.1 National research and data collection

Numerous monitoring initiatives are in operation to evaluate the location, extent, and quality of mussel beds in intertidal areas of The Netherlands, in relation with the National Statutory Research Tasks (WOT) for fisheries. In line with the expectation that they cannot be established on the open sea floor, there are no surveys of offshore mussel beds in the EEZ.

2.3.7.2 Project monitoring

There are no mussel cultivation or mussel bed restoration projects in the EEZ, hence there is no monitoring either. Pilot projects for aquaculture in or near the Voordelta area are being planned to start this or next year, by the Dutch mussel grower association (PO Mossel) and the companies Krijn Verwijs and OOS. In all cases, the effects on marine nature will be monitored and reported (pers. comm. A. Risseeuw, C. Verwijs and P. Kamermans, 2023).

2.3.7.3 Restoration pilots

No restoration pilots are taking place in the EEZ, see above.

2.3.7.4 International research and data collection

In other North Sea countries, sublittoral mussel bed monitoring has been taking place (see par. 2.3.3).

2.3.8 Knowledge gaps

The main knowledge gap concerning mussel beds is the extent in which offshore mussel cultivation would enhance marine nature and possibly also reef formation by other species. This knowledge gap will be gradually filled in once the planned projects in or near the Voordelta have been started.

Secondary knowledge gaps regard the mechanisms behind the existence of a sublittoral mussel bed in the Voordelta and the role which mussels on wind farm scour protection or other hard substrate on the seabed may play in the local ecosystem.

2.3.9 Threats, impacts and opportunities

Since North Sea offshore mussel beds are not likely to occur on the open sea floor of the EEZ, there are no particular threats. The main opportunity lies in biodiversity enhancement by mussel cultivation in or near the borders of the EEZ, such as the Voordelta area.

2.3.10 Potential success of measures

See par. 2.3.9.

3 Annelid worms

3.1 Lanice conchilega

3.1.1 General description

The sand mason worm *Lanice conchilega* (see fig. 3.1 below) is a tube forming polychaete worm species found in both inter- and sub-tidal environments of the Atlantic and Pacific Ocean and is observed along the entire European shore, except for the Arctic region (Callaway et al., 2010). Generally, the worm has a length of around 30 cm (but can be up to 65 cm long) from which 1-4 cm of the anterior end rises above the sediment of the seabed (Ager, 2008; Callaway et al., 2010). The worms construct a tube, with a diameter of around 0.5 cm and a length of up to 70 cm (Gruet, 1982), from sand and small shell fragments, with an inner organic layer which keeps the tube together (Callaway et al., 2003) and (Callaway et al., 2010). The body of the worm consists of 150-300 segments and an additional 17 chaetiger segments in the frontal region. Additionally, the species is characterized by three pairs of gills and a yellow/pink/brownish appearance (Ager, 2008).

FIGURE 3.1 SAND MASON WORM REEF (*LANICE CONCHILEGA*) OFFSHORE FROM DEN HELDER (PHOTO: OSCAR BOS, WAGENINGEN MARINE RESEARCH).

The Sand mason worm can change its feeding behaviour depending on available food and intraspecific competition. The species can both act as an active suspension/filter feeder and surface deposit feeder. At low densities, surface deposit feeding is likely to be the dominant feeding mechanism, but at higher densities the worm will trap suspended material (plankton and detritus) from the water column by the fringe end at the top of the tube, which resembles a crown of white tentacles (Ager, 2008). Individuals are of separated sex. Juvenile recruitment varies with the years depending on environmental conditions (Callaway et al., 2010). The spawning season is a little unclear, but larvae peaks are observed between April and October, with a pelagic larval stage of approximately 1-2 months. Depending on the hydrographical regime, this may cause a large larval dispersal potential

(Ager, 2008). Larvae preferably settle on existing aggregations close to their adults due to hydrodynamic alterations caused by the biogenic mounds (Rabaut et al., 2009). The species has an overall life span of around 1-2 years (Beukema et al. 1978, Callaway et al. 2010).

3.1.2 Legislative and policy context

In the Netherlands, *Lanice conchilega* is not protected. However, it is a typical species for H1110 and H1140 under the Habitat Directive and there is an environmental target to restore biogenic reef building species under the MSFD (see table 3.1).

TABLE 3-1 (INTER)NATIONAL LEGAL AND POLICY INSTRUMENTS AND THEIR APPLICABILITY FOR *LANICE CONCHILEGA* ("YES" = RELEVANT; "NO" = NOT RELEVANT).

Instrument	Description	Lanice
International		
Habitats Directive (HD) Annex 1	In the Netherlands, *Lanice* reefs are not yet considered to be part of HD habitat type H1170 reefs (Ministerie LNV, 2014). To change this, the Dutch definition of the habitat type H1170 (Ministerie LNV, 2014) should be adapted.	No
HD Typical species	*Lanice conchilega* is a typical species for Natura 2000 habitat type H1110 (Min LNV, 2014) and H1140 ((Min LNV, 2008).	Yes
OSPAR List of Threatened and/or Declining Species and Habitats	In order to protect biodiversity, OSPAR has defined a list of 'threatened and declining species and habitats' that are in need of protection (OSPAR, 2008). *Lanice* is not on this list.	No
The EU Common Fisheries Policy (CFP)	Offshore fishery measures in MSDF and N2000 areas are established under the Art 11 of the CFP. These zones offer protection from bottom contacting fisheries. EUR-Lex – L:2023:048:TOC – NL – EUR-Lex (europa.eu). *Lanice* may profit from these closures.	Yes
National		
Dutch Nature Conservation Act (Wet Natuurbescherming)	*Lanice* is not protected under the Nature Conservation act.	No
Dutch Marine Strategy Framework	D6T5: return and recovery of biogenic reefs (Marine Strategy Part 1, 2018) (IenW & LNV, 2018)	Yes
Red List	A Red List is an overview of species that have disappeared or are in danger of disappearing from the Netherlands. Red list do not have a legal status. There is no Dutch Red List for marine benthic species, including Sabellaria.	No
North Sea Agreement	The North Sea Agreement (OFL, 2020) includes the agreements between central government and stakeholder parties about choices and policy aimed at the balance in activities in the North Sea up to and including 2030 and beyond. As part of the North Sea Agreement, species protection plans will be developed and implemented.	Yes

In summary, related to the EEZ:

- Natura 2000/Habitats Directive: *Lanice* reefs are not included within this regulatory framework for Dutch waters.
- Marine Strategy Framework Directive: D6T5: Return and recovery of biogenic reefs is a target.
- OSPAR: No targets or recommendations to protect or enhance *Lanice* reefs.

3.1.3 Distribution

L. conchilega is characterized by an amphiboreal distribution in the northeast Atlantic and can be found along the entire European coastline (except the Arctic region) even in more tropical waters (Callaway et al., 2010). It can form dense aggregations on flats of medium fine to muddy sand (Mcquillan & Tillin, 2006).

L. conchilega is one of the most frequently found species in the Greater North Sea. In the EMODnet data base (https://emodnet.ec.europa.eu/en), it occupies rank 9 in the list of the most frequent species, ranging from the tidal estuaries to the Dogger Bank and sometimes exceeding densities over 4700 ind./m^2 (Coolen et al., 2015). Highest densities in the EEZ are so far observed north of the Wadden islands, from Terschelling to the eastern limit of the Dutch section of the North Sea, including the Borkum Reef Grounds (fig. 3.2).

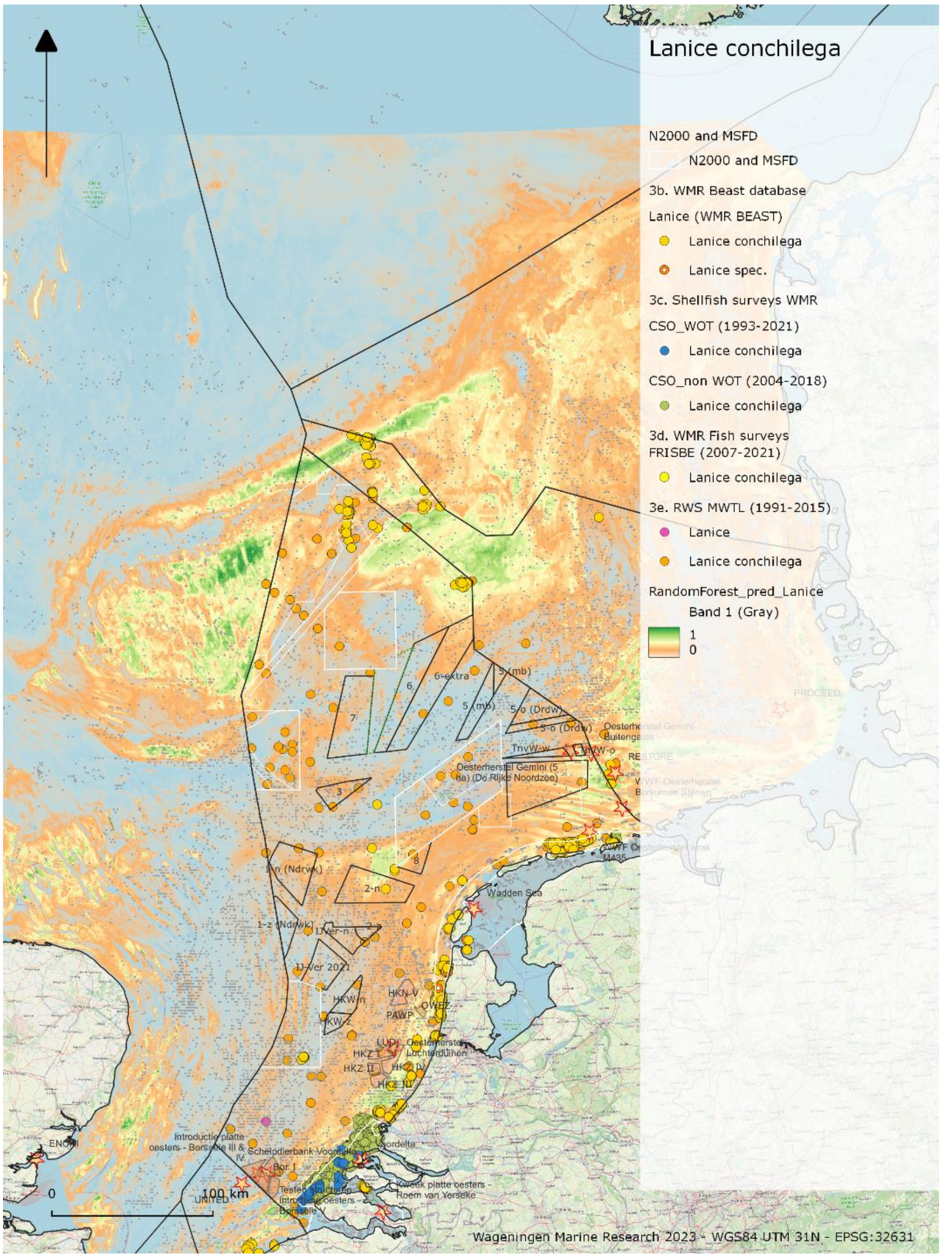

FIGURE 3.2: *LANICE CONCHILEGA*. PREDICTED HABITAT SUITABILITY (HERMAN & VAN REES, 2022) AND RECORDINGS OF OBSERVATIONS (BOS ET AL., 2023, IN PREP).

3.1.4 Habitat requirements

Sand mason worms occur on sandy and muddy seabed, often in places where seagrass and benthic algae (diatom frustules which grow on the seabed) are also found (Callaway et al., 2010).

According to Herman & van Rees (2022) *Lanice* has a clear preference for areas with a reasonably high bottom shear stress and some influence of waves. Hence, it can be found from the beach down to a few tens of meters, in sandy areas. At a relatively small scale, the distribution of the species seems to be influenced by small-scale patterns in bathymetry, where its occurrence is linked to the relief of ridges and hollows in between. The species is very tolerant to a range of water quality parameters, incl. turbulence. It is well able to withstand low salinity levels, but often occurs in fully marine environments too.

When present in high densities, sand mason worms can stabilise the seabed and reduce sediment movement, even in relatively turbulent conditions. The critical shear stress inside patches of *l. conchilega* can be more than twice that of surrounding bare sand patches and appears to be linearly dependent on the density (Rabaut et al., 2009; Van Hoey et al., 2008).

3.1.5 Habitat formation and ecosystem function

Aggregations of *L conchilega* have an impact on the near bed flow (Friedrichs et al., 2000). The lower flow velocities near the bed lower the local shear stress and hence limit erosion, while the higher turbulence above the patch increases transfer of oxygen and particulate matter towards the bed (Forster & Graf, 1995).

Whether the sand mason worm should really be regarded as a reef-building species is the subject of some debate (Callaway et al., 2010). In general, the sand mason worm fields are higher (up to 30 cm) than their environment owing to their sediment-stabilising effect. According to some definitions, dense aggregations qualify as reefs (Rabaut et al., 2009). The 'reefs' consist of individual tubes of at least 500 individuals $m^{-2,}$which (unlike *Sabellaria* reefs) do not knit together to form a hard structure. Large and dense aggregations of sand mason worms can continue to exist for several decades (Callaway et al., 2010).

Although not in the same magnitude as e.g., shellfish reefs, *Lanice* reefs are known to significantly consolidate the sediment as well as increase the species richness (with a significantly different community structure of associated fauna than in *Lanice*-free areas) and therefore are classified as real eco-engineers (De Smet et al., 2015; Rabaut et al., 2007, 2009). In that sense, it is immaterial whether *Lanice* aggregations are real ‘reefs’ or not, but nonetheless we will refer to dense aggregations as ‘reefs’ in this study.

Seabed-disturbance by natural factors, such as turbulence, or human bottom disturbance can have a strong impact on dense aggregations of *Lanice*. But these may only cause superficial destruction of the tubes above the sediment, allowing the worms to stay alive and reconstruct the tubes (Ager, 2008). That is why reefs may return after a disturbance event. However, if the disturbance happens too frequently, the worms themselves may undergo too much stress and therefore become harmed and even die (pers. comm. G. van Hoey, 2023). All in all, it is unclear whether human disturbance (including bottom trawling activities) is a decisive factor in *Lanice* reef occurrence, since the species occurs in areas with different intensities of bottom fisheries (fig. 3.2).

Offshore wind farms can have a negative impact on *Lanice* reefs at the time of their construction and also the deployment of hard substrate for e.g., scour protection can hamper reef formation. Yet, the presence of wind farms in the Belgian section of the North Sea appears to have had a positive impact, primarily in the vicinity of construction foundations (Coates et al., 2014).

3.1.6 Monitoring and research on current reef locations

3.1.6.1 National research and data collection

There is no specific monitoring targeting *Lanice* in the Netherlands. However, the species is recorded in MWTL/MSFD benthos sampling and when encountered in annual shellfish or fish surveys (WOT) (see Bos et al. 2023, in prep and Table 3.1). Since *Lanice* reefs are surface structures on the sea floor, with strongly varying density, localized bottom sampling (including fishery) does not lead to adequate mapping of reef dimensions. Modern scanning techniques (SONAR-based), combined with ground truthing, will therefore deliver a much better impression of the occurrence of *Lanice* reefs and therefore can be employed for mapping these in the EEZ (Degraer et al, 2008). However, this should not be undertaken just for mapping purposes, but to answer specific research questions, such as the difference in reef formation and its ecosystem function in trawled versus non-trawled areas.

A survey of biogenic reefs, including *Lanice*, with such modern techniques is currently planned in the MONS program (action ID56), to be executed in 2023. Given the remark above, the best strategy is to formulate the most relevant research questions first and then define areas where such mapping could lead to added value in terms of understanding habitat requirements and ecosystem function of *Lanice*.

3.1.6.2 Project monitoring

Since the species is already omnipresent in the EEZ, there is no need for active restoration. Possibly, more reefs will be formed in areas where bottom trawling is prohibited, so that a monitoring strategy as outlined in par. 3.1.6.1 could lead to added value.

Possibly, *Lanice* reef data are recorded during routine sea floor surveys aimed at planning and maintaining offshore wind farms, whereas these data are not analysed for the purpose of identifying/mapping biogenic reefs. It may be worthwhile to investigate whether this is the case and if so, whether these can still be analysed and used for *Lanice* reef mapping.

3.1.6.3 Restoration pilots

In Belgium, some pilot studies targeting restoration of *Lanice* were undertaken, but with inconclusive effects (see Coastbusters, 2020). But, as stated above, there is no need for active restoration in the EEZ.

3.1.6.4 International research and data collection

There is no harmonised international North Sea research and data collection on *Lanice*, see table 3.2. There is much more attention to *Lanice* reefs in the Belgian North Sea, where both sea floor surveys and habitat suitability mapping have led to a good impression where *Lanice* reefs are located and where there is potential for more development if bottom disturbance is curtailed (Pecceu et al., 2021).

TABLE 3.1: OVERVIEW OF NATIONAL AND MONITORING PROGRAMS AND (INTER)NATIONAL STATUS ASSESSMENTS FOR *LANICE CONCHILEGA*.

National monitoring programs and status assessments	**Species/habitat**
National Water Systems Monitoring Program (MWTL monitoring) (this is MSDF/Natura 2000 monitoring under Dutch Marine Strategy part 2)	Not specifically
Monitoring Research-Nature restoration-Species protection (MONS monitoring)	Biogenic reef survey programmed for 2023
Statutory Research tasks (WOT) and Policy Support tasks (BO) monitoring	Not specifically
Offshore wind ecological program (WOZEP) monitoring	No (but data may be available)
(Inter)national monitoring programs and status assessments	
Habitats Directive Art. 17	No
MSDF/KRM Mariene Strategie Deel 1, 2018	No
OSPAR Intermediate Assessments 2017	No
OSPAR species/habitat status assessment	No
Trilateral Wadden Sea Cooperation	No
ICES stock assessment	No
N2000 management plan evaluation	Unknown

3.1.7 Knowledge gaps

See above: current occurrence of *Lanice* reefs as well as the potential for these to return in areas where human-induced sea floor disturbance is curtailed are not very well known, although neither the species nor the reef structures are particularly rare. The potential area (based on statistical models) where the species may be able to sustain reef structures is relatively large in comparison to most other reef builders (Herman & Van Rees, 2022). Monitoring with modern scanning techniques (plus ground truthing) may help to close these knowledge gaps.

3.1.8 Threats, impacts and opportunities

The protection of *Lanice* reefs is not regulated within the Natura2000/Habitats Directive in the Netherlands, so that these have no formal protection status in the EEZ. Hence, an opportunity is to include *Lanice* reefs in this regulatory framework.

As stated in par. 3.1.5, it is unclear whether human disturbance (including bottom trawling activities) is a decisive factor in *Lanice* reef occurrence.

As mentioned in par. 3.1.6, a biogenic reef survey is already planned in the MONS program and should aim at answering relevant research questions, such as the difference in reef formation and its ecosystem function in trawled versus non-trawled areas. Another opportunity is to investigate whether existing or future wind farm survey data can be employed for *Lanice* reef mapping.

3.1.9 Potential success of measures

Since the species is present in large amounts (see par. 3.1.3), it is generally assumed that there are still enough larvae in the North Sea water to cause reef formation if conditions are adequate. Hence, no measures at all are needed to secure the abundant occurrence of the species. Whether its presence will increase or decrease after cessation of intensive bottom-trawling fisheries, is an interesting question that can be answered by monitoring governmentally closed areas and wind farms versus trawled areas.

3.2 *Sabellaria spinulosa*

3.2.1 General description

Sabellaria spinulosa (Ross worm, fig. 3.3) is a tube forming polychaete worm species found in subtidal environments and occasionally in the lower intertidal with an average size between 3-10 cm. The tube with a circular cross section consists of cemented sand and shell grains and can be enclosed by an operculum made up by bristles from the worm's head. The species' most defining characteristics are three thoracic segments with paired chaetal sheaths, distally pointed opercular chaetae, and an outer layer of serrated chaetae (Jackson & Hiscock, 2008).

Figure 3.3: Ross worm, *Sabellaria spinulosa, in UK waters* (Photo: Oscar Bos, Wageningen Marine Research).

The Ross worm is an active suspension/filter feeder, trapping plankton and other detritus material with its tentacles from the water column. Individuals are of separated sex. Spawning season is a little unclear, but peaks are observed between January and March, with a larval stage of approximately 1-2 months and a dominant settlement period in March (George & Warwick, 1985; Jackson & Hiscock, 2008; Wilson, 1971). The species requires a location with hard substrate/material for the settlement and relatively high amounts of sand moving in the water above the sea floor, hence at locations with relatively high shear stress on the sea floor. It prefers spots that are presently in use or have been previously used by the species. Other frequently chosen settlement sites are on *Pecten maximus* and *Buccinum undatum* and sometimes on *Aequipecten opercularis*. Once settled, the species can survive up to about 2-5 years (Jackson & Hiscock, 2008).

The worms develop tubes independently. When there is little competition for space, the tubes will attach to the substrate over their whole length. However, at denser clumps space is scarce and tubes will coalesce and grow vertically outwards from the substrate forming a crust on the seabed

(Jackson & Hiscock, 2008). Over the majority of its distribution range the species does not build reefs and is found in small groups or individually. At certain places extensive reefs can form of several hectares wide and to around 60 cm high. This leads to an elevated seabed compared to the surroundings. Despite the fact that individual aggregations may frequently form and collapse, the reefs themselves can remain in a region for many years (Jackson & Hiscock, 2008; OSPAR, 2013). It is classified as a typical species for habitat type H1170 ('open-sea reefs') under the Habitats Directive/Natura 2000 (Annex A-2).

S. spinulosa is most sensitive to substrate loss or displacement. If the worms are detached, they cannot form a new tube or find a new location to attach. No specific sensitivity or vulnerability is recorded with regards to changes in water quality and chemicals (Holt et al., 1998; Jackson & Hiscock, 2008). Physical damage appears to potentially affect the reefs the most, with damage coming from activities such as dredging, trawling, net fishing, potting, and the installation of infrastructure (OSPAR Commission, 2013). However, the species is considered an r-strategist, i.e. its recoverability potential is considered high due to its fast recolonization potential. This is in line with reef occurrence at locations where disturbances take place regularly such as storms and pollution (OSPAR Commission, 2013).

3.2.2 Legislative and policy context

In the Netherlands, *Sabellaria spinulosa* is not protected. However, there are incentives to protect and restore the species, because *Sabellaria spinulosa* is a typical species for H1110 under the Dutch implementation of the Habitat Directive, it is mentioned as a reef building species for H1170 in the Interpretation Manual of EU habitats (https://eunis.eea.europa.eu/references/2435), it is on the OSPAR list and there is an environmental target to restore biogenic reef building species under the Dutch implementation of the MSFD (Table 3.2).

TABLE 3.2 (INTER)NATIONAL LEGAL AND POLICY INSTRUMENTS AND THEIR APPLICABILITY FOR *SABELLARIA SPINULOSA* ("YES" = RELEVANT; "NO" = NOT RELEVANT).

Instrument	Description	Sabellaria
International		
Habitat Directive (HD) Annex 1	In the Netherlands, *Sabellaria* reefs are not yet considered to be part of HD habitat type *H1170* reefs (Ministerie LNV, 2014).	No
HD Typical species	*Sabellaria* is a typical species for Natura 2000 habitat type H1110 (Ministerie LNV, 2014).	Yes
OSPAR List of Threatened and/or Declining Species and Habitats	In order to protect biodiversity, OSPAR has defined a list of 'threatened and declining species and habitats' that are in need of protection (OSPAR, 2008). *Sabellaria spinulosa* is on this list.	Yes
The EU Common Fisheries Policy (CFP)	Offshore fishery measures in MSDF and N2000 areas are established under the Art 11 of the CFP. These zones offer protection from bottom contacting fisheries. EUR-Lex - L:2023:048:TOC - NL - EUR-Lex (europa.eu). *Sabellaria* may profit from these closures.	Yes
National		
Dutch Nature Conservation Act (Wet natuurbescherming)	*Sabellaria* is not protected under the Nature Conservation act.	No
Dutch Marine Strategy	D6T5: return and recovery of biogenic reefs (Marine Strategy Part 1, 2018) (IenW & LNV, 2018)	Yes?
Red List	A Red List is an overview of species that have disappeared or are in danger of disappearing from the Netherlands. Red list do not have a legal status. There is no Dutch Red List for marine benthic species, including *Sabellaria*.	No
North Sea Agreement	The North Sea Agreement (OFL, 2020) includes a paragraph (4.35) describing the need to investigate occurrence and protection of *Sabellaria* reefs.	Yes

In summary, related to the EEZ:

- Natura 2000/Habitats Directive: *Sabellaria* reefs are not included within this regulatory framework for Dutch waters.
- Marine Strategy Framework Directive: D6T5: Return and recovery of biogenic reefs is a target.
- OSPAR: It is recommended to protect *Sabellaria* reefs.
- North Sea Agreement: the occurrence and need for protection of *Sabellaria* reefs will be investigated.

3.2.3 Distribution

In their main area of distribution, mostly along the S-E English coasts, the species is found very frequently in samples. However, the localization of dense aggregations remains more difficult, due to describe their continuously changing structure. The temporal instability of the reefs would require frequent monitoring in order to adequately map it (OSPAR Commission, 2013). Yet, this does not seem to be a high priority, given the sustained and predictable presence of the species, which ranks 49 in the list of most frequently found species in the Greater North Sea (Emodnet database; https://emodnet.ec.europa.eu/en). This is within the top 2% of all species.

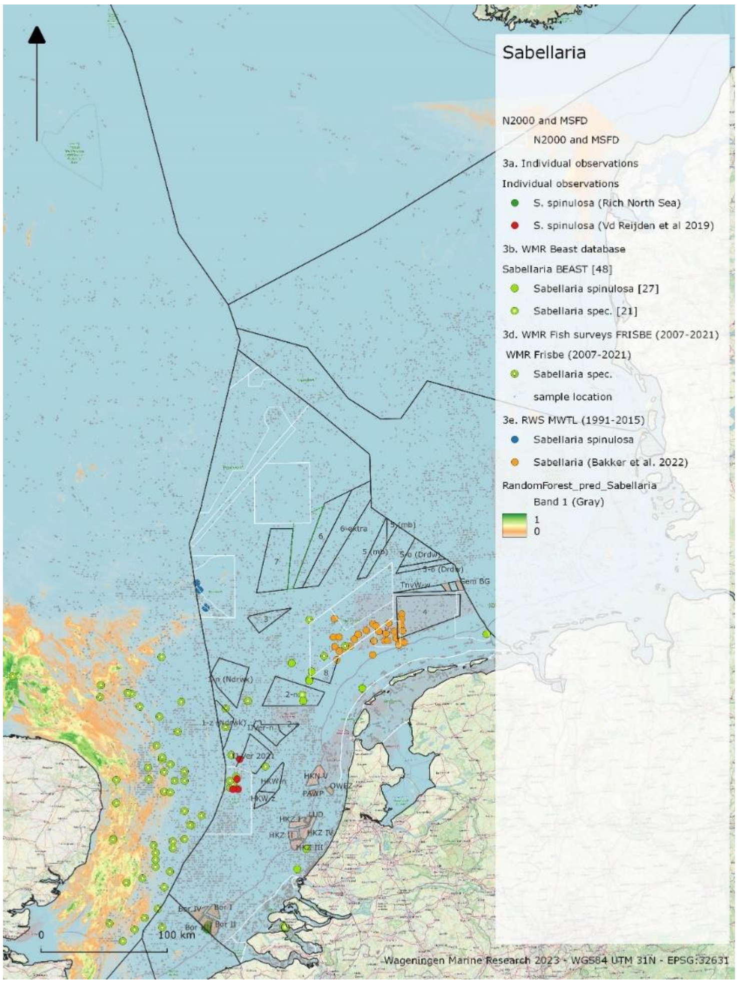

FIGURE 3.4: *SABELLARIA SPINULOSA*. PREDICTED HABITAT SUITABILITY (HERMAN & VAN REES, 2022) AND RECORDINGS OF OBSERVATIONS. RECORDINGS IN THE EEZ ARE MOSTLY ON ARTIFICIAL HARD SUBSTRATES (BOS ET AL., 2023, IN PREP).

The species is widely distributed along almost all European coasts and in the open sea, either in reef form or as individuals. The occurrence of dense aggregations in the form of reefs is however scarce and restricted to areas with high turbidity and sufficient supply of sand. In line with this, the preferences of the species are guided by high bottom shear stress and high gravel content of the sediment (Herman & Van Rees, 2022). Dense aggregations of *S. spinulosa* have been observed in the UK and the southern North Sea (OSPAR Commission, 2013). Habitat suitability modelling shows that the most suitable areas are indeed along the UK coast (Herman & Van Rees, 2022). See Figure 3.44.

In the EEZ, reef formation of the species is less common (Van Duren et al., 2017), but reefs are also found at the Brown Bank and possibly in the Frisian Front (van der Reijden et al., 2019); https://www.nioz.nl/en/blog/niozatsea-north-sea-expediton-22-29-oktober-2019). A recent survey (Bakker et al., 2023) confirmed *Sabellaria* presence in the Frisian Front and in the area to the south of it, attached to *Spisula* shells. It is not clear whether this constitutes a sufficiently dense aggregate to function as reef.

Small patches are also found on artificial structures in the EEZ (Bos et al., 2019). *Sabellaria* has already been encountered as a 'monitoring bycatch' in Borssele offshore wind farm at flat oyster restoration sites (R. Olie per com; Bos et al., 2023, in prep). These can be favorable places for the formation of new reefs in an otherwise mostly sandy environment, which will allow larvae of *S. spinulosa* to attach. Additionally, the rigid structures will enhance local scouring that increases bottom shear stress and makes mobile sand available for the worms to build reef structures (Herman & van Rees, 2022b).

3.2.4 Habitat requirements

S. spinulosa appears to need some hard substrate (a few rocks or shells) if it is to start forming a reef, but thereafter the structures are able to convert sandy substrate into hard, three-dimensional substrate (Maddock, 2008b).

For reef formation *Sabellaria* appears to require relatively high levels of suspended sediment (Callaway et al., 2010; Davies et al., 2009; Maddock, 2008b). This agrees with the results of (Herman & Van Rees, 2022) who found that in contrast to most other reef building species, *Sabellaria* was positively correlated with high levels of bed shear stress, which is required to resuspend sediment. According to (Davies et al., 2009) a minimum of 20 g/m^3 of suspended solids is required for these worms to initiate reef building. There are not many surface waters along the Dutch coast where this is the case (Pietrzak et al., 2011), but there are areas where high concentrations of suspended materials are transported over the seabed (Van der Hout et al., 2015). Even in areas where average near-bed concentrations are low, there may be local conditions (as in the vicinity of the scour protection of wind turbines; see par. 3.2.3) where locally enhanced turbulence occurs and the situation may be suitable. UK studies concerning oil and gas exploration platforms in the southern part of the North Sea have shown that *Sabellaria* reef structures are regularly found around pipelines and other oil and gas infrastructure structures (Spence, 2015). (Pearce et al., 2014) describe *Sabellaria* occurrence in a UK wind farm.

3.2.5 Habitat formation and ecosystem function

Sabellaria reefs are widely seen as important eco-engineers which add topographical complexity and biodiversity to the North Sea environment (Braeckman et al., 2014; Dubois et al., 2006; Pearce et al., 2012). Control factors have been identified which could facilitate reef formation by this species (see par. 3.2.4 and 3.2.4), and the reef structures have been identified as fostering biodiversity.

3.2.6 Monitoring and research on current reef locations

3.2.6.1 National research and data collection

There is no specific regular monitoring targeting *Sabellaria* in the Netherlands. However, the species is recorded when encountered in annual governmental shellfish or fish surveys (WOT) and benthos surveys. (MWTL/MSFD) (see Bos et al. in prep). The species is also encountered during WMR-bycatch monitoring at sea by fishermen, but is not recorded, since it is not considered to be of interest. Furthermore, the species is encountered during RWS monitoring in the North Sea, but until so far it was not included in the survey protocol (Bakker et al. ,2023).

Since *Sabellaria* reefs, similar to *Lanice* reefs, are surface structures on the sea floor, the same considerations and techniques as for the latter are relevant here (see section 3.1.6.1) and the surveys of biogenic reefs planned in MONS (actions ID46, ID49 and ID55) therefore also should include *Sabellaria*. Again, this should not be undertaken just for mapping purposes, but to answer specific research questions, such as the difference in reef formation and its ecosystem function in trawled versus non-trawled areas, with focus on those areas where natural *Sabellaria* occurrence is already observed, such as in the Brown Bank, the Frisian Front and the area to the south of the Frisian Front (see par. 3.2.3).

3.2.6.2 Project monitoring

There have been a number of small monitoring projects in the EEZ, targeting *Sabellaria* by NIOZ (Vrooman, 2019) and WMR (J. Coolen pers. com) after the discovery of *Sabellaria* reefs in the Brown Bank area during the 2017 Oceana expedition (Van der Reijden et al., 2019). Besides, monitoring was performed in a UK offshore wind farm, as described by e.g. (Pearce et al., 2014).

Furthermore, there are various benthic sampling projects during which the species is recorded when encountered (e.g. WMR BEAST database). As is mentioned for *Lanice* in par. 3.1.6.2, routinely collected sea floor data in wind farms may reveal *Sabellaria* reef data and could be checked for this.

3.2.6.3 Restoration pilots

Active restoration attempts by introducing the species have not been made in the North Sea and are also not necessary, given the widespread occurrence of *Sabellaria* in the EEZ. Yet, given the positive effects of both hard substrate and turbulence in offshore wind farms, *Sabellaria* is of interest for habitat restoration. Testing suitable substrate to enhance *Sabellaria* settlement and growth under North Sea conditions is part of the EU-project ULTFARMS (P. Kamermans, pers. comm. 2023).

3.2.6.4 International research and data collection

There is no harmonised international research and data collection on *Sabellaria*. However, OSPAR assessments are made for *Sabellaria* (OSPAR, 2010) and individual national datasets are combined by OSPAR to create distribution maps (https://jncc.gov.uk/our-work/marine-habitat-data-product-ospar-threatened-andor-declining-habitats/). See Table 3.3.

Table 3.3: Overview of national and monitoring programs and (inter)national status assessments regarding *Sabellaria spinulosa*.

National monitoring programs and status assessments	**Species/habitat**
National Water Systems Monitoring Program (MWTL monitoring) (this is MSDF/Natura 2000 monitoring under Dutch Marine Strategy part 2)	Not specifically
Monitoring Research-Nature restoration-Species protection (MONS monitoring)	Planned
Statutory Research tasks (WOT) and Policy Support tasks (BO) monitoring	Not specifically
Offshore wind ecological program (WOZEP) monitoring	No
Project monitoring: WMR (Coolen, pers. com) and NIOZ projects (Vrooman, 2019)	Yes
(Inter)national monitoring programs and status assessments	
Habitats Directive Art. 17	No
MSDF/KRM Mariene Strategie Deel 1, 2018	No
OSPAR Intermediate Assessments 2017	No
OSPAR species/habitat status assessment	Yes
Trilateral Wadden Sea Cooperation	No
ICES stock assessment	No
N2000 management plan evaluation	No

3.2.7 Knowledge gaps

Since there is no systematic *Sabellaria* investigation of artificial hard substrates, *Sabellaria* is mainly found due to accidental discoveries (Van der Reijden et al., 2019). "*Our data suggests that dedicated surveys should focus on sandbank trough areas with low fishing pressures and an average grain size of 350µm. In* particular*, efforts should be focussed on the small-scale refuge areas located in sand waves valleys, which unfortunately cannot be predicted by fishing intensity maps alone. Areas prohibited for fisheries, like safety zones around oil platforms and offshore wind farms could also form a useful focus for future studies*" (Van der Reijden et al., 2019). Existing research programmes do not always take *Sabellaria* into account, although they are sampled (e.g. bycatch of fisheries by WMR; sampling by Rijkswaterstaat).

Hence, as with *Lanice*, seabed-disturbing activities (bottom trawling, sand and gravel extraction, dredging and construction work etc.) which compromise the integrity of sea floor can be a threat to *Sabellaria* reef formation. Even though the species is able to recover relatively fast after a disturbance event. Curtailing such activities in parts of the EEZ areas where *Sabellaria* may find natural conditions conducive to reef formation, such as the Brown Bank, the Borkum Reef Ground and possibly the Frisian Front and its neighbouring area, could therefore have a positive influence on *Sabellaria* reef formation. Also, the construction of offshore wind farms will probably have a positive impact on *Sabellaria* reef formation, due to the triple effect of absence of bottom disturbance (after construction has taken place), the addition of hard substrate and the scouring around structures on the seabed, causing extra sediment suspension. This can be investigated by monitoring (with SONAR techniques or otherwise) in those areas.

Under the MONS programme, a first step could be to analyse existing side scan and multibeam SONAR data of Rijkswaterstaat that cover up to 50% of the EEZ (J. Asjes, pers. com.) for the presence of habitats such as *Sabellaria* reefs. Possibly, SONAR data by other parties, such as wind farm operators, can be analysed for this purpose too.

3.2.8 Threats, impacts and opportunities

The protection of *Sabellaria spinulosa* reefs is not regulated within the Natura2000/Habitats Directive in the Netherlands, so that these have no formal protection status in the EEZ. Hence, an opportunity is to include *Sabellaria spinulosa* reefs in this regulatory framework.

As mentioned earlier, a biogenic reef survey is planned in the MONS program. This is an important step to become more acquainted with *Sabellaria* presence and its reef formation condition, in particular in trawled versus non-trawled areas with a natural occurrence such as the Brown Bank and possibly also the Frisian Front. Another opportunity is to investigate whether existing or future wind farm survey data can be employed for *Sabellaria* reef mapping.

3.2.9 Potential success of measures

Since the species is still present in large amounts (see par. 3.2.3), it is generally assumed that there are still enough larvae in the North Sea water to cause establishment of reefs if conditions are adequate. As with *Lanice* it is not completely clear what these conditions are, although relatively more is known for *Sabellaria* (see par. 3.2.4). In particular, the addition of hard substrate and the scouring around structures on the seabed, causing extra sediment suspension, may have a positive effect on reef formation.

Yet, as with *Lanice*, the extent in which reefs will autonomously re-occur in areas where bottom disturbance is curtailed is not clear, so that it is important to monitor the possible re-establishment of *Sabellaria* reefs in areas where human bottom disturbance is banned (such as nature protection areas and wind farms) and where *Sabellaria* reefs may have a natural occurrence.

4 General discussion and recommendations

Differences in relevance and reef-forming potential

The species characteristics described in Chapters 2 and 3 show that an important distinction can be made concerning their reef-forming abilities:

The annelid worms (*Sabellaria spinulosa* and *Lanice conchilega*) and blue mussels (*Mytilus edulis*) are already present to such extent that active restoration will not be required for these species.

Sabellaria spinulosa and *Lanice conchilega* will probably return to a greater extent and may even form reefs on the North Sea bottom in those areas where human disturbance is removed and where the habitat it suitable. For *Sabellaria*, the best conditions in the EEZ will probably be in the Brown Bank. Also, the construction of wind farms will probably constitute opportunities for small *Sabellaria* reef aggregations, in particular in or near scour protection. For *Lanice*, the extent of suitable area may be larger, since it is better adapted to the overall conditions of the EEZ, including bottom trawling.

Flat oysters (*Ostrea edulis*) will most probably not (within a foreseeable timespan) form reefs on their own account but will need a starting population and further enhancement measures, such as the deployment of clean substrate at the time when larvae are in the water. A survey of the projects undertaken with flat oysters starting populations imported from very different areas shows that the general environmental conditions in the North Sea, also beyond the borders of the EEZ, are still suited for the oysters to survive, grow, and reproduce. However, the re-creation of self-sustaining or autonomously growing reefs on the North Sea bottom, which is the ultimate restoration objective, requires a stable start population on the sea floor with local recruitment and these requirements are not yet fulfilled.

Knowledge gaps

There are various knowledge gaps concerning the annelid worms, in particular concerning their reef-forming potential: it is still not very well known which are the exact conditions for these reefs to become re-established, so it remains to be seen whether the areas where human bottom disturbance is or will become abolished are adequate for reef formation. Also, it is not certain, whether some interventions (such as supplying substrate) may significantly speed up (*Sabellaria spinulosa*) or hamper (*Lanice conchilega*) reef formation.

Why sublittoral blue mussel beds are present on offshore hard substrate, but not on the open sea floor, is a question that deserves more investigation. Also, to find out whether cultivation of mussels in particular areas may locally assist mussel bed formation.

For flat oysters, there are key knowledge gaps on a wide range of reef restoration aspects:

- How to enhance recruitment during population initiation, given the strong currents and turbulence in a substantial part of the EEZ.
- The minimum size of a flat oyster reef which is required to cause substantial recruitment within the reef area in offshore conditions, and the effect of settling stimulation measures on recruitment and therefore also on minimum reef size.

- How to avoid a start population becoming buried in the sea floor, or widely spread, again given currents and turbulence in a substantial part of the EEZ, with the loose (sandy/silty) sea floor as extra negative factor.
- The overall understanding of the conditions suitable for offshore flat oyster reef formation/restoration is still limited, since it is largely derived from historical information (when the reefs were still present). The presence of oyster reefs influences local conditions, conducive to survival and/or growth of these reefs. Hence, it is understood only roughly where the best reef formation/restoration conditions are located in the present situation (being without the reefs).
- Detection of flat oyster recruitment in the turbulent, dark and often turbid North Sea bottom region is very hard, so that monitoring the potential success of reef restoration attempts is handicapped.
- Specifically related to production in hatcheries (as such being the most appropriate method for large-scale seed oyster production): the reliability is still low, due to sudden larval mortality incidents, whereas the causes for this phenomenon are largely unknown.

Recommendations

None of the species, or their reefs/beds, described in this report are currently directly protected within the Dutch implementation of the Natura2000/Habitats Directive. Yet, the Dutch implementation of the Marine Strategy Framework Directive does include biogenic reefs. Hence, it is recommended to include these species and their reefs/beds more consistently in these regulatory frameworks.

A biogenic reef survey is planned in the MONS program. It is recommended to select specific areas where the natural conditions for these reefs are probably suited and to monitor the effect of curtailing bottom disturbance there. Possibly, already existing bottom survey SONAR data (by Rijkswaterstaat, wind farm operators or others) can be analysed for reef presence too. It is also recommended to improve habitat suitability models on the basis of such monitoring data.

For flat oyster reef restoration, an integrated research and development program for the North Sea offshore situation is recommended, which builds on the current projects and programmes which are characterized by learning-by-doing as well as fundamental research (such as the overarching The Rich North Sea program), but which has a larger scale and a stronger overall coordination. At least, it should contain the following elements:

- Development of adequate restoration techniques, applicable on a sufficiently large scale to create self-sustaining flat oyster reefs.
- Improved habitat suitability modelling, to better understand the conditions required for the formation and/or restoration of these reefs in the current situation.
- In selected areas with strong spatial heterogeneity, such as the Borkum Reef Grounds: better mapping of the sea floor habitat, to investigate where appropriate conditions for reef restorations may exist.
- Development of monitoring techniques which allow detection of recruitment.

- Research and development to improve the reliability of flat oyster production in hatcheries.

This programme should also lead to the operationalisation of the agreement by the North Sea Platform (‘Noordzee Overleg’), to create 100 km^2 flat oyster reef in the Frisian Front.

There may be other species or species groups which form reefs or support reef formation, such as hydroids, but this is largely unknown. More research into such species will lead to a better understanding and description of their potential role in biogenic reef formation in the North Sea.

For the comprehensive monitoring, research & development actions described above, it is also recommended to cooperate more intensively with other North Sea countries, since the ecosystem does not stop at borders and since there are various related projects and programmes being undertaken in the other North Sea countries. Besides, there is a common policy context with most North Sea countries, such as the Habitats Directive, the Marine Framework Strategy Directive and the prospective EU Nature Restoration Law.

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