Suitability for the development of flat oyster populations in new offshore wind farm zones and two search areas for restoration projects in the Dutch section of the North Sea.

Suitability for the development of flat oyster populations in new offshore wind farm zones and two search areas for restoration projects in the Dutch section of the North Sea.

Author(s)
Luca van Duren[1]
Pauline Kamermans[2]
Frank Kleissen[1]

[1]Deltares
[2]Wageningen Marine Research

Dit onderzoek is uitgevoerd door Deltares en Wageningen Marine Research en gesubsidieerd door het Ministerie van Landbouw, Natuur en Voedselkwaliteit, in het kader van het Beleidsondersteunend onderzoekthema 'Duurzame voedselvoorziening & -productieketens & Natuur' (projectnummer BO-43.116.01-016)

Photo cover: Oscar Bos

Suitability for the development of flat oyster populations in new offshore wind farm zones and two search areas for restoration projects in the Dutch section of the North Sea.

Client	Ministry for Agriculture, Nature and Food Quality
Contact	Edo Knegtering
Reference	
Keywords	Restoration, *Ostrea edulis*, Offshore wind farms, habitat suitability

Document control	
Version	0.5
Date	11-04-2022
Project nr.	11208312-002
Document ID	11208312-002-ZKS-0001
Pages	24
Classification	
Status	final

Author(s)		
	Luca van Duren	
	Pauline Kamermans	
	Frank Kleissen	

Doc. version	**Author**	**Reviewer**	**Approver**	**Publish**
0.1	Luca van Duren	Peter Herman	Toon Segeren	
	Pauline Kamermans			
	Frank Kleissen			

Summary

The Ministry of Agriculture, Nature and Food Quality has requested Deltares and Wageningen Marine Research (WMR) to execute an assessment of areas on suitability for restoration projects of the European flat oyster (*Ostrea edulis*). The study concerns eight designated wind farm zones for wind farm development before 2030 for their suitability for nature-inclusive design projects and two areas on the Frisian Front in future exclusion zones for bottom trawling, for large-scale restoration projects for oyster reefs. The assessment was made on available information of habitat suitability for oyster reefs and dispersal models for larvae.

Of the wind farm zones, only one (Wind Farm Zone 5 East) appears to be suitable for oyster restoration purposes. This area has abiotic habitat conditions conducive to the presence of oyster reefs and good larval retention. It is located within the historic distribution area of the species. The other wind farm zones are likely unsuitable for restoration projects, in most areas the presence of mobile bed forms is inhibitive for the formation of sustainable oyster beds. Two of the wind areas may have potential for the cultivation of oyster larvae for the purpose of restoration (Wind Farm Zone 1 North and Wind Farm Zone 2 North). Larvae produced in these areas have a reasonable probability of reaching suitable habitat and serve as a source for oyster larvae. The other wind farm zones may be biologically suitable for off-bottom cultivation, but larvae are unlikely to reach suitable habitat in one dispersal event.

The two potential restoration areas in the Frisian Front area both appear to be suitable. Both have a high suitability in terms of habitat for oyster reefs, high larval retention and from both locations larvae can also reach other suitable habitat that is protected from bottom trawling (either area that is in the future exclusion zone for fishing or future wind farm areas). Based on the information available there is very little difference between these sites in terms of suitability.

Contents

1 Introduction

The flat oyster (*Ostrea edulis*) used to be a keystone species in the North Sea but is currently functionally extinct in the North Sea. The Ministry of Agriculture, Nature and Food Quality has requested Deltares and Wageningen Marine Research (WMR) to execute an assessment of areas on suitability for restoration projects of the European flat oyster (*Ostrea* edulis). The study concerns eight search areas for future wind farm development for their suitability for nature inclusive design pilots and two areas on the Frisian Front in future exclusion zones for bottom trawling, for large-scale restoration projects for oyster reefs.

1.1 Rationale

The Dutch government has the return and recovery of biogenic reef structures (such as the flat oyster) in the North Sea as an environmental target. The North Sea Programme 2022 – 2027 (Ministerie van Infrastructuur en Waterstaat et al. 2022) comprises several activities to protect biogenic reefs and to increase their probabilities of recovery (Ministerie van Infrastructuur en Waterstaat et al. 2022). This includes restoration in designated N 2000 areas as well as stimulating the reintroduction of flat oysters through nature-inclusive design options in (future) wind farms. Having prior insights into the suitability of areas for the establishment of reef structures on the bed or for cultivation of flat oysters in the water column is essential.

As part of the “North Sea Agreement”, designated areas in the no-fisheries zones on the Frisian Front will be used for oyster restoration. Recently two search areas have been indicated, both measuring 100 km^2. These two areas will be assessed on their suitability to re-establish reef structures of flat oysters on the seabed.

1.2 Locations

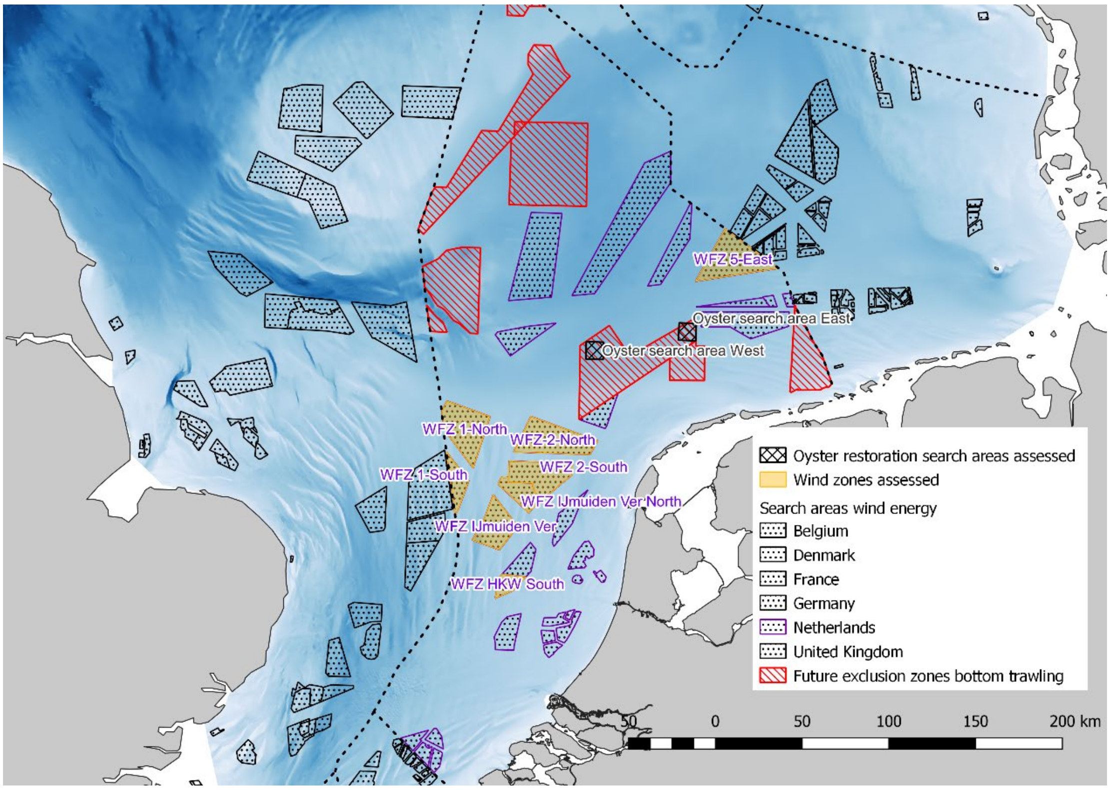

Figure 1.1: The Dutch continental shelf with the recently designated wind farm zones as well as the oyster restoration search areas indicated.

Earlier studies looked at suitability of existing and planned wind areas (Offshore Wind Energy Roadmaps 2023 and 2030) wind farm zones and virtual potential future wind energy areas (Smaal *et al.*, 2017; Kamermans *et al.*, 2018).

The new Wind Farm Zones relevant for this study are:

- 1 North
- 1 South
  2 North
- 2 South
- 5 West
- IJmuiden Ver (i.e. now the southern part of the previously designated Wind Farm Zone “IJmuiden Ver”)
- IJmuiden Ver Noord
- HKW (southern part)

These have been recently designated by means of the Programma Noordzee 2022-2027 (Ministerie van Infrastructuur en Waterstaat et al. 2022).

The two search areas for oyster restoration are located in the N 2000 area Frisian Front. In this study they are indicated as Oyster area west and Oyster area east.

The relevant areas are highlighted and named in Figure 1.1. In the “no fisheries zone” on the Frisian Front (where the two oyster search areas are located) no fishing at all will be allowed. Other exclusion zones under the North Sea agreement (indicated in red hatched areas in subsequent maps) concern the exclusion of bottom trawling, but other forms of fisheries may be allowed. Central coordinates and approximate surface areas of the different areas are given in Table 1.1.

Table 1.1: Coordinates and approximate surface area of the investigated areas

Wind search areas	**Latitude (WGS84)**	**Longitude (WGS84)**	**Surface area (km^2)**
Wind farm zone 1 North	53.4310	3.2233	592
Wind farm zone 1 South	53.1474	3.1475	201
Wind farm zone 2 North	53.2176	3.9425	644
Wind farm zone 2 South	52.9858	3.7936	514
Wind farm zone 5 East	54.2540	5.6158	643
Wind farm zone IJmuiden Ver	52.8656	3.5342	417
Wind farm zone IJmuiden Ver North	52.9858	3.6619	242
Wind farm zone HKW South	52.2740	3.6329	132
Oyster restoration search areas			
Oyster area West	53.7744	4.3429	100
Oyster area East	53.8760	5.1535	100

2 Methodology

2.1 Habitat suitability for oyster reefs

The general method of assessment is based on previous similar work (Smaal et al. 2017, Kamermans et al. 2018a, Kamermans et al. 2018b). This approach involved assessing abiotic and biotic habitat conditions that are relevant to this species. Most important habitat characteristics are:

- The presence / absence of mobile sand waves
- Bed shear stress
- Bed composition (specifically mud content)
- Depth

In these previous studies the historical presence of oyster reefs, based on the Piscatorial atlas of Olsen was also taken into account (Olsen 1883). In addition to the previous study a few extra layers were added. These include bed shear stress data from the new DCSM-FM model (Zijl et al. 2018), which has much finer resolution and appears to perform better (in terms of transport and stratification) than the former “ZUNO-DD” model results , data on mud content of the seabed (Stephens 2015) and bathymetric data (depth and bathymetric gradients).

In this new study we have also included new research, on mapping habitat suitability for reef forming organisms (Herman and Van Rees 2022). This study involved analyses based on historic data on the distribution in the nineteenth and early twentieth century in Dutch, German and Belgian waters of *O. edulis* using 2 types of spatial statistical methods, a “logistic regression” and a “random forest regression”. The predictions are made based on presence / absence of oysters, linked to abiotic habitat conditions. Both methods yielded results that were in good agreement. Full description of the methodology as well as the used R-scripts can be found in Herman and Van Rees et al (2022). The random forest method yields higher resolution data. The data used in the analysis of Herman and Van Rees (2022) include the data by Olsen, but also other sources (Houziaux et al. 2008, Bennema et al. 2020). Resulting probability maps were incorporated in the set of GIS layers. Results from both logistic regression and random forest regression methods were used.

2.2 Suitability of areas for flat oyster restoration

The current situation in the North Sea is one without the presence of flat oysters and hence also no presence of flat oyster larvae. Flat oysters have pelagic larvae that stay around 10 days in the water column, prior to settling on suitable locations (Korringa 1940, Ó Foighil and Taylor 2000). Due to the absence of larvae, even if there is suitable habitat, this will not automatically be colonised by oyster larvae. This also means that any successful flat oyster restoration project will have to take larval retention into account. A restoration location where reefs are intended to develop should have a relatively high retention of larvae produced in that area. Areas that do not have suitable habitat for the development of oyster reefs could still act as a source location, if oysters in that area are cultivated off the seabed, using aquaculture techniques and larvae produced in that area are transported by residual currents into suitable areas.

In the previous studies larval dispersal has been modelled using a particle distribution model (Smaal et al. 2017, Kamermans et al. 2018a, Kamermans et al. 2018b). An overview of the various locations for which the model was run can be found in Figure 2.1. The results of these model runs have been used in this study to qualitatively assess the larval retention from certain areas and the probability that larvae are able to reach areas with suitable habitat. Table 2.1 gives the model locations used as a proxy for the different areas in this study.

Some of the areas in the current assessment had release locations in them. For other areas one or two close release locations were used as a proxy, assuming that transport rates do not differ significantly over relatively small distances. The larval dispersal model also does not account for larval behaviour. The larvae are modelled as neutrally buoyant particles. Particularly during the older larval stages can alter their behaviour when in the vicinity of suitable settlement substrate, resulting in becoming negatively buoyant. The model may therefore lead to some over-estimation of the actual dispersal (Smaal et al. 2017).

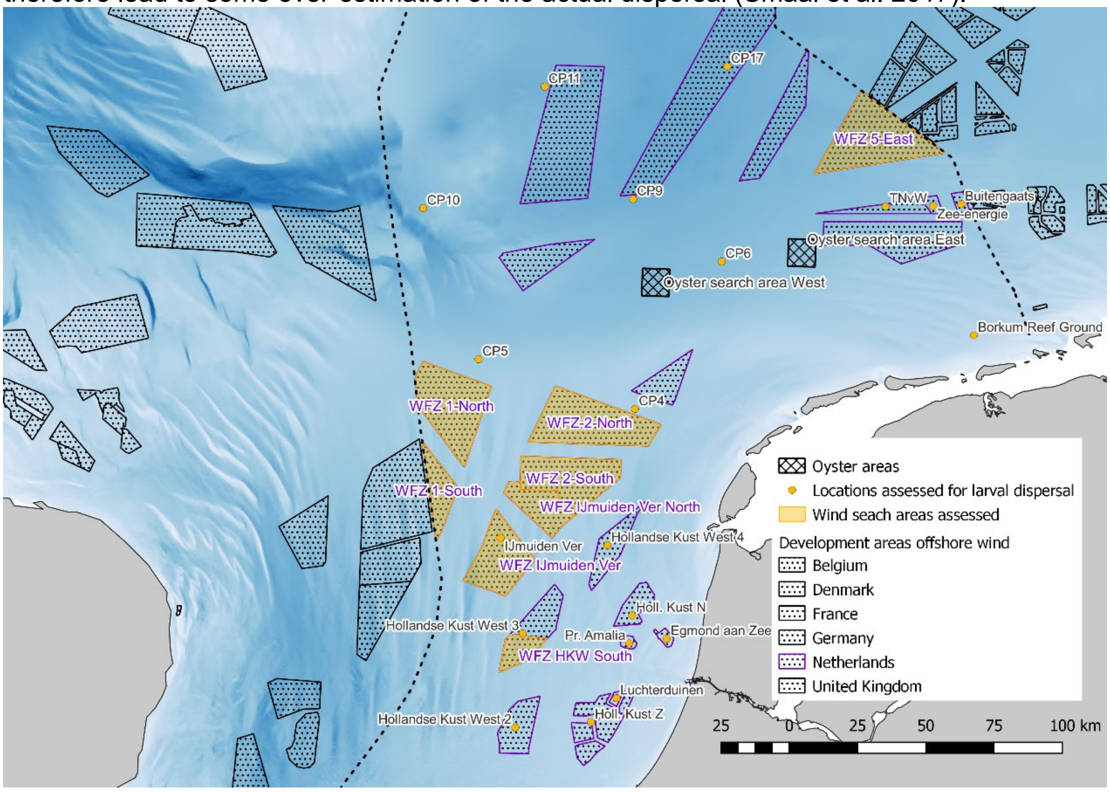

Figure 2.1: Overview of the locations for which larval dispersal has been assessed.

Table 2.1: Indication which larval release points used in the dispersal modelling were used to give a qualitative assessment of larval retention and probability of larvae reaching suitable habitat for the wind farm zones and search areas for oyster restoration in the present study. Proxies indicated refer to locations previously analysed by Smaal et al. (2017) and Kamermans et al. (2018a).

Analysis areas	Proxy larval release location
Wind Farm Zones	
1 North	CP5
1 South	CP5 / IJmuiden Ver
2 North	CP4
2 South	CP4/Hollandse Kust West Noord
5 East	TNvW / Zee-energie / Buitengaats / CP17
IJmuiden Ver	IJmuiden Ver
IJmuiden Ver North	IJmuiden Ver
HKW South	Hollandse Kust West 3
Search areas for oyster restoration	
Oyster area West	CP6
Oyster area East	CP6

2.2.1 Qualitative comparison with new DCSM model

It must be noted that the larval dispersal module (D-PART) from the previous studies was based on an older hydrodynamic schematisation (ZUNO-DD), which has a fine resolution near the coast, but is relatively coarse away from the coast. In the near future, it will be possible to D-PART with the new North Sea model (DCSM-FM), which is e.g. also used in the Wozep studies (Van Duren et al. 2021) and is far superior in performance. Within the timeframe of this project this was not yet possible. A qualitative assessment of the likely differences between the two models based on the estimates of residual currents follows below.

A direct comparison of the ZUNO-DD and DCSM-FM was not possible because the development and validation of the DCSM was on water levels, salinity, temperature, and stratification (Zijl et al. 2021). Results that are presented in that report include an overview of residual currents near the surface and the bed. For 2007 the mean surface currents in the North Sea are in the region of 5 to 10 cm/s, with the highest residual currents near the Dutch shoreline. Currents near the bed are significantly lower and are of the order of a few cm/s or less. Earlier results of the investigations into opportunities for flat oysters in the North Sea (Smaal et al. 2017) indicate a general advection of approximately 4 to 5 cm/s. This is based on the general distance of the larvae from its source after 10 days after release, and accounts for the vertically distributed currents.

2.3 Mud content of the seabed

Sediment composition is important for flat oysters as it determines substrate suitability for recruitment. Shells and existing oyster beds will promote recruitment. In the absence of information on shells, and lacking oyster beds at present, sediment grain size is the most commonly used parameter. Hydrodynamic conditions have impact on sediment composition. Silt tends to accumulate in sheltered spots, while coarser sediment particles are found in exposed areas. As a rule, average grain size varies according to the average current velocity. Burial under a layer of fine sediment will impede oyster survival (Wasson 2010).

The information regarding the habitat requirements of oysters with respect to fine sediment is slightly conflicting. Smaal et al. (2017) describe sediment with grain sizes coarser than 210 μm as unsuitable for flat oysters, sediment with grain sizes lager than 63 μm as moderately suitable and gravel and silt with shell fragments as suitable. The oyster status assessment by OSPAR indicates that oysters are highly sensitive to high silt deposition (OSPAR 2020). The analysis by Herman and Van Rees (2022) indicates that oysters occur preferentially in habitats with relatively high mud content. This is also confirmed by other observations reported in literature finding that highest numbers were found on substratum of shell, followed by silty sediments (Allison et al. 2020). Very high levels (50-100%) of mainly unconsolidated mud are prohibitive (Houziaux et al. 2011). As most of the North Sea is still regularly fished by bottom trawling, consolidation may be a problem, particularly for settlement.

2.4 Redundant data layers

2.4.1 Bed shear stress

Bed shear stress (τ) is the force the water exerts on the seabed. This can influence habitat suitability directly in two ways 1) high bed shear stresses can dislodge shells and 2) high bed shear stresses can limit the ability for larvae to settle. The exact limits for τ regarding these two processes, is not quite known. For dislodgement, likely maximum values are important, for settlement likely mean values are more relevant.
As bed shear stress is explicitly included in the habitat suitability analyses by Herman and Van Rees (2022), this parameter is not discussed here separately.

2.4.2 Oxygen

Oxygen content is another important factor in survival of flat oysters. Bivalve shellfish can survive without oxygen for a time, because they are adapted to temporary exposure to the air at low tide when they close their shells and switch to breathing without requiring oxygen. At low temperatures they can survive closed for several days. The minimum oxygen content for short-term survival is 0.5 mg/l (Davis 1975). A review has shown that the 412-hour LC 50 for oxygen, that is, the oxygen concentration that allows 50% of bivalve shellfish to survive for 412 hours, is 1.5 mg/l (Vaquer-Sunyer and Duarte 2008). The LC 90 for oxygen, with 90% surviving, is 3.5 mg/l. In the central part of the North Sea, stratification can occur and occasionally lead to oxygen depletion (Greenwood et al. 2010, Queste et al. 2016). From the modelled stratification regime in the North Sea (Van Leeuwen et al. 2015) it can be concluded that the locations of the present study do not show strong seasonal or permanent stratification. Thus, oxygen is not considered a limiting factor for habitat suitability for oysters at those locations.

2.4.3 Food availability

The availability of food is important to sustain growth. Phytoplankton is the main food source for flat oysters, and this is expressed as the amount of chlorophyll per litre. Hatchery studies have shown that 1.68 μg/l is the optimal concentration for reproduction (Millican and Helm 1994). Effective growth is achieved as soon as the available concentration exceeds 0.5 μg/l (Yildiz et al. 2011). Shallow waters contain more phytoplankton than deeper offshore waters, but enough food can be found even there (Herman et al., 2014). It is safe to assume that at all locations of the present study, the supply of phytoplankton during most of the year is sufficient to sustain the growth and reproduction of flat oysters.

3 Results

3.1 Presence of mobile sand waves

Based on published results (Damen et al. 2018) we georeferenced two important figures from this publication: one indicating the sand wave height and sand wave asymmetry. The latter gives an indication for mobility, more asymmetrical sand waves are more mobile than symmetrical ones. Sand waves are the large mobile structures (lengths hundreds of metres, heights 1-15 metres) in the North Sea, megaripples (i.e., with wave lengths from meters to tens of meters and wave heights from a few decimetres to several meters) and sand ripples (i.e. lengths and heights order centimetres) are smaller, but tend to move faster and can also be prohibitive for the formation of oyster reefs. Much less is known about these structures and no spatial information is available. However, it is reasonable to assume that the edges of the area dominated by sand waves are still too mobile for the establishment of flat oyster beds.

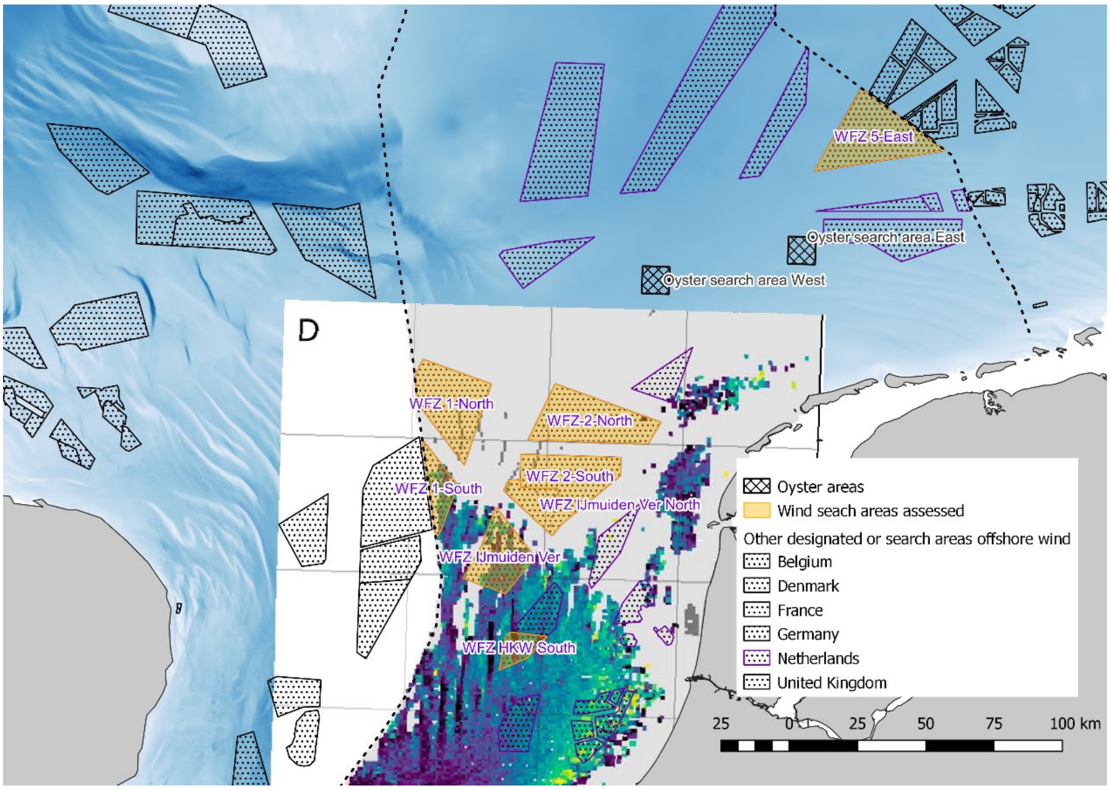

Figure 3.1: Figure 5D from Damen et al. (2018) (mean absolute asymmetry of sand waves) georeferenced and fitted under the wind farm locations. Areas north of the figure cut-out do not have sand waves. Dark purple colours indicate symmetry and green / yellow colours indicate higher levels of asymmetry.

The North Sea has been characterised into 'seascapes', to indicate areas with similar geomorphological characteristics (van der Reijden et al. 2018). The sand wave area falls within the delineation of the seascape characterised by tidal ridges. The Wind Farm Zones HKW South, IJmuiden Ver and 1 North all have asymmetric sand waves and are clearly unlikely to see significant development of oyster reefs. Wind Farm Zone 5 east and both oyster restoration search areas are well outside of mobile sand waves. The other four have a few small sand waves and will likely contain smaller bed forms.

3.2 Habitat suitability based on statistical analysis

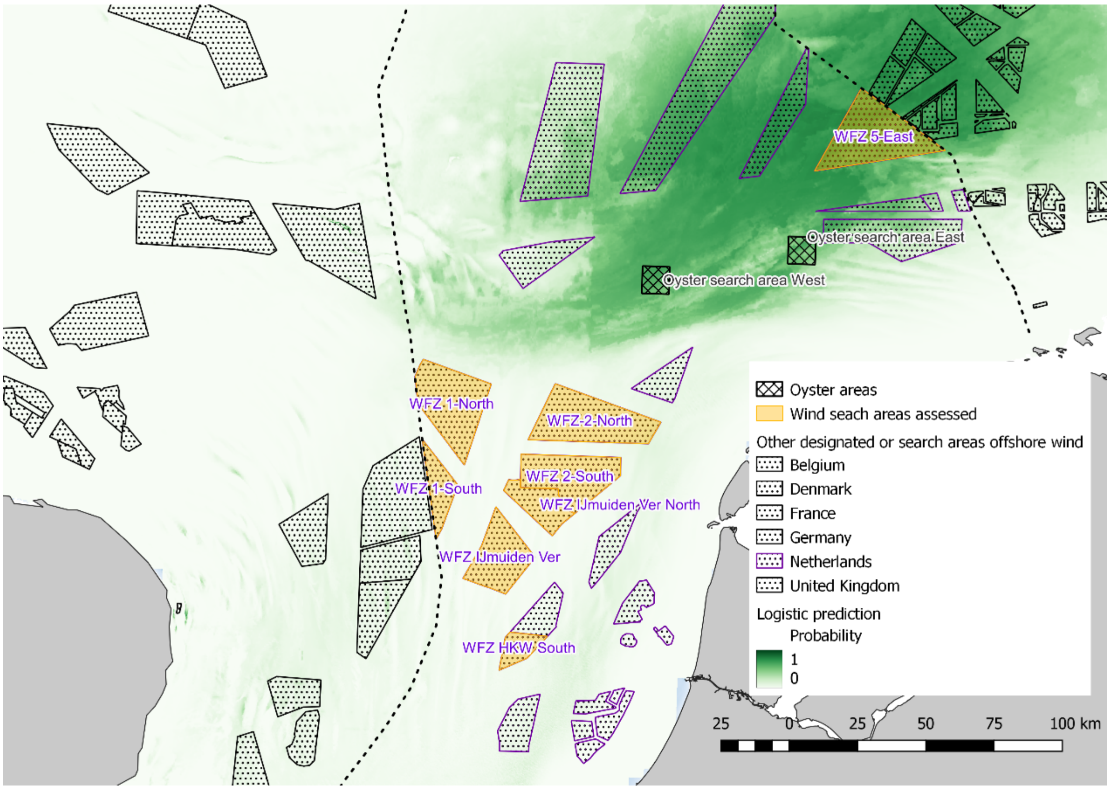

Figure 3.2: The logistic probability of habitat suitability for oysters from (Herman and Van Rees 2022).

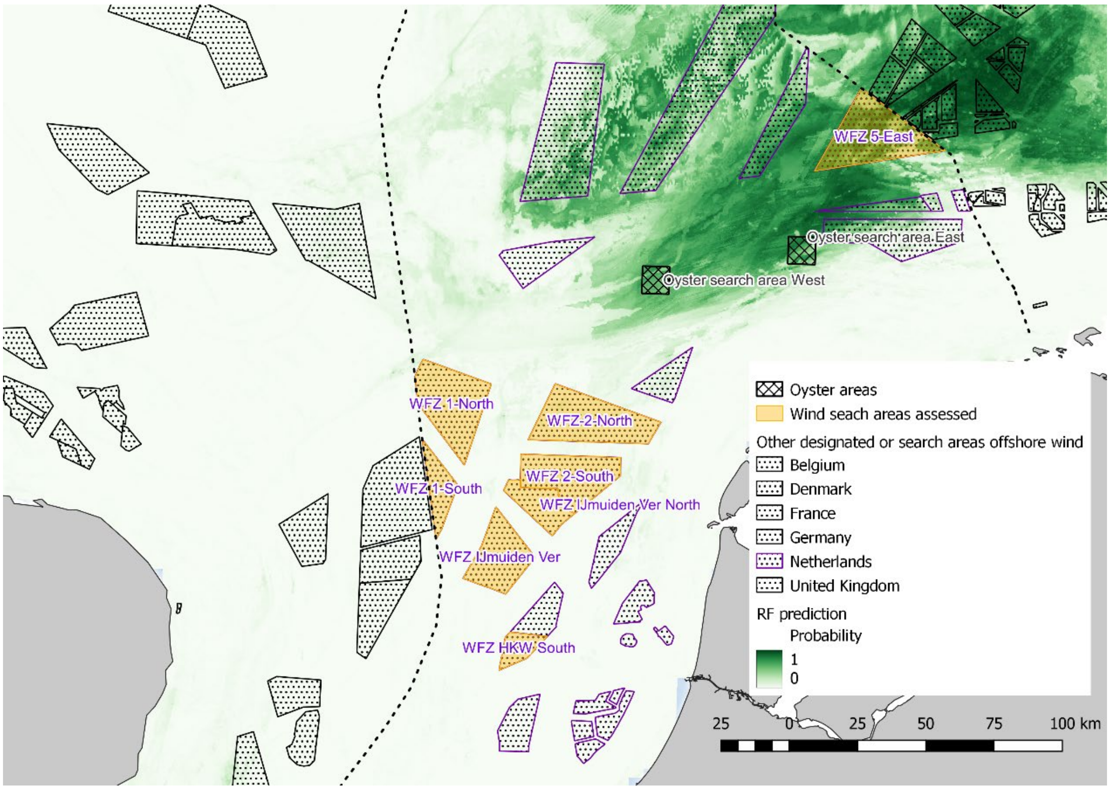

Figure 3.3: The random forest prediction for habitat suitability of oysters (Herman and Van Rees 2022)

Both statistical analysis methods indicate high suitability for flat oyster reef formation in both oyster restoration search areas and in Wind Farm Zone 5 east. The other wind farm zones analysed appear to have very low suitability for reef formation.

3.3 Dispersal

3.3.1 Wind farm zones

The wind farm zone with the highest suitability (i.e., Wind Farm Zone 5 east) for the development of oyster reefs also has good larval retention. We used the locations TNvW, Zee-energie, Buitengaats and CP17 (see Smaal *et al.* 2017 and Kamermans *et al.* 2018a) as a proxy for dispersal for this location. Plumes extend around 75 km north east (for CP17 a bit more north – north east), and around 25 km in the opposite direction (Figure 3.4). Transposing such a plume to Wind Farm Zone 5 east means that most of the plume would reach suitable habitat, although none of the habitat outside the wind farm zones falls within areas protected from bottom trawling. However, it would reach other wind farm areas in Germany.

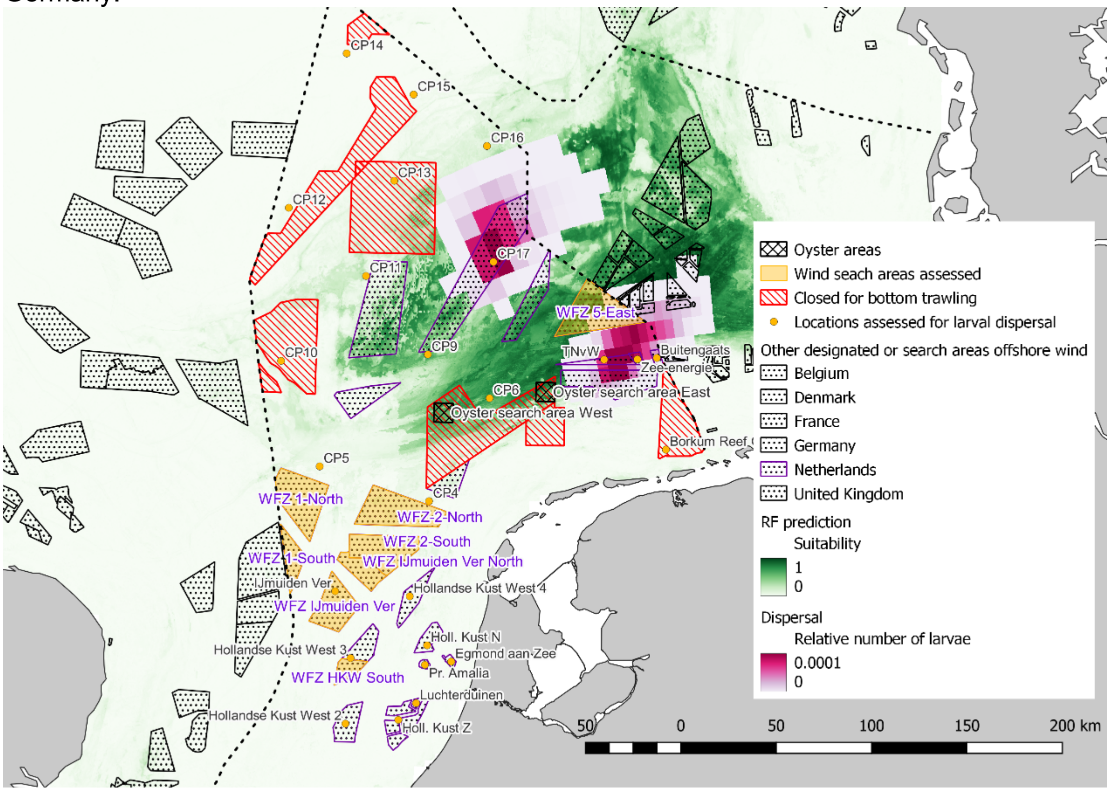

Figure 3.4: Dispersal from location CP17 and TnVW, two of the locations used to qualitatively assess dispersal. The plumes of "Buitengaats"and "Zee-energie" are not shown but are similar to that of TNvW

For Wind Farm zones 1 and 2 North and Wind Farm Zone 2 South, the habitat suitability for reef formation are poor, but larvae produced in these areas may reach areas that are suitable (Figure 3.5). From Wind Farm Zone 2 North (with CP4 (see Kamermans *et al.* 2018a) as the best proxy) the dispersal plume would reach not only habitat that is suitable, but also within the exclusion zone for bottom trawling.

The plume from CP4 extends more than 120 km north-eastwards. So even if dispersal is slightly over-estimated with this model, due to the fact that behaviour is not included, off-bottom flat oyster cultivation in this – potential - wind farm area could serve as a larval source for suitable and protected habitat. For Wind Farm Zone 2 South, also some larvae may reach areas that are suitable for reef formation, but this will be substantially less than for Wind Farm Zone 2 North. For this area CP4 and "Hollandse Kust West 4" (see Kamermans *et al.* 2018a) are used as proxies (Figure 3.5). For Wind Farm Zone 1 North CP5 is used as a proxy. The plume extends about 85 km north eastward and would also reach some suitable area, but most of this is not protected from bottom trawling.

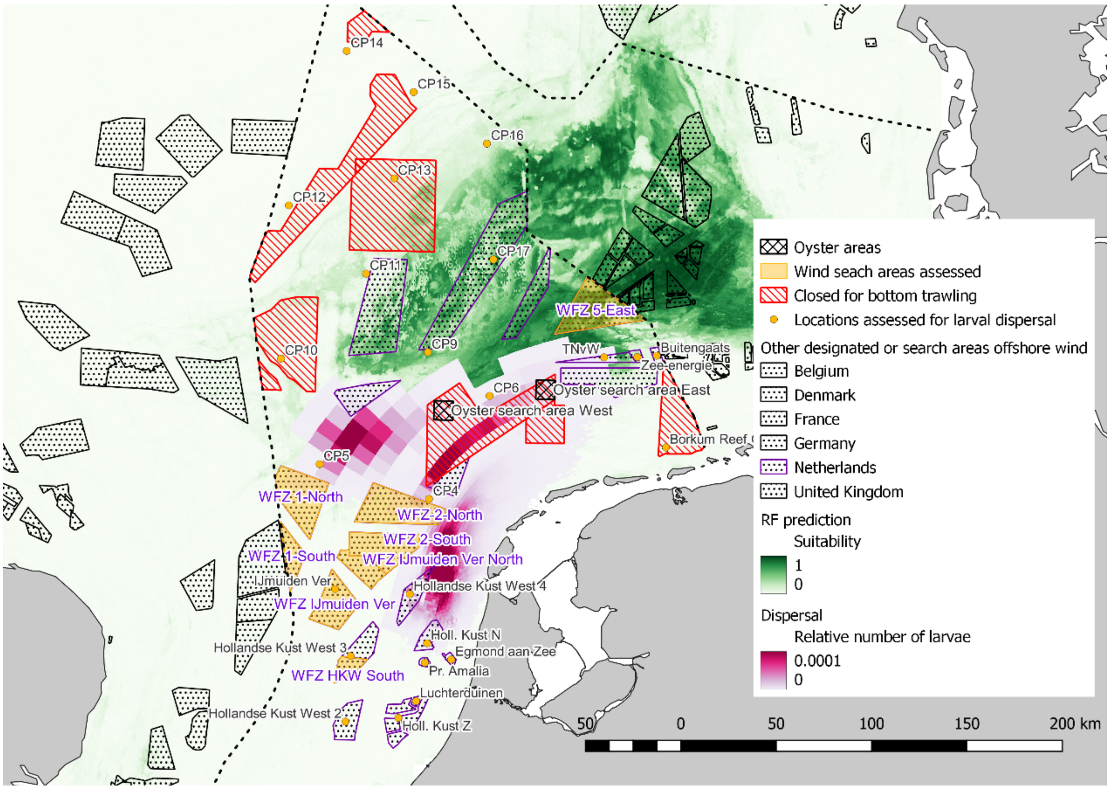

Figure 3.5: Dispersal plumes from locations CP4, CP5 and Hollandse Kust West 4, plumes slightly overlap.

The other four wind farm zones (Wind Farm Zones 1 South, IJmuiden Ver, IJmuiden Ver North and HKW South) are not only unsuitable as habitat for oyster reefs, dispersal from these sites is such that no or only a very small proportion of larvae produced will get near suitable habitat.

For these Wind Farm Zones 1 South CP5 and IJmuiden Ver (see Kamermans et al. 2018a are both used as a proxy (Figure 3.6). Of these two, IJmuiden Ver has the farthest dispersal distance (about 100 km north-eastward). Transposing this plume to Wind Farm Zone 1 South, the edge would just reach an area with higher suitability. However, as with this model dispersal is likely slightly overestimated, this area is in all likeliness not a great source location.

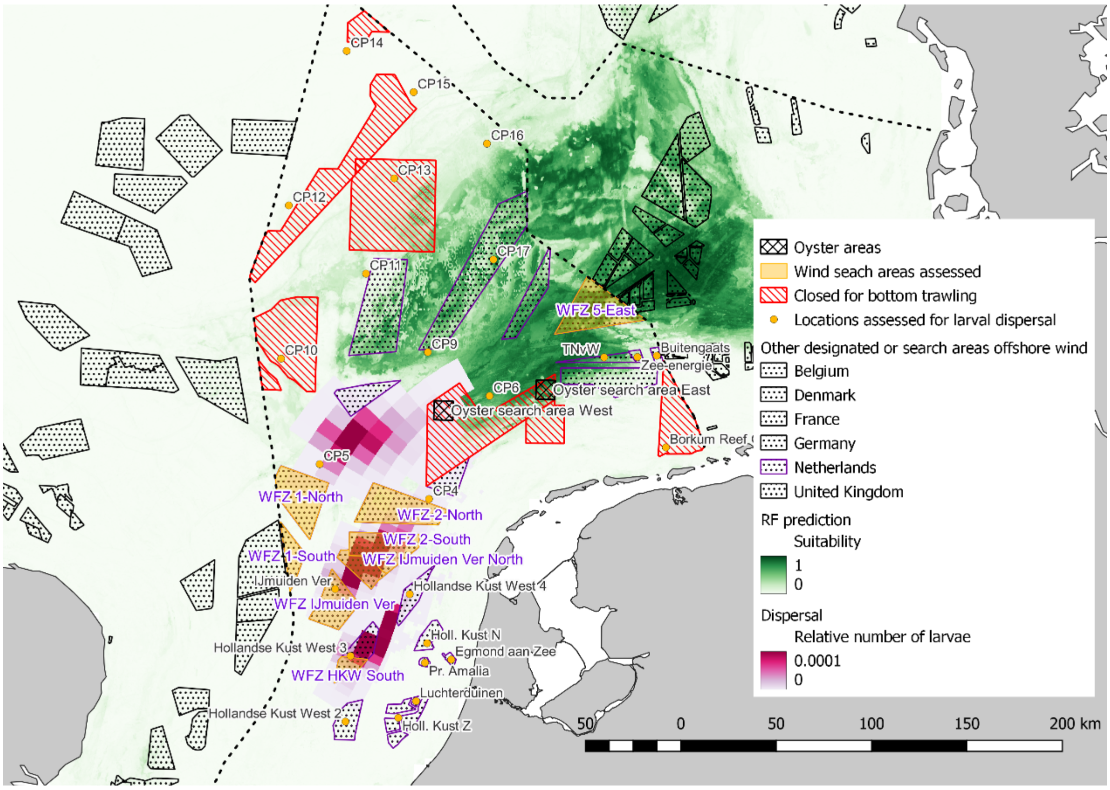

Figure 3.6: Dispersal from locations Hollandse Kust West 3, IJmuiden Ver and CP5.

3.3.2 Oyster restoration areas

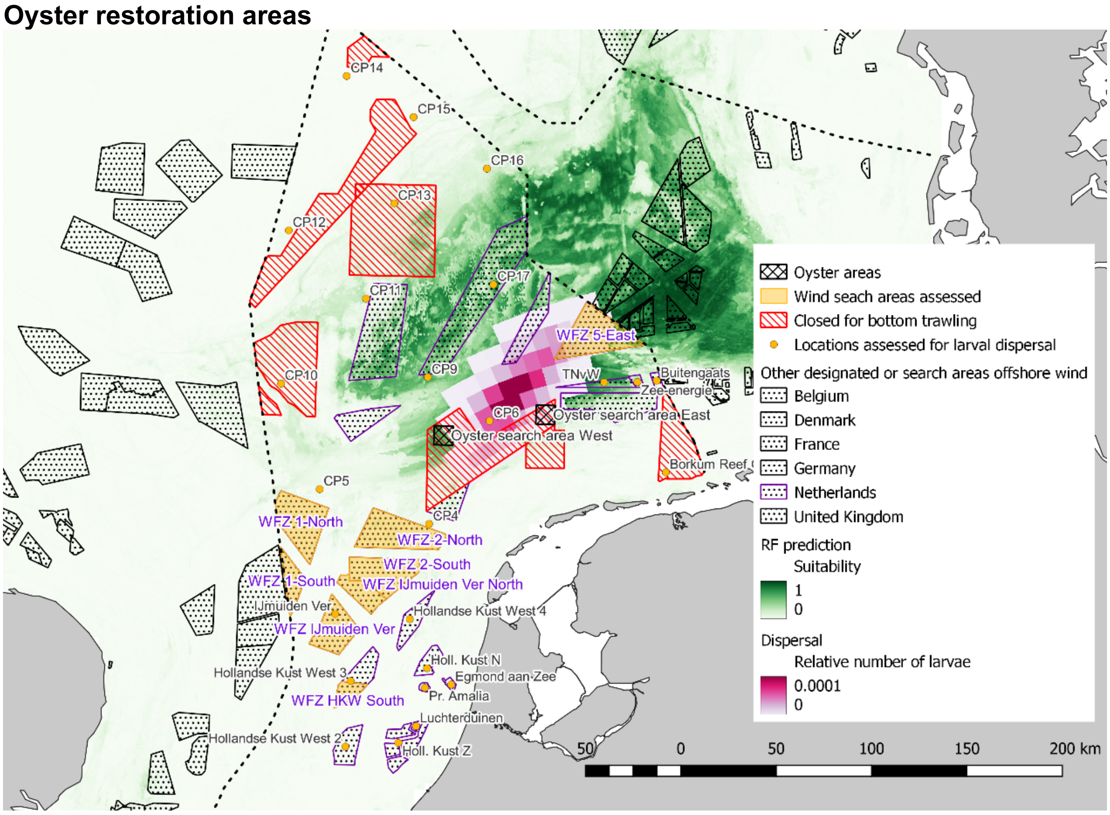

Figure 3.7: Model results for larval dispersal from location CP6.

Location CP6 (see Kamermans *et al.* 2018a) is used as a proxy for both flat oyster restoration search areas. The plume extends about 85 km in north easterly direction and much less (about 35 km) in the opposite direction (Figure 3.7). Transposing the plume to either of the two oyster areas would mean the bulk of the larvae would end up in area that is deemed suitable for the development of oyster beds (based on the predictions of the statistical model by Herman and Van Rees (2022). Particularly from the western location the plume would also cover suitable flat oyster habitat that is protected from trawling by the fishing exclusion zone. From the eastern location, larvae are likely to end up in some of the future wind development areas.

3.4 Mud content of the seabed

Flat oysters appear to have a preference for consolidated sediment with a relatively high mud content. However, sea beds with extremely high (>50%), unconsolidated mud are unsuitable (Houziaux et al. 2011). Such excessively high concentrations are rarely found in the open North Sea and not at all in the areas of interest.

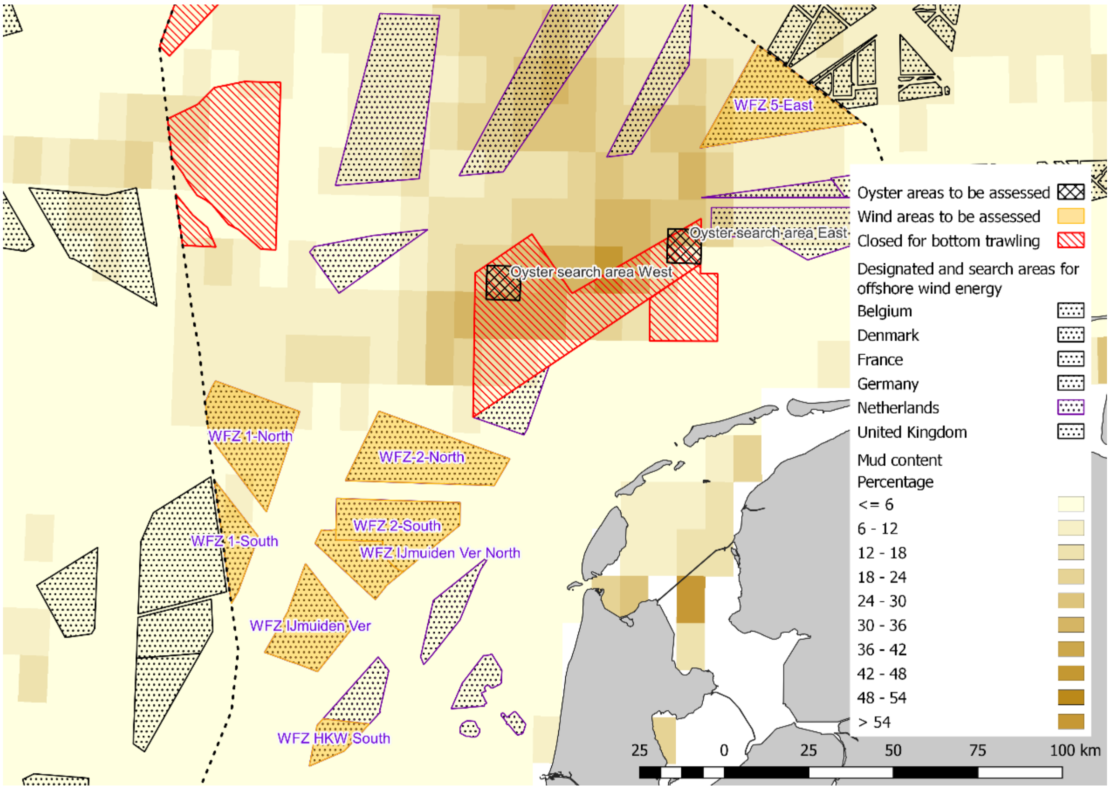

Figure 3.8: Percentage mud in the sea bed

With an average of 24.3% the western oyster search area has the highest mud content, followed by the eastern oyster search area (18.9) and Wind Farm Zone 5 east (10.1%). Wind Farm Zone 1 North has an average of 4.7 % mud (ranging between 1.3 and 8.1%). All other areas have very low mud content (averaging below 2%).

4 Conclusions and recommendations

4.1 Wind farm zones

Of the new wind farm zones analysed only Wind Farm Zone 5 east is really suitable to attempt restoration of oyster beds within the wind farm zone. All other wind farm zones analysed are predicted as unsuitable by both statistical approaches (Table 4.1). This appears to be most likely due to the presence of mobile sand waves and smaller bed forms, making the seabed too dynamic for the presence of persistent oyster beds.

Although the seabed is too dynamic, cultivation of flat oysters higher up into the water column may be an option from a biological point of view. Whether this is an option from a commercial point of view may be debatable. Cultivation of flat oysters for commercial purposes (i.e. outgrow of already settled spat in off-bottom cages) may be possible in all areas. The previous studies (Smaal et al. 2017, Kamermans et al. 2018a, Kamermans et al. 2018b) have indicated no prohibitive circumstances in terms of oxygen levels, temperature ranges, salinity ranges or limited food supply. Off-bottom cultivation of oysters with the purpose of providing a source of larvae that are likely to reach suitable areas where flat oyster beds can develop is likely possible in Wind Farm Zone 1 North and Wind Farm Zone 2 North. As the dispersal model tends to over-estimate the dispersal distance, most other areas are unlikely to be successful source locations Table 4.1.

Table 4.1: overview of the most relevant habitat characteristics, the predicted model results for suitability for flat oyster reef development, local larval retention and probability of larval dispersal into suitable habitat from the investigated wind farm zones for offshore wind development. Numbers are averages for the specific area, with minimum and maximum values found.

Wind Farm zones	Sand waves	mud content (%)	Reef prediction (logit)	Reef prediction (RF)	Larval retention	Dispersal into suitable habitat
WFZ 1 North	some	4.7 (1.3 - 8.1)	0.01 (0.00 - 0.16)	0.03 (0.01 - 0.09)	poor	good
WFZ 1 South	yes	0.9 (0.0 - 1.7)	0.02 (0.00 - 0.06)	0.01 (0.00 - 0.09)	poor	some
WFZ 2 North	some	1.6 (0.8 - 2.3)	0.04 (0.01 - 0.12)	0.02 (0.00 - 0.17)	moderate	good
WFZ 2 South	some	1.5 (0.3 - 2.3)	0.02 (0.01 - 0.06)	0.01 (0.00 - 0.11)	poor	some
WFZ 5 East	no	10.1 (8.1 - 16.0)	0.67 (0.45 - 0.79)	0.64 (0.07 - 0.98)	good	good
WFZ IJmuiden Ver	yes	0.0 (0.0 - 0.1)	0.01 (0.00 - 0.04)	0.00 (0.00 - 0.07)	poor	poor
WFZ IJmuiden Ver North	some	0.9 (0.0 - 2.4)	0.02 (0.00 - 0.04)	0.01 (0.00 - 0.06)	moderate	poor
WFZ HKW South	yes	0.0 (0.0 - 0.0)	0.03 (0.00 - 0.09)	0.00 (0.00 - 0.09)	moderate	poor

4.2 Search areas for flat oyster restoration

The two search areas for flat oyster restoration on the Frisian Front that were assessed, both appear to be very suitable for restoration efforts (Table 4.2). In terms of suitability there is not much to choose between the two. The logistic prediction is slightly higher for the western one, the random forest approach predicts higher values for the eastern one, but the predictions on suitability are both in the same ballpark range. Variability of suitability appears to be larger in the eastern area, which also appears to have a large range in mud content (Table 4.2).

Table 4.2: Overview of the most relevant habitat characteristics, the predicted model results for suitability for reef development, local larval retention and probability of larval dispersal into suitable habitat from the search areas for flat oyster restoration. Numbers are averages for the specific area, with minimum and maximum values found.

Oyster restoration search areas	Sand waves	mud content (%)	Reef prediction (logit)	Reef prediction (RF)	Larval retention	Dispersal into suitable habitat
Oyster search area West	no	24.3 (19.9 - 32.5)	0.61 (0.48 - 0.68)	0.59 (0.39-0.78)	good	good
Oyster search area East	no	18.9 (4.43 - 29.8)	0.53 (0.30 - 0.67)	0.62 (0.17-0.89)	good	good

Therefore, although average conditions are very comparable, the eastern site may contain a few areas that are less suitable.
As these areas were regularly fished until recently, consolidation of the top layer of the bed may be limited, which might be inhibitive for settlement of oysters. Both areas will be surveyed in the near future (Kamermans et al., in prep.), to get more detailed information on local bed conditions, such as bed composition as well as the presence of stones or shell material. Oyster spat most readily settles on live shell material, but in the absence of live conspecifics there does not appear to be much difference between stones and shell (Rodriguez-Perez et al. 2019). It would be sensible to await the results of the survey and if clear differences in availability of small pockets of hard substrate emerge, to make a choice for the area with most settlement opportunities.

5 References

Allison, S., M. Hardy, T. Cameron, and G. J. C. Underwood. 2020. Strongholds of Ostrea edulis populations in estuaries in Essex, SE England and their association with traditional oyster aquaculture: evidence to support a MPA designation. Journal of the Marine Biological Association of the United Kingdom **100**:27-36.

Bennema, F. P., G. H. Engelhard, and H. Lindeboom. 2020. Ostrea edulis beds in the central North Sea: delineation, ecology, and restoration. ICES Journal of Marine Science.

Damen, J. M., T. A. G. P. van Dijk, and S. J. M. H. Hulscher. 2018. Spatially Varying Environmental Properties Controlling Observed Sand Wave Morphology. Journal of geophysical research **123**:19.

Davis, J. C. 1975. Minimal Dissolved Oxygen Requirements of Aquatic Life with Emphasis on Canadian Species: a Review. Journal of the Fisheries Research Board of Canada **32**:2295-2332.

Greenwood, N., E. R. Parker, L. Fernand, D. B. Sivyer, K. Weston, S. J. Painting, S. Kröger, R. M. Forster, H. E. Lees, D. K. Mills, and R. W. P. M. Laane. 2010. Detection of low bottom water oxygen concentrations in the North Sea; implications for monitoring and assessment of ecosystem health. Biogeosciences **7**:1357-1373.

Herman, P. M. J., and F. F. Van Rees. 2022. Mapping Reef forming North Sea Species. 11207716-000-ZKS-0001, Deltares, Delft.

Houziaux, J. S., M. Fettweis, F. Francken, and V. Van Lancker. 2011. Historic (1900) seafloor composition in the Belgian-Dutch part of the North Sea: A reconstruction based on calibrated visual sediment descriptions. Continental Shelf Research **31**:1043-1056.

Houziaux, J. S., F. Kerckhof, K. Degrendele, M. Roche, and A. Norro. 2008. The Hinder banks: yet an important area for the Belgian marine biodiversity ? , Belgian Science Policy, Brussels.

Kamermans, P., L. A. Van Duren, and F. Kleissen. 2018a. European flat oysters on offshore wind farms: additional locations; Opportunities for the development of European flat oyster (Ostrea edulis) populations on planned wind farms and additional locations in the Dutch section of the North Sea Wageningen Marine Research, Yerseke.

Kamermans, P., B. Walles, M. Kraan, L. van Duren, F. Kleissen, T. van der Have, A. Smaal, and M. Poelman. 2018b. Offshore Wind Farms as Potential Locations for Flat Oyster (Ostrea edulis) Restoration in the Dutch North Sea. Sustainability **10**:3942.

Korringa, P. 1940. Experiments and Observations on Swarming, Pelagic Life and Setting in the European flat oyster, Ostrea edulis RIVO, IJmuiden.

Millican, P. F., and M. M. Helm. 1994. Effects of nutrition on larvae production in the European flat oyster, Ostrea edulis. Aquaculture **123**:83-94.

Ministerie van Infrastructuur en Waterstaat, Ministerie van Landbouw Natuur en Voedselkwaliteit, Ministerie van Economische Zaken en Klimaat, and Ministerie van Buitenlandse Zaken en Koninkrijksrelaties. 2022. Programma Noordzee 2022-2027.

Ó Foighil, D., and D. J. Taylor. 2000. Evolution of Parental Care and Ovulation Behavior in Oysters. Molecular Phylogenetics and Evolution **15**:301-313.

Olsen, O. T. 1883. The piscatorial atlas of the North Sea, English and St. George's Channels, illustrating the fishing ports, boats, gear, species of fish (how, where, and when caught), and other information concerning fish and fisheries. . Taylor and Francis, London.

OSPAR. 2020. European flat oyster and Ostrea edulis beds. BDC2020, OSPAR.

Queste, B. Y., L. Fernand, T. D. Jickells, K. J. Heywood, and A. J. Hind. 2016. Drivers of summer oxygen depletion in the central North Sea. Biogeosciences **13**:1209-1222.

Rodriguez-Perez, A., M. James, D. W. Donnan, T. B. Henry, L. F. Møller, and W. G. Sanderson. 2019. Conservation and restoration of a keystone species: Understanding the settlement preferences of the European oyster (Ostrea edulis). Marine Pollution Bulletin **138**:312-321.

Smaal, A., P. Kamermans, F. Kleissen, L. A. Van Duren, and T. van der Have. 2017. Platte Oesters in offshore windparken Wageningen Marine Research; Deltares; Bureau Waardenburg, Yerseke.
Stephens, D. 2015. North Sea and UK shelf substrate composition predictions, with links to GeoTIFFs.*in* Pangaea, editor.
van der Reijden, K. J., N. T. Hintzen, L. L. Govers, A. D. Rijnsdorp, and H. Olff. 2018. North Sea demersal fisheries prefer specific benthic habitats. PLoS ONE **13**:21.
Van Duren, L. A., F. Zijl, V. T. M. van Zelst, L. M. Vilmin, J. Van der Meer, G. M. Aarts, J. Van der Molen, K. Soetaert, and A. W. Minns. 2021. Ecosystem effects of large upscaling of offshore wind on the North Sea - Synthesis report. 11203731-004-ZKS-0010, Deltares, Delft.
Van Leeuwen, S., P. Tett, D. Mills, and J. van der Molen. 2015. Stratified and nonstratified areas in the North Sea: Long-term variability and biological and policy implications. J. Geophys. Res. **120**:4670-4686.
Vaquer-Sunyer, R., and C. M. Duarte. 2008. Thresholds of hypoxia for marine biodiversity. Proceedings of the National Academy of Sciences **105**:15452-15457.
Wasson, K. 2010. Informing Olympia Oyster Restoration: Evaluation of Factors That Limit Populations in a California Estuary. Wetlands **30**:449-459.
Yildiz, H., S. Berber, S. Acarli, and P. Vural. 2011. Seasonal variation in the condition index, meat yield and biochemical composition of the flat oyster Ostrea edulis (Linnaeus, 1758) from the Dardanelles, Turkey. Italian Journal of Animal Science **10**:e5.
Zijl, F., J. Veenstra, and J. Groenenboom. 2018. The 3D Dutch Continental Shelf Model - Flexible Mesh (3D DCSMFM) : setup and validation. 1220339, Deltares, Delft.

Deltares is an independent institute for applied research in the field of water and subsurface. Throughout the world, we work on smart solutions for people, environment and society.

Deltares