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Offshore wind farms contribute to epibenthic biodiversity in the North Sea

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ABSTRACT

The North Sea was once abundantly covered with hard substrates such as oyster beds, coarse peat banks and glacial erratics, providing habitat to a rich community of marine species. Most of these habitats were destroyed by bottom-trawl fisheries over the past century, and today, the seabed hosts a relatively poor species community. Emerging offshore windfarms include the re-introduction of hard substrate by means of scour protection around the foundation of wind turbines. It is assumed that the new habitat will contribute to marine biodiversity, and this study aims to demonstrate that. Video data were collected using a Remotely Operated Vehicle in four wind farms in the southern North Sea. A quantitative assessment was made to determine the effect of scour protection on community structure. The assessment revealed distinct community clusters for geographic location and seabed type. Windfarms closely located to each other had a more similar epibenthic community compared to those further away. The epibenthic community at the rocky armour layer of the scour protection had a different species composition and a higher species abundance than the one at the sandy seabed surrounding it. Species diversity by means of richness, evenness and the Shannon diversity index was not consistently higher or lower for the communities at the different seabed types.

This study shows that marine life inhabits scour protection in offshore wind farms and that it is different from the community living at the surrounding seabed. Knowing the potential epibenthic community structure at and around a scour protection supports the development of new wind farms that include components to enhance their ecological value. Herewith, our study contributes to efforts to restore biodiversity in the North Sea.

1. Introduction

Historical maps show that the North Sea was once covered with hard substrates such as oyster beds, coarse peat banks and glacial erratics (Olsen, 1883). These substrates provided habitat for many associated marine species, but were destroyed by bottom-trawl fisheries, over-exploitation and diseases (Gross and Smyth, 1946; Korringa, 1952). The most notable change is the loss of oyster beds, which covered approximately 21,000 km^2 in the southern part of the North Sea (Olsen, 1883). Today, large parts of the seabed are characterized by sandy or silty soft substrate, hosting an epibenthic species community that is different and less diverse compared to the one at the remaining natural hard substrate like pebbles and boulders (Bos et al., 2011; Coolen et al., 2015).

Human constructions in the North Sea provide an opportunity to redevelop the hard substrate habitat and its associated marine life. Research shows that offshore oil and gas platforms, shipwrecks and wind farms act as artificial reefs, hosting a broad range of marine species such as algae, invertebrate species and fish (e.g., Leewis et al., 2000; Consoli et al., 2018). Also, offshore oil and gas platforms and wind farms have been observed to act as stepping stones and connect species between otherwise isolated populations due to their geographic distribution (Thorpe, 2012; Adams et al., 2014). The current rollout of offshore windfarms in the North Sea provides an opportunity to further reinstate epibenthic communities associated with hard substrates. For example, in the Dutch part of the North Sea, the government now requires developers to include elements that benefit ecology in the design of offshore wind farms (e.g. Dutch Ministry of Economic Affairs and Climate, 2022). This implies that new wind farms should make a positive contribution to the marine ecosystem. However, designing offshore wind farms that are practical in installation and technically functional during operation, but also promote positive effects on selected species, proves to be challenging. For example, by increasing the complexity in

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the contours of human-made structures to attract more fish species (Consoli et al., 2018). In most wind farms in the North Sea, layers of rock material are placed at the base of the wind turbines and on top of cable crossings, to prevent the seabed from scouring. More variety in shape and dimension of this so-called scour protection will increase the habitat complexity and is expected to result in a higher biodiversity (Lapointe and Bourget, 1999; Firth et al., 2014). The increasing amount of offshore wind farms being developed is expected to affect the spread of marine life due to a stepping stone effect offered by the numerous scour protections deployed (Adams et al., 2014; De Mesel et al., 2015). The total area of scour protection in wind farms in the southern North Sea was assessed to be approximately 1.80 km^2 at the start of the year 2021 (Ter Hofstede et al., 2022). Rock-associated epibenthic species benefit from this wide distribution of hard substrate, and more variety in its complexity has the potential to further increase biodiversity. Yet, the composition of benthic communities at and around the scour protection in offshore wind farms is poorly known.

To understand the consequences of the presence of scour protection for epibenthic life, data was collected on species communities in four offshore wind farms in the southern North Sea by monitoring using a Remotely Operated Vehicle (ROV). These scour protections differ in lifetime, geographic location, and rock grading. A quantitative assessment was made to determine the effect of these differences on species abundance and species diversity. This study sets a baseline for the value of scour protection for epibenthic communities in offshore wind farm in the southern North Sea.

2. Materials and method

2.1. Study sites

First, an inventory was made of 16 offshore wind farms in the southern part of the North Sea to select study sites (see Fig. 1). All turbines in these wind farms are installed on a monopile foundation with pancake-shaped layers of rock material at its base to prevent the seabed from erosion. This scour protection is often composed of a filter layer of small-sized quarried rock, such as granite, topped with an armour layer of large-sized quarried rock. The lifetime, geographic location, and rock grading of the scour protection are expected to have an effect on the species living at and around it. Based upon their range in these characteristics and willingness of the wind farm operators to allow monitoring, four windfarms were selected to study these effects: Princess Amalia (NL), Belwind (B), Gemini (NL) and Luchterduinen (NL) (see Table 1). In each of these four wind farms, the scour protection and its surrounding of three randomly selected wind turbines was monitored.

2.2. Video transects

Video footage was collected using an ROV to quantitatively determine epibenthic organisms at and around the scour protection. The Bluestream Cougar XT ROV was deployed, equipped with 4 K subsea camera, adjustable LED lights, and two-line lasers to estimate object sizes and to frame the surface of video transects at a distance of 28 cm. Radial transects were scheduled to be made towards and away from the monopile at 0, 45, 90, 135, 180, 225, 270 and 315 degrees (see Fig. 2). Depending on hydrodynamic conditions, a minimum of four transects of different angles per pile were surveyed, with the aim to cover opposite directions. At each radial transect, a distance of 5 m was kept between the tracks flown towards and away from the monopile. The transects covered all substrate types present around a monopile: the armour layer, the transition zone (or filter layer, if present) and the seabed. Experienced ROV pilots were instructed to consistently record video following the transects with a speed of 0.14 m/s and a distance of 0.5 m from the substrate, and to correct for overexposure manually.

2.3. Video analysis

Video transects were analysed using the software package TransectMeasure. Video frames suitable for image analysis were selected on the following criteria: image quality, visibility of laser lines and good display of the seabed in the transect. The laser lines were used as a reference to determine the surface area of each video frame. A minimum

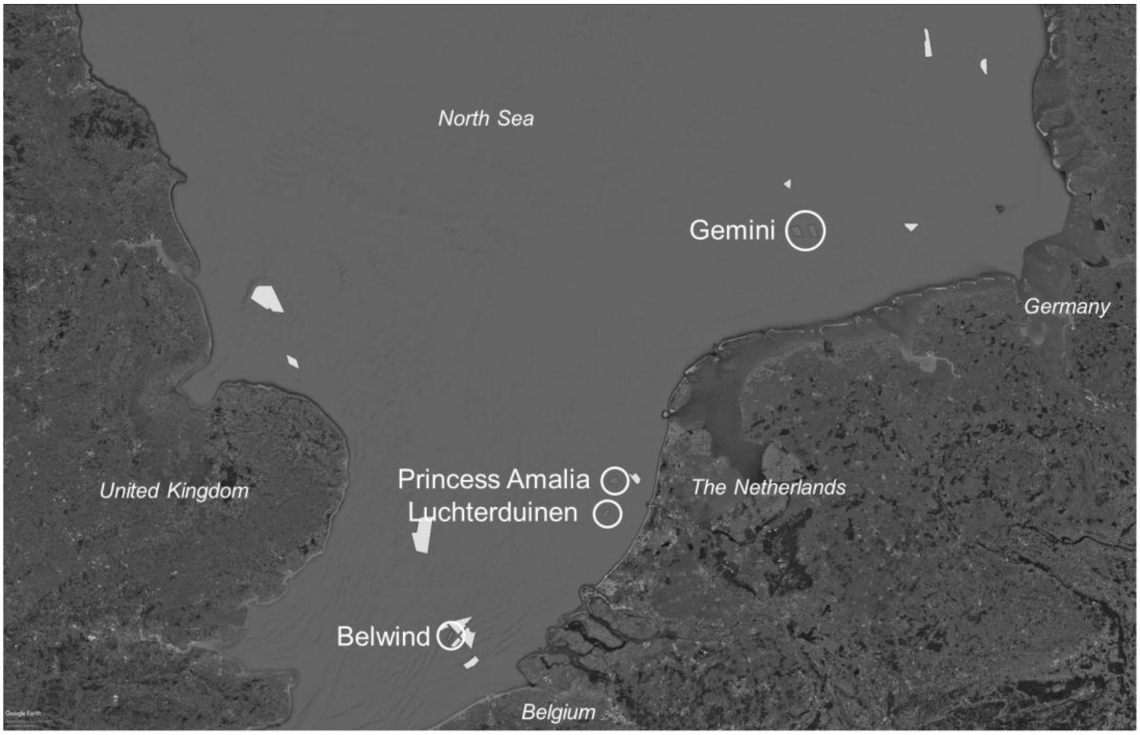

Fig. 1. Map of the southern North Sea indicating the offshore wind farms explored (in white) and the four selected (in grey, encircled) for the monitoring.

Table 1
Main characteristics of the offshore wind farms in which the species assemblage at and around the scour protection was investigated.

Wind farm	Country	Year of installation	Location		Min. water depth (m)	Armour layer			Filter layer		
			lat	lon		grading (mm)	radius (m)	thickness (m)	grading (mm)	radius (m)	thickness (m)
Belwind	Belgium	2011	51°40	2°48	16.0	185/500*	28.0	0.74	–	–	–
Gemini	Netherlands	2015	54°02	5°57	29.5	63/200	21.3	1.0	22/90	30.2	0.5
Luchterduinen	Netherlands	2014	52°24	4°09	19.5	185/500*	18.2	0.8	22/90	27.4	0.3
Princess Amalia	Netherlands	2009	52°35	4°12	21.0	185/500*	20.0	1.2	–	–	–

* Converted from 10 to 200 kg

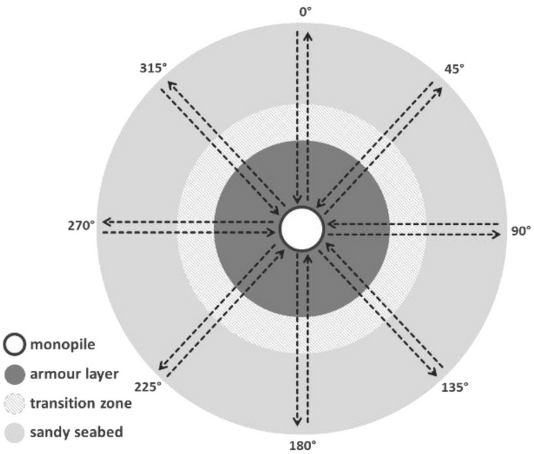

Fig. 2. Schematic overview of the ROV flight plan for monitoring the epibenthic community at the scour protection and seabed around a monopile, showing 8 radial transects, each comprising a track towards and a track away from the centre of the monopile.

of five frames per substrate type were selected for each track, evenly distributed over the transect, and representing the overall species communities observed. For each video frame, individual species were counted and identified to the lowest taxonomic level possible (species, genus, family, class or phylum level). The minimum species size detection limit in frames of good quality was approximately 1 cm. Clustering species such as hydroids and tunicates (see Table 3) were also identified to the highest taxonomy level possible, marking the percentage of the area covered in the video frame.

Distinctive parameters were reported for each video frame: the substrate type was labelled as "armour layer", "transition zone" or "sand"; the laser lines were scored as "present", "partially present" or "absent"; and image quality was scored as "good", "sufficient" or "bad". The "transition zone" is the part around the edges of the armour layer were the rock material is gradually disappearing under the sand (see Fig. 2). Note that if a filter layer is installed as part of the scour protection, this layer generally extends from underneath the armour layer. The filter layers installed in Gemini and Luchterduinen had largely disappeared under a layer of sand, for which these layers were also classified as "transition zones"; similar to the wind farms Belwind and Princess Amalia in which no filter layers were installed.

2.4. Data analysis

Species observations were reported by their densities. Species density of individual species was calculated as the number of individuals per m^2 in a video frame. Species density of clustering species was calculated in percentage as covered area per video frame. To allow for a combined analysis of densities of individual species and clustering species, data were transformed to the ordinal Marine Nature Conservation Review (MNCR) SACFOR scale using the method of Connor et al. (2004). The SACFOR abundance scale assigns the following numerical values to densities: Superabundant = 7, Abundant = 6, Common = 5, Frequent = 4, Occasional = 3, Rare = 2, Present = 1.

Before statistical analyses, species with only 1 observation in the dataset were removed to minimize the influence of rare species in multivariate analyses (Poos and Jackson, 2012). Statistical analyses were performed using the software package R version 3.6.3 (R Core team, 2016) with several functions from the 'vegan package' (Oksanen et al., 2014). Data frames were constructed for hierarchical analysis of species composition per cluster, which was the combination *windfarm x turbine x substrate type*. For each cluster, the mean numerical SACFOR species abundance was calculated. Bray-Curtis dissimilarity distance matrices were created and differences between the clusters were tested using PERMOVA. The clusters were presented in dendograms and Non-metric Multi-Dimensional Scaling (NMDS) plots. NMDS plots were created by scaling down the distribution of samples in multidimensional space to 2 dimensions, until a stress value of approximately 0.05 was reached. Finally, stress plots were created to assess whether the original dissimilarities were well preserved in the reduced number of dimensions of the NDMS plot.

The epibenthic community structure in terms of species abundance and diversity was calculated for the main relevant clusters identified from the hierarchical cluster analysis, i.e. wind farms and substrate types. Mean species abundance (A) was calculated from the numerical SACFOR abundance data, which included data of both individual and clustering species. Diversity is described by species richness (S), species evenness (E) and Shannon diversity index (H). Species richness is the number of species in a community. Species evenness describes the distribution of abundance across the species in a community. A higher evenness implies that the species are present in more similar proportions, meaning that the community is more diverse. The Shannon diversity index combines species richness and evenness by taking into account both the number of species and their relative abundance. A higher Shannon index corresponds to a higher species diversity. Species richness (S) was calculated by counting the number of species within a certain cluster. The Shannon diversity index (H) was calculated as $H = -\Sigma(Pi^{*}\ln[Pi])$, where Pi is the proportion of species i relative to the total number of species. Species evenness (E) was calculated by dividing the Shannon diversity index H by the natural logarithm of species richness $ln(S)$ ($E = H / ln(S)$).

Because the diversity of a community is positively correlated to the number of frames observed, the dataset was first balanced by applying the Monte Carlo resampling strategy. For each cluster *wind farm x seabed type*, an equal amount of video frames was randomly selected from the entire set, and this process was repeated 100 times. The amount of selected video frames equalled the minimum amount of frames available per seabed type within the cluster, i.e. Belwind $N = 20$, Gemini $N = 31$, Luchterduinen $N = 19$, Princess Amalia $N = 28$. The average of these 100 random selections provided a balanced dataset per wind farm on which further analyses were performed. When a species was not observed, abundance was assumed to be zero. In all cases, the results presenting variability refer to the standard deviation of the mean.

To investigate differences between the community structure at the three types of seabeds within the wind farms, analysis of variance (ANOVA) was used. This was combined with Tukey-test for comparing means with a significance level of $p \leq 0.05$.

3. Results

In total, over 10 h of ROV video footage was collected, from which 1497 video frames were selected for analysis, based upon image quality that allowed for identification up to species level (see Table 2). The frames covered on average 0.061 ± 0.017 m^2 per frame, without significant variation between the wind farms and seabed types ($p = 0.55$). The number of frames analysed varied between windfarms, turbines and seabed type due to variation in video quality and number of radial transects flown per turbine. Wind farm Belwind had the lowest number of analysed video frames, mainly due to low light conditions, which often made the footage unsuitable for analysis as species smaller than 5 cm could not be identified. In each wind farm, the number of analysed video frames for the transition zone were much lower than for the armour layer and sandy seabed, because the area covered by the transects was lowest in the transition zones. No species were observed in 210 of the 1497 video frames. These were all recorded above the sandy seabed, and most of them in wind farm Belwind (60%).

3.1. *Species inventory*

In total, 47 species from 7 different phyla were identified from the video footage, of which 15 species could only be identified at genus level. Table 3 shows for each species the total number of observations (left), and the mean SACFOR abundance and number of observations per wind farm (middle) as well as per seabed type (right). Many species (21) were observed at all seabed types in all wind farms, the most common being anemones (*Metridium senile* and *Sagartia* spec.), the edible crab (*Cancer pagurus*), swimming crabs (*Liocarcinus* spec., *Necora puber*), the common starfish (*Asterias rubens*), gobies (*Gobius* spec.), and cod-like fish (*Trisopterus* spec., *Gadus morhua*). Some species were mainly or uniquely observed at the scour protection, such as the dead men's finger (*Alcyonium digitatum*), the common lobster (*Homarus gammarus*), tunicates (*Diplosoma*), goldsinny wrasse (*Ctenolabrus rupestris*), and the rock gunnel (*Pholis gunnellus*). Other species were mainly or uniquely recorded at the sandy seabed, such as the mason sand worm (*Lanice conchilega*), the sand sea star (*Astropecten irregularis*), dragonets (*Callionymus*), and the common sole (*Solea solea*). Ten species were only observed once, unrelated to wind farm or seabed type, and discarded from further analyses to minimize noise in the data caused by rare species.

3.2. *Species groups per wind farm*

The hierarchical clustering of all offshore windfarms and the three survey locations (turbines) within each wind farm showed a clustering at ~50% dissimilarity in species composition of the offshore windfarms Luchterduinen and Princess Amalia located near the West coast of The Netherlands compared to Gemini and Belwind located respectively north of the Wadden Sea and near the coast of Belgium (Fig. 3Figure 3; left). Wind farms Luchterduinen and Princess Amalia have a fairly similar species composition (~30% dissimilarity), as is to be expected because they are closely located. A NMDS plot confirmes this clustering (Figure 3; right), and illustrates that some species were more associated to certain wind farms than to others. For example, the sand sea star *A. irregularis (air)* was only observed in the most northernly located wind farm Gemini and the sea beard *Nemertesia (nem)* only in Belwind, while common species such as the plumose anemone *M. senile (mse)*, edible crab *C. pagurus (cpa)*, and common starfish *A. rubens (aru)*, were observed in all windfarms.

3.3. *Species groups per seabed type*

The hierarchical clustering of the seabed types and the surveyed locations in the wind farms showed a clustering at ~80% dissimilarity of the species composition mostly associated with the armour layer compared to the sandy seabed (Fig. 4; left). The transition zone can be described as a habitat containing both rocks and sand, and the epibenthic community associated with this seabed type clusters therefore mainly with either the armour layer or the sandy seabed. The NDMS plot (Fig. 4; right) illustrates the distinction of the epibenthic species between the armour layer and sandy seabed, as well as its overlapping properties in the transition zone. Species with a preference for a certain seabed type can be clearly distinguished, such as *Jassa (jas)* and dead men's thumb *Alcyionidium digitatum (adi)* have for the armour layer, and brittle star *Ophiura (oph)* and common hermit crab *Pagurus bernardus (pbe)* for the sandy seabed.

3.4. *Epibenthic community structure*

Comparisons among the epibenthic communities are made between wind farms and seabed type using the attributes species richness (S), species evenness (E), Shannon diversity index (H) and SACFOR abundance (A). Using the balanced dataset of each wind farm, the means for each attribute per wind farm and seabed type were calculated. The mean species richness, the mean species evenness, and the mean Shannon diversity index of the balanced dataset generally differed between wind farms and per seabed type within a wind farm, while the mean SACFOR abundance more often did not vary between communities.

Species richness (S) was significantly highest for the communities at the armour layer in both Belwind ($p < 0.001$) and Gemini ($p < 0.001$), and lowest at the armour layer in Luchterduinen ($p < 0.001$) and Princess Amalia ($p < 0.001$). Species richness did not differ between the communities at the transition zone and sandy seabed in Luchterduinen ($p = 0.31$), and between the armour layer and sandy seabed in Princess Amalia ($p = 0.67$) (see Fig. 5-I).

Species evenness (E) was remarkably high at the sandy seabed in Belwind ($p < 0.001$) (see Fig. 5-II), which is explained by a relatively high amount of samples of videoframes ($N = 23$) in which only a small amount of species (2–4) was observed that all were represented by only 1 individual per framework. Similar to the diversity indicator species richness, species evenness was lowest at the sandy seabed in Gemini ($p < 0.001$), lowest at the armour layer in Luchterduinen ($p < 0.001$) and Princess Amalia ($p < 0.001$), and did not significantly differ between the communities at the armour layer and sandy seabed in Princess Amalia ($p = 0.052$).

Table 2
The number of video frames analysed and area covered per seabed type in each wind farm.

	Belwind		Gemini		Luchterduinen		Princess Amalia		All wind farms	
Seabed type	number (#)	area (m^2)	number (#)	area (m^2)	number (#)	area (m^2)	number (#)	area (m^2)	number (#)	area (m^2)
Armour layer	116	7.23	212	13.29	125	7.23	188	13.73	641	41.47
Transition zone	20	1.23	31	1.92	19	1.08	28	1.84	98	6.08
Sand	160	9.81	195	11.71	176	9.59	227	12.15	758	43.27
Total	296	18.27	438	26.92	320	17.90	443	27.72	1497	90.82

Table 3

Mean abundance per species by offshore windfarm and by seabed type, using the numerical SACFOR scale. Superabundant = 7, Abundant = 6, Common = 5, Frequent = 4, Occasional = 3, Rare = 2, Present = 1.

Phylum	Species	Observations	Offshore wind farm								Seabed type					
	(code)		Belwind		Gemini		Luchterduinen		Princess Amalia		armour layer		transition zone		sand	
		(# frames)	N	mean(±sd)	N	mean(±sd)	N	mean(±sd)	N	mean(±sd)	N	mean(±sd)	N	mean(±sd)	N	mean(±sd)
Porifera	*Cliona celata*[*#] *(cce)*	1			1	1							1	1		
	Suberites ficus[#] *(sfi)*	2	1	3	1	3					2	3(±0)				
Cnidaria	*Actinothoe sphyrodeta (asp)*	92	16	5.7(±0.5)			1	5	75	5.8(±0.6)	79	5.9(±0.6)	6	5.5(±0.5)	7	5.1(±0.4)
	Alcyonium digitatum[#] *(adi)*	16	1	4	4	1.8(±0.5)			11	1.5(±0.5)	15	1.7(±0.8)	1	1		
	Diadumene cincta (dci)	6	1	5					5	5.6(±0.5)	5	5.6(±0.5)			1	5
	Halecium[*#] *(hal)*	1			1	3					1	3				
	Hydractinia echinate[#] *(hec)*	16					8	1.1(±0.4)	8	1.3(±0.7)	1	3			15	1.1(±0.3)
	Metridium senile[#] *(mse)*	556	118	6.7(±0.5)	105	6.5(±0.5)	126	6.9(±0.3)	207	6.9(±0.3)	497	6.8(±0.4)	47	6.5(±0.5)	12	6.2(±0.4)
	Nemertesia[#] *(nem)*	11	11	3.9(±1.3)							11	3.9(±1.3)				
	Sagartia (sag)	77	5	6(±0)	34	6.1(±0.4)	16	6.5(±0.5)	22	6.2(±0.4)	33	6.2(±0.5)	23	6.2(±0.4)	21	6.2(±0.4)
	Sagartia elegans[#] *(sel)*	210	30	6.7(±0.4)	99	6.3(±0.5)	28	6.7(±0.5)	53	6.7(±0.5)	198	6.5(±0.5)	10	6.1(±0.3)	2	6(±0)
	Sagartia troglodytes (str)	91			13	6.1(±0.3)	58	6.6(±0.5)	20	6.2(±0.4)	17	6.3(±0.5)	26	6.4(±0.5)	48	6.5(±0.5)
	Sagartiogeton undatus (sun)	14			5	6.2(±0.4)	1	6	8	6(±0)	6	6(±0)	3	6.3(±0.6)	5	6(±0)
	Urticina (urt)	15	5	6(±0)	6	6(±0)	2	6(±0)	2	6(±0)	12	6(±0)	1	6	2	6(±0)
Annelida	*Lanice conchilega (lco)*	435	14	5.2(±0.4)	124	5.5(±0.5)	90	5.7(±0.8)	207	6.2(±0.7)	3	6(±0)	21	6(±0.7)	411	5.9(±0.8)
Arthropoda	*Cancer pagurus (cpa)*	176	20	6.9(±0.3)	93	7(±0)	17	6.9(±0.2)	46	6.9(±0.2)	151	7(±0.2)	16	7(±0)	9	7(±0)
	Caprella[*] *(cap)*	1					1	5			1	5				
	Homarus gammarus (hga)	3			3	7(±0)					3	7(±0)				
	Hyas[*] *(hya)*	1	1	6							1	6				
	Inachus (ina)	8					2	5(±0)	6	5.2(±0.4)	2	5(±0)	1	5	5	5.2(±0.4)
	Jassa[#] *(jas)*	13							13	4.2(±1.1)	13	4.2(±1.1)				
	Liocarcinus (lio)	94	1	6	35	6(±0)	42	6(±0)	16	6(±0)	10	6(±0)	4	6(±0)	80	6(±0)
	Necora puber (npu)	233	40	6(±0)	78	6(±0)	40	6(±0.2)	75	5.9(±0.3)	190	6(±0.2)	25	6(±0)	18	6(±0)
	Pagurus bernhardus (pbe)	41	2	6(±0)	4	6(±0)	20	6(±0)	15	6(±0)	2	6(±0)			39	6(±0)
	Pisidia longicornis (plo)	2					1	5	1	5	2	5(±0)				
Mollusca	*Alloteuthis*[*] *(all)*	1	1	7											1	7
	Mytilus edulis[#] *(med)*	27	15	5.6(±0.5)			10	5.8(±0.8)	2	6(±0)	20	5.8(±0.6)	2	5.5(±0.7)	5	5.4(±0.5)
	Sepia officinalis[*] *(sof)*	1	1	7											1	7
Echinodermata	*Asterias rubens (aru)*	336	32	7(±0)	99	7(±0)	117	7(±0.1)	88	6.9(±0.2)	130	6.9(±0.2)	42	7(±0)	164	7(±0)
	Astropecten irregularis (air)	22			22	6(±0)					2	6(±0)	2	6(±0)	18	6(±0)
	Ophiura (oph)	24	1	6	3	6(±0)	7	6(±0)	13	6(±0)			1	6	23	6(±0)
Chordata	*Callionymus (cal)*	23			6	6(±0)	5	6(±0)	12	6(±0)	1	6	1	6	21	6(±0)
	Chelidonichthys lucerna[*] *(clu)*	1			1	7									1	7
	Ctenolabrus rupestris (cru)	17	1	6	16	6(±0)					17	6(±0)				
	Diplosoma[#] *(dip)*	21	6	2(±1.1)	15	2(±0.5)					21	2(±0.7)				
	Entelurus aequoreus[*] *(eae)*	1							1	7					1	7
	Gadus morhua (gmo)	16	1	7	14	7(±0)			1	6	11	6.9(±0.3)	4	7(±0)	1	7
	Gobius (gob)	114	9	6(±0)	19	6.1(±0.2)	56	6(±0.1)	30	6(±0)	8	6(±0)	8	6.1(±0.4)	98	6(±0.1)
	Mullus surmuletus (msu)	12	3	7(±0)	7	7(±0)			2	6.5(±0.7)	3	6.7(±0.6)	1	7	8	7(±0)
	Myoxocephalus (myo)	3			2	7(±0)	1	7			2	7(±0)	1	7		
	Parablennius gattorugine[*] *(pga)*	1							1	6			1	6		
	Pholis gunnellus (pgu)	7			5	7(±0)	2	7(±0)			7	7(±0)				
	Platichthys flesus[*] *(pfl)*	1							1	7					1	7
	Solea solea (sso)	6	2	7(±0)	4	7(±0)					1	7	1	7	4	7(±0)
	Syngnathus (syn)	3							3	7(±0)					3	7(±0)
	Taurulus bubalis[*] *(tbu)*	1					1	6			1	6				
	Trisopterus (tri)	50	22	7(±0)	4	7(±0)	4	6.8(±0.5)	20	7(±0.2)	40	7(±0.2)	7	7(±0)	3	7(±0)

[*] Species excluded from data analyses.

[#] Clustering species.

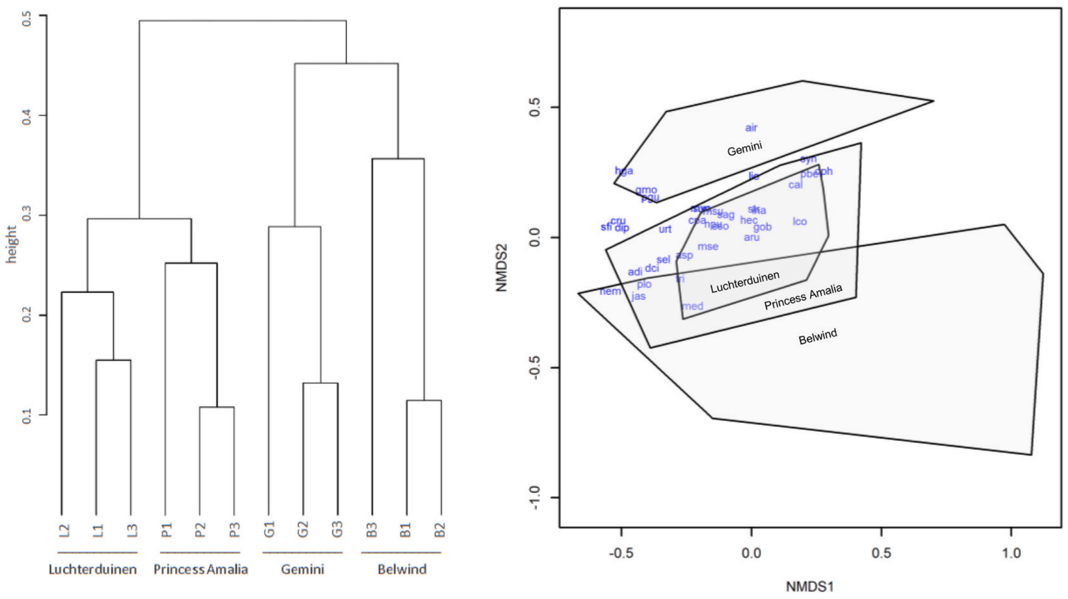

Fig. 3. Hierarchical cluster dendogram (left) and NMDS plot (right) of the benthic community structure of the three surveyed locations within each of the wind farms. Dendrogram based on Bray Curtis dissimilarity distances calculated from mean numerical SACFOR species abundances (abbreviations indicate wind farm (B-G-L-P) and location number (1–2–3)). NMDS plot (stress = 0.05) shows species (3-letter codes) in relation to each wind farm (polygons).

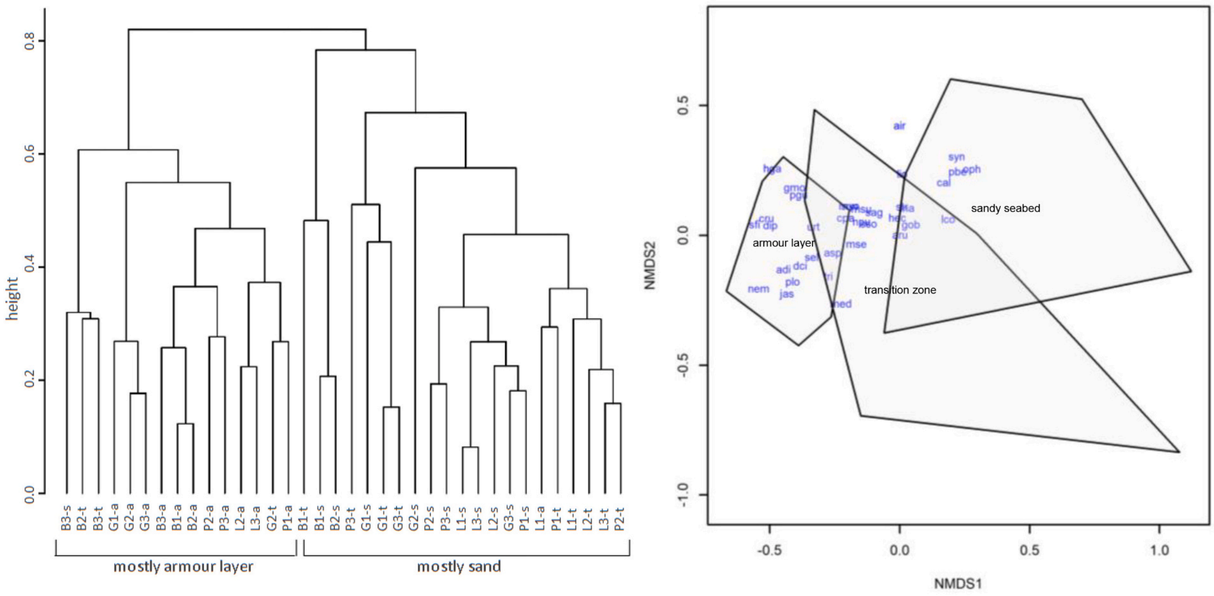

Fig. 4. Hierarchical cluster dendogram (left) and NMDS plot (right) of the benthic community structure of the different seabed types at the surveyed locations within the wind farms. Dendrogram based on Bray Curtis dissimilarity distances calculated from mean numerical SACFOR species abundances (abbreviations indicate wind farm (B-G-L-P), location number (1-2-3) and seabed type (a-t-s)). NMDS plot (stress = 0.05) shows species (3-letter codes) in relation to each seabed type (polygons).

Comparing communities between the armour layer and the sandy seabed shows a significantly higher Shannon diversity index (H) at the armour layer in wind farms Belwind ($p < 0.001$) Gemini ($p < 0.001$) and Princess Amalia ($p < 0.001$), but a lower species diversity at the armour layer in Luchterduinen ($p < 0.001$) (see Fig. 5-III). The area defined as a transition zone has significantly the highest Shannon diversity index wind in farms Gemini ($p < 0.001$; filter layer) and Princess Amalia ($p < 0.001$; no filter layer).

The mean abundance using SACFOR scale (A) ranged from 5.9 ± 0.7 at the sandy seabed in Belwind to 6.7 ± 0.5 at the armour layer in Luchterduinen (see Fig. 5-IV), which translates to 'abundant epibenthic marine life'. Mean SACFOR abundances differed between wind farms at the armour layer ($p < 0.001$), but not at the transition zone ($p = 0.14$), and mostly not at the sandy seabed (only between Princess Amalia and Gemini ($p = 0.01$) and Princess Amalia and Luchterduinen ($p = 0.01$)). Mean SACFOR abundance was lowest at the sandy seabed in each windfarm (Belwind $p < 0.001$; Gemini $p < 0.001$; Luchterduinen $p < 0.001$; Princess Amalia $p = 0.16$, n.s.).

4. Discussion

4.1. ROV video monitoring

This study provides insight in the structure of epibenthic

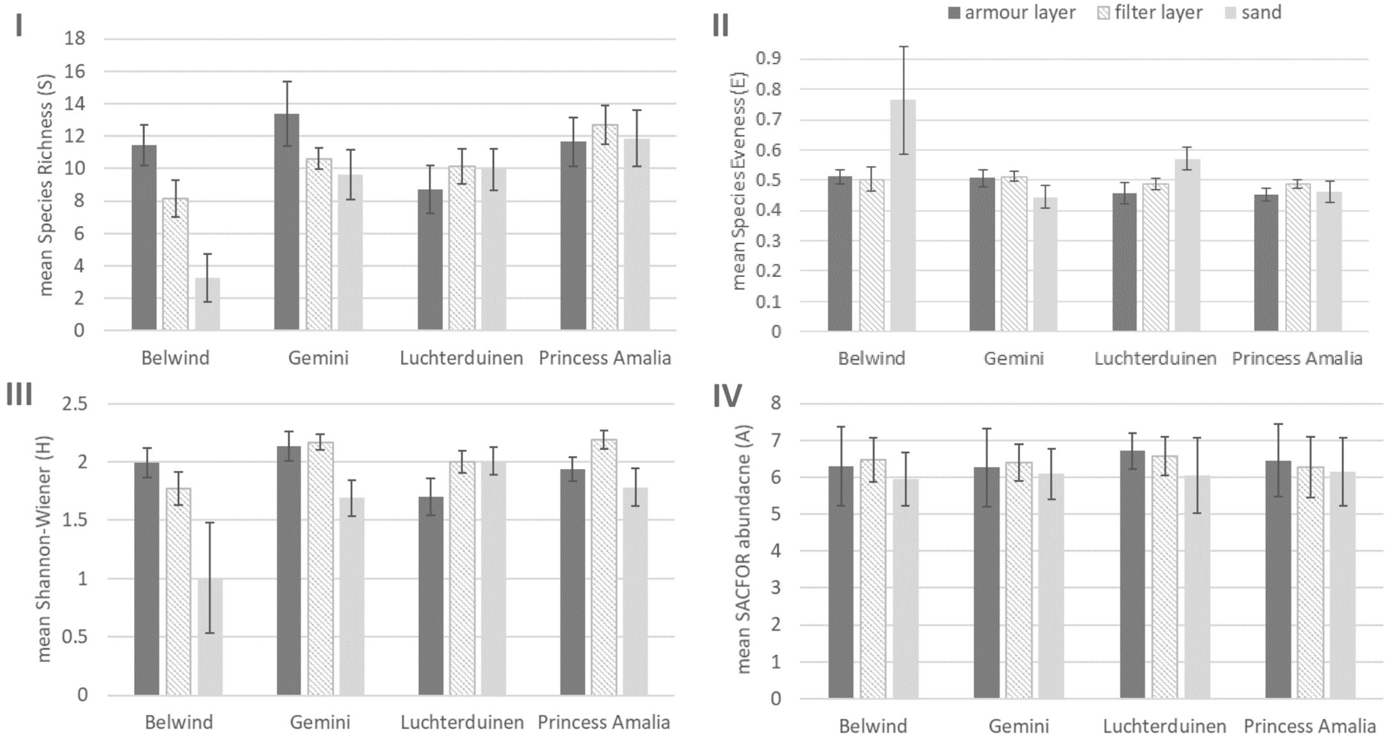

Fig. 5. Community attributes for different seabed types in the four offshore windfarms. I) mean (± SD) Species Richness (S), II) mean (± SD) Species Evenness (E), III) mean (± SD) Shannon-Wiener diversity (H), and IV) mean (± SD) abundance using SACFOR scale (A).

communities living at and around scour protections in four offshore wind farms in the southern North Sea. A rich epibenthic species community was observed using ROV footage, consisting of 47 species from 7 different phyla. This is slightly higher compared to other ROV studies of hard substrate associated communities on offshore oil and gas platforms in the southern North Sea. For example Van der Stap et al. (2016) reported 30 taxa from 7 phyla, and Schutter et al. (2019) observed 38 species from 8 phyla. These lower numbers of species abundance compared to our study can likely be explained as these studies used ROV footage collected for inspections of the technical integrity of the installations, while our monitoring with ROV was designed specifically for biological research. It should be noted that ROV surveys underestimate the abundance and diversity of a benthic community. Video footage collected along transects only shows benthic organisms present on the surface, not those that are hidden in cavities, underneath fouling layers, or in the seabed. Furthermore, limitation in light, unstable footage due to movement of the camera, and a required distance between the camera and the substrate, make it difficult to identify small-sized organisms. More detailed monitoring techniques such as visual observations by scientific divers and taking samples for analyses under laboratory conditions, would result in higher diversity estimates of the community. Coolen et al. (2020) assessed data from studies of the epibenthic community at the scour protection in wind farm Princess Amalia by Vanagt et al. (2013) and Vanagt and Faasse (2014). Small rocks were collected at random locations around four turbine foundations, and on these rocks 95 species were identified. This is twice the amount as observed during our ROV survey. In particular, the accurate analysis of samples in a laboratory contributes to a higher biodiversity estimate, as it allows species identification at a microscopic level.

4.2. Comparing wind farms

The variation in species presence at (artificial) reefs depends on various drivers, such as age, materials used, and complexity of the structures. Epifouling communities on offshore installations evolve over time with dominance changing among species (Whomersley and Picken, 2003), and species richness may increase with installation age (Van der Stap et al., 2016). Texture and structure of marine constructions determine settlement and growth conditions for algae and macrobenthos (Borsje et al., 2011; Green et al., 2012). Structural complexity of (artificial) reefs, e.g. by means of crevices and pits, increases the abundance and diversity of benthic species living at and in the structures (Lapointe and Bourget, 1999; Firth et al., 2014). When comparing these drivers that determine a community structure, no major differences are observed between the four studied wind farms. Wind farm Gemini does have a smaller rock grading of the armour layer than the other three wind farms, and both Belwind and Princess Amalia do not have a filter layer. These differences in rock material used in the scour protection were not reflected in the associated epibenthic communities. However, in general the scour protections in the four wind farms studied do not differ much in age (about 5 years maximum), face relatively similar offshore conditions in terms of depths and hydrodynamics, and are structurally comparable, i.e. pancake shapes made of quarried rock with a transition zone between an armour layer and the surrounding seabed. Therefore, it is not unexpected that no remarkable differences in community structure were observed between the wind farms using hierarchical clustering, showing a similarity of ~50% between the wind farms. More variation in the scour protections, for example in shape, dimensions and rock grading would probably have resulted in a more distinct benthic communities, as habitat complexity generally leads to more diversity in marine life (Lapointe and Bourget, 1999; Firth et al., 2014; Consoli et al., 2018). The similarity in epibenthic community structure is also shown as most of the species are observed in multiple wind farms, and generally no major differences in species abundance were observed between the wind farms. Wind farms Luchterduinen and Princess Amalia are most similar in epibenthic community structure (~70%), likely because these two wind farms have a similar rock grading at the armour layer (10-200 kg) and are geographically closely located (21 km centre-centre). Benthic communities in newly created habitats such as these wind farms, are likely more similar within a closer geographic range as the larval distribution of benthic organisms in the North Sea is generally limited to distances up to tens of kilometres only (Mayorga-Adame et al., 2022).

4.3. Effect of seabed type on epibenthic communities

Our observations indicate that seabed type is a much stronger explanator of the epibenthic community structure than wind farm. Clusters of 'mostly armour layer' and 'mostly sandy seabed' were distinguished at ~80% dissimilarity, which means that the epibenthic community at these seabed types is similar in structure for approximately 20% only. Species abundance and species diversity of epibenthic communities are generally higher at rocky habitats than in sandy systems (e.g. Buhl-Mortensen et al., 2012), as a rocky habitat can be very stable to support a variety of marine organisms, while a sandy system is unstable at its surface as the fine mineral particles are easily moved by currents and waves. In line with this, our observations show that the epibenthic communities have lowest species abundances at the sandy seabed in each of the four windfarms. Also, species diversity (richness, evenness, Shannon index) is generally highest for the community at the armour layer in both Belwind and Gemini, although little differences were observed in Princess Amalia and species diversity was unexpectedly higher at the sandy seabed than at the armour layer in Luchterduinen, for which no clear explanation can be provided. Fact remains that the deployment of rock material as scour protection at the base of wind turbines results in the creation of isolated rocky habitats in a sandy environment. This allows the accumulation of both rocky and sandy species communities in a wind farm, leading to an increase of total biodiversity in the area, meaning that a wind farm area would host a more diverse epibenthic community than the surrounding areas. One could further stimulate the abundance and diversity of the epibenthic community structure around wind turbines by providing more complexity in the scour protection by means of shape and materials used, proving habitat and shelter to both rocky and sandy species. The scour protection itself provides a three-dimensional hard-substrate habitat which is used by marine life to settle, forage and shelter. Changing its conventional flat pancake shape into a star shape or even more organic amoeboid shape, with irregular extensions in both vertically and horizontally directions by making heaps and berms, will increase surface area and provide many leesides for shelter. Narrowing down the grading width of the rocks used will result in more crevices between the rocks that can be inhabited by marine life. An additional variation in rock size at different areas of the scour protection would offer different sized cavities, serving a wider size-range of rock-dwelling species. The use of calcareous rock such as limestone or marble, will trigger increased settlement by shellfish (Hidu et al., 1975; Soniat et al., 1991), opposed to the conventionally used non-calcareous rock such as granite and eclogite. In addition, these small islands of scour protection in offshore wind farms provide stepping stones for rock-dwelling species (Adams et al., 2014), which may enhance the movement of these species throughout the North Sea. Therefore, the installation of wind turbine infrastructure and adjustments thereof, is expected to have an effect on epibenthic communities at the scale of the wind farm itself, as well as at the wider area.

5. Conclusion

Offshore wind farms are observed to have a positive effect on epibenthic communities during their operational lifetime (e.g. Bergström et al., 2013; De Mesel et al., 2015; Raoux et al., 2017). The absence of bottom-disturbing activities such as bottom-trawl fisheries, and also the installation of wind farms structures, provide refuge and complex habitat to many benthic species (Coates et al., 2014; Langhamer, 2012; Petersen and Malm, 2006). An increase in benthic life will provide additional food sources for the higher trophic levels, including fish, mammals and birds (Reubens et al., 2014; Russell et al., 2014). Our study shows that the epibenthic community at the scour protection in offshore wind farms is different from the community living at the surrounding seabed. Species abundance was found to be higher on the scour protection than on the surrounding seabed. Also species typically associated with rocky habitat such as lobster and several fish species, were observed to inhabit the scour protection. This demonstrates that marine life can benefit from scour protection in offshore wind farms, as these provide hard substrate that otherwise would not be present in the area. Rock-dwelling species now get an opportunity to thrive in the largely sandy system of the southern North Sea. This study shows that the addition of scour protection results in a higher abundance and diversity of epibenthic species in offshore wind farms. Integrating tailor-made components into the design of scour protection that further benefit epibenthic biodiversity could assist new wind farms to contribute to biodiversity in the North Sea.

Contributors

RtH designed the research, analysed the data and wrote the manuscript, FMFD analysed the ROV videos, PJE coordinated the ROV survey, MvK contributed to the outline of the manuscript, MS contributed to the data-analyses. All authors reviewed and commented on versions of the manuscript before submission.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Adams, T., Miller, R.G., Aleynik, D., Burrows, M.T., 2014. Offshore marine renewable energy devices as stepping stones across biogeographical boundaries. J. Appl. Ecol. 51, 330–338.

Bergström, L., Sundqvist, F., Bergström, U., 2013. Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community. Mar. Ecol. Prog. Ser. 485, 199–210.

Borsje, B.W., van Wesenbeeck, B.K., Dekker, F., Paalvast, P., Bouma, T.J., van Katwijk, M.M., de Vries, M.B., 2011. How ecological engineering can serve in coastal protection. Ecol. Eng. 37 (2), 113–122.

Bos, O.G., Witbaard, R., Lavaleye, M., Van Moorsel, G., Teal, L.R., Van Hal, R., van der Hammen, T., Ter Hofstede, R., van Bemmelen, R., Witte, R.H., Geelhoed, S., Dijkman, E.M., 2011. Biodiversity Hotspots on the Dutch Continental Shelf: A Marine Strategy Framework Directive perspective. IMARES, IJmuiden. Report C071/11 (145 pp).

Buhl-Mortensen, L., Buhl-Mortensen, P., Dolan, M.F.J., Dannheim, J., Bellec, V., Holte, B., 2012. Habitat complexity and bottom fauna composition at different scales on the continental shelf and slope of northern Norway. Hydrobiologia 685, 191–219.

Coates, D.A., Deschutter, Y., Vincx, M., Vanaverbeke, J., 2014. Enrichment and shifts in macrobenthic assemblages in an offshore wind farm area in the Belgian part of the North Sea. Mar. Environ. Res. 95, 1–12.

Connor, D.W., Allen, J.H., Golding, N., Howell, K.L., Lieberknecht, L.M., Northen, K.O., Reker, J.B., 2004. The Marine Habitat Classification for Britain and Ireland. Version 04.05. JNCC, Peterborough (ISBN 1 861 07561 8).

Consoli, P., Mangano, M.C., Sarà, G., Romeo, T., Andaloro, F., 2018. The influence of habitat complexity on fish assemblages associated with extractive platforms in the Central Mediterranean Sea. Adv. Oceanogr. Limnol. 9 (2), 59–67.

Coolen, J.W.P., Bos, O.G., Glorius, S., Lengkeek, W., Cuperus, J., van der Weide, B.E., Agüera, A., 2015. Reefs, sand and reef-like sand: a comparison of the benthic biodiversity of habitats in the Dutch Borkum reef grounds. J. Sea Res. 103, 84–92.

Coolen, J.W.P., van der Weide, B.E., Cuperus, J., Blomberg, M., van Moorsel, G.W.N.M., Faasse, M.A., Bos, O.G., Degrear, S., Lindeboom, H.J., 2020. Benthic biodiversity on old platforms, young wind farms and rocky reefs. ICES J. Mar. Sci. 77 (3), 1250–1265.

De Mesel, I., Kerckhof, F., Norro, A., Rumes, B., Degraer, S., 2015. Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species. Hydrobiologia 756, 37–50.

Dutch Ministry of Economic Affairs and Climate, 2022. Regeling vergunningverlening windenergiegebied Hollandse Kust (west) kavel VI. Staatscourant 7107 (01) (16 pp).

Firth, L.B., Thompson, R.C., Bohna, K., Abbiati, M., Airoldi, L., Bouma, T.J., Bozzeda, F., Ceccherelli, V.U., Colangelo, M.A., Evans, A., Ferrario, F., Hanley, M.E., Hinz, H., Hoggart, S.P.G., Jackson, J.E., Moore, P., Morgan, E.H., Perkol-Finkel, S., Skov, M. W., Strain, E.M., van Belzen, J., Hawkins, S.J., 2014. Between a rock and a hard place: environmental and engineering considerations when designing coastal defence structures. Coast. Eng. 87, 122–135.

Green, D.S., Chapman, M.G., Blockley, D.J., 2012. Ecological consequences of the type of rock used in the construction of artificial boulder-fields. Ecol. Eng. 46, 1–10.

Gross, F., Smyth, J., 1946. The decline of oyster populations. Nature 157, 540–542.

Hidu, H., Chapman, S., Soule, P.W., 1975. Cultchless setting of European oysters, Ostrea edulis, using polished marble. Proceedings of the National Shellfish Association 65, 13–14.

Korringa, P., 1952. Recent advances in oyster biology. Q. Rev. Biol. 27 (4), 339–365.

Langhamer, O., 2012. Artificial reef effect in relation to offshore renewable energy conversion: state of the art. Sci. World J. 8. https://doi.org/10.1100/2012/386713, 386713.

Lapointe, L., Bourget, E., 1999. Influence of substratum heterogeneity scales and complexity on a temperate epibenthic marine community. Mar. Ecol. Prog. Ser. 189, 159–170.

Leewis, R.J., van Moorsel, G.W.N.M., Waardenburg, H.W., 2000. Shipwrecks on the Dutch continental shelf as artificial reefs. In: Jensen, A.C., Collins, K.J., Lockwood, A. P.M. (Eds.), Artificial Reefs in European Seas. Kluwer Academic Publishers, Dordrecht, pp. 419–434.

Mayorga-Adame, C.G., Polton, J.A., Fox, A.D., Henry, L.A., 2022. Spatiotemporal scales of larval dispersal and connectivity among oil and gas structures in the North Sea. Mar. Ecol. Prog. Ser. 685, 49–67.

Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Wagner, H., 2014. Vegan: Community Ecology Package. R Package Version 2.2–0. http://CRAN.Rproject.org/package=vegan.

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.

Petersen, J.K., Malm, T., 2006. Offshore windmill farms: threats to or possibilities for the marine environment. AMBIO: a journal of the human. Environment 35 (2), 75–80.

Poos, M.S., Jackson, D.A., 2012. Addressing the removal of rare species in multivariate bioassessments: the impact of methodological choices. Ecol. Indic. 18, 82–90. https://doi.org/10.1016/j.ecolind.2011.10.008.

R Core team, 2016. R: A language and envrionemnt for statistical computing. R foundation for Statistical Computing, Vienna, Austria.

Raoux, A., Tecchio, S., Pezy, J.P., Lassalle, G., Degraer, S., Wilhelmsson, D., Cachera, M., Ernande, B., Le Guen, C., Haraldsson, M., Grangeré, K., Le Loc'h, F., Dauvin, J.C., Niquil, N., 2017. Benthic and fish aggregation inside an offshore wind farm: which effects on the trophic web functioning? Ecol. Indic. 72, 33–46.

Reubens, J.T., Degraer, S., Vincx, M., 2014. The ecology of benthopelagic fishes at offshore wind farms: a synthesis of 4 years of research. Hydrobiologia 727, 121–136.

Russell, D.J.F., Brasseur, S.M.J.M., Thompson, D., Hastie, G.D., Janik, V.M., Aarts, G., McClintock, B.T., Matthiopoulos, J., Moss, S.E.W., McConnell, B., 2014. Marine mammals trace anthropogenic structures at sea. Curr. Biol. 24 (14), 638–639.

Schutter, M., Dorenbosch, M., Driessen, F.M.F., Lengkeek, W., Bos, O.G., Coolen, J.W.P., 2019. Oil and gas platforms as artificial substrates for epibenthic North Sea fauna: effects of location and depth. J. Sea Res. 153, 101782.

Soniat, T.M., Broadhurst, R.C., Haywood, E.L., 1991. Alternatives to clamshell as cultch for oysters, and the use of gypsum for the production of cultchless oysters. Journal of Shellfish Resesearch 10, 405–410.

Ter Hofstede, R., Williams, G., Van Koningsveld, M., 2022. The potential impact of human interventions at different scales in offshore wind farms to promote flat oyster (*Ostrea edulis*) reef development in the southern North Sea.

Thorpe, S.A., 2012. On the biological connectivity of oil and gas platforms in the North Sea. Mar. Pollut. Bull. 64, 2770–2781.

Van der Stap, T., Coolen, J.W.P., Lindeboom, H.J., 2016. Marine fouling assemblages on offshore gas platforms in the southern North Sea: effects of depth and distance from shore on biodiversity. PLoS One 11 (1) (16 pp).

Vanagt, T., Faasse, M., 2014. Development of hard substratum fauna in the Princess Amalia wind farm. Monitoring six years after construction. In: eCOAST report 2013009. Oostende, Belgium (106 pp).

Vanagt, T., Van de Moortel, L., Faasse, M.A., 2013. Development of Hard Substrate Fauna in the Princess Amalia Wind Farm. eCOAST Report 2011036. Oostende, Belgium (42 pp).

Whomersley, P., Picken, G.B., 2003. Long-term dynamics of fouling communities found on offshore installations in the North Sea. J. Mar. Biol. Assoc. U. K. 83, 897–901.