A wind of change for soft-sediment infauna within operational offshore windfarms

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ABSTRACT

In this study, "artificial reef" (AR) impacts of offshore windfarms (OWFs) on the surrounding soft-sediments were investigated. Benthic grab samples were collected at nearby (37.5 m) and distant (500 or 350 m) positions from turbines of two Belgian OWFs (Belwind: monopiles and C-Power: jackets). Higher macrobenthos abundance and species richness were found nearby jacket foundations of C-Power compared to distant positions and differences were most pronounced within deeper sediments (i.e., gullies between sandbanks) at intermediate levels of fine sand fractions (10–20%) and total organic matter (0.5–0.9%). Strong benthic enrichment (>1000 ind. m^{-2}, >20 spp. sample^{-1}) was also linked with higher fine sand fractions ($>20\%$) near the jackets. Moreover, nearby sediments showed higher occurrences of coastal species and habitat diversification was promoted by *Mytilus edulis* shell debris and alive organisms ("biofouling drop-offs"). The lack of similar results around monopiles (Belwind) confirms that the extent of detectable AR-effects depends on site- and turbine specific factors.

1. Introduction

With the implementation of the European Green Deal, the European Union (EU) aspires to be climate-neutral by 2050 (Papalexandrou, 2021). The combination of rough weather conditions and the relatively shallow bathymetry of the North Sea make this area the perfect platform for offshore wind energy development (ICES, 2018). As a result, this maritime industry has been put forward as a cornerstone of the energy transition within the EU (Lindeboom et al., 2015). However, the associated expansion of man-made structures also involves pressures that can affect different ecosystem components, including soft-sediment benthic communities (Dannheim et al., 2020; Methratta, 2021; Coolen et al., 2022). Macrobenthic distribution patterns in the North Sea are tightly associated with local physico-chemical properties such as water depth, wave and current regimes, sediment type and food availability (Armonies et al., 2014; Breine et al., 2018; Armonies, 2021). Therefore, it is believed that the long-term presence of underwater structures during the operational phase of an OWF may result in the modification of soft-sediment habitats as a consequence of several changes that occur due the overarching "artificial reef" (AR) effect mechanism (Dannheim et al., 2020; Degraer et al., 2020).

Physical factors associated with the presence of artificial structures, such as the alteration of water-flow intensities and sediment resuspension patterns are known to influence local sediment granulometric properties and food availability around the turbines (Maar et al., 2009; De Backer et al., 2014; Coates et al., 2014; Dannheim et al., 2020). Moreover, biological factors such as the rapid colonization of hard substrates (i.e., turbines, erosion protection layers) by fouling fauna, increases overall biodiversity in these otherwise exposed soft-sediments (Coolen et al., 2020, 2022; Karlsson et al., 2022; Zupan et al., 2023). In addition, established biofouling communities are mainly composed of suspension feeders such as *Mytilus edulis* (blue mussel) and *Metridium senile* (anemone), which filter organic matter from the water column and organically enrich the surrounding seabed through the deposition of sediment and organic matter particles (Sverker and Kautsky, 1987; Maar et al., 2009; Mavraki et al., 2022). A final but eminent aspect of these biofouling communities is the process of "biofouling drop-offs", where entire organisms or parts (e.g., shell litter) fall off onto the surrounding soft-sediments (Keeley et al., 2013; Degraer et al., 2020; Hutchison et al., 2020). As such, the enhanced habitat complexity provided by these biofouling products might allow an expansion of the AR effect to areas further away from the turbines through the introduction of habitat-forming species and the concomitant ephemeral or even prolonged establishment of biogenic structures (Keeley et al., 2013;

Hutchison et al., 2020; Degraer et al., 2020).

Despite the clear identification of the main pressures and extensive description of potential long-term OWF effects on soft-sediment benthos, there is hardly any quantitative data to support the above hypotheses (Jak and Glorius, 2017). Most of the available information on OWF-related impacts arises from studies that have investigated patterns on the turbines and their immediate vicinity (<3 m), with an emphasis on fouling fauna and fish communities (Coolen et al., 2020; Gill et al., 2020; Glarou et al., 2020; Buyse et al., 2022; Zupan et al., 2023). In contrast, studies on soft-sediment benthic communities surrounding the foundations are scarce and usually performed within a relatively short time period (1–5 years) after construction (Zucco et al., 2006; Jak and Glorius, 2017). The fact that these effects act in a gradual manner, where impact intensity decreases with increasing distance from the turbines and with age (i.e., years since construction) of the OWF (Methratta, 2021), poses an additional challenge. Moreover, the described physical (i.e., altered water-flow and sedimentation patterns) and biological (i.e., "biofiltering" and "biofouling drop-off") impact factors related to the AR effect mechanism are strongly interlinked, which makes it difficult to investigate true cause-effect relationships and assess the complex benthic responses (e.g., nonlinear relationships) that they might induce (Lindeboom et al., 2015; Dannheim et al., 2020; Couce et al., 2020). Consequently, findings from classical monitoring surveys often fail to incorporate the spatio-temporal variability and complexity of turbine-related impacts and are not always suited to detect potential ecological changes of benthic communities within OWF sites.

The present study aims to tackle these issues by assessing turbine-induced infaunal responses in a quantitative way through a distance-based sampling strategy, in which benthic grab samples were collected over three consecutive years (2017–2019) at nearby and distant sampling positions within two long-term operational (≥5 years) Belgian OWFs (Belwind and C-Power). It is hypothesized that the proposed AR-related effects may progressively enrich the sediments adjacent to the foundations both in terms of fine sediment ("sediment fining hypothesis") and organic matter ("organic enrichment hypothesis") particles (Coates et al., 2014; Dannheim et al., 2020; Degraer et al., 2020). These sedimentary changes could in turn lead to a shift towards more abundant and diverse macrobenthic communities, comparable to the ones typically found within nearshore, finer-grained sediments (Wilding et al., 2012; Coates et al., 2014; De Backer et al., 2014; Breine et al., 2018). Given the applied sampling design, generalized additive models (GAMs) were used to test if biotic univariate indices (total abundance/species richness) are comparable between sampling positions (nearby vs. distant samples) and assess relationships with the environmental variables (i.e., water depth, granulometric properties and total organic matter content). Multivariate analyses were also performed to investigate whether nearby and distant sediments contain similar infauna in terms of community composition. Lastly, potential biofouling effects such as the introduction of drop-off material (e.g., shells, alive individuals) and increased habitat heterogeneity were also examined by means of a descriptive analysis of the nearby collected sediments during the last year of sampling (2019).

2. Material and methods

2.1. Study area

2.1.1. OWFs

Sampling was conducted in two OWFs located in the eastern concession zone of the Belgian Part of the North Sea (BPNS) namely, Belwind and C-Power (Fig. 1). The Belwind OWF (~17 km²) consists of 55 monopile foundations, which have been operational since 2010 (https://www.belgianoffshoreplatform.be). These monopiles consist of steel cylinders (Fig. 2, ø 5m, surface area: 518 m²) with various lengths, depending on local water depths and capacity (Schultze et al., 2020). In addition, local erosion is prevented by the construction of an erosion
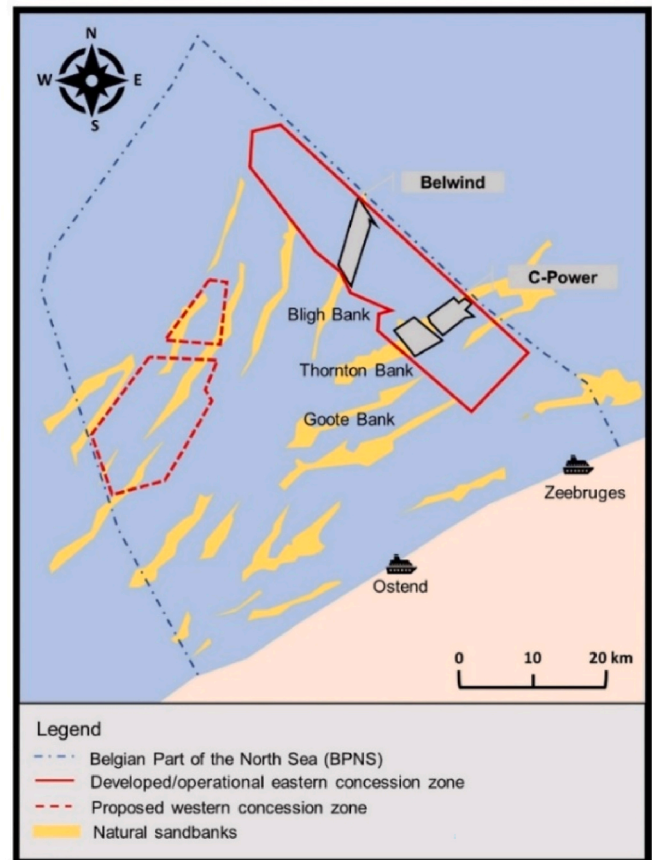

Fig. 1. Map of the Belgian Part of the North Sea (BPNS) with the position of natural sandbank systems (yellow). Full-lined red area represents the recently developed eastern concession zone with the two offshore windfarms under study (C-Power, Belwind). Dotted red area corresponds to a newly proposed western concession zone.

protection layer (EPL), with a radius of ~16.5 m starting from the monopile (Buyse et al., 2022). Construction of the C-power OWF (~20 km²) started in 2008, but the OWF became fully operational in 2013 and is composed of six gravity-based foundations and 48 jacket foundations (http://www.c-power.be). The jackets are four-legged constructions which are based on a square of 18 × 18 m (Fig. 2, surface area: 1280 m²), interconnected by slender steel braces to form a lattice tower, with openings through which currents can flow and are not surrounded by an EPL (http://www.c-power.be). In this study, only data from sediments around jacket foundations in C-Power and monopiles in Belwind are used.

2.1.2. Environmental and biological conditions

The current regime in the BPNS is characterized by semidiurnal tidal current ellipses along a northeast-southwest orientation (Vlaeminck et al., 1989; Baeye and Fettweis, 2015). The dominant wind direction is west-southwest (W-SW), with increasing average wind speed with the distance to the coast (Van Hulle et al., 2004; Baeye and Fettweis, 2015). The Belwind OWF is located at 49 km off the port of Zeebrugge on the Bligh Bank (BB, Fig. 1), which is part of the Hinder Banken subtidal sandbank system (Vlaeminck et al., 1989). This area is solely influenced by the clear waters (i.e., low turbidity and high salinity) entering from the English Channel (Vlaeminck et al., 1989). The C-Power OWF was built on the Thornton Bank (TB, Zeeland Banken system, Fig. 1), which is situated at approximately 30 km from the coastline and this convergence zone is still under the influence of coastal waters (i.e., higher turbidity and lower salinity) (Lacroix et al., 2004). Sampling positions in this
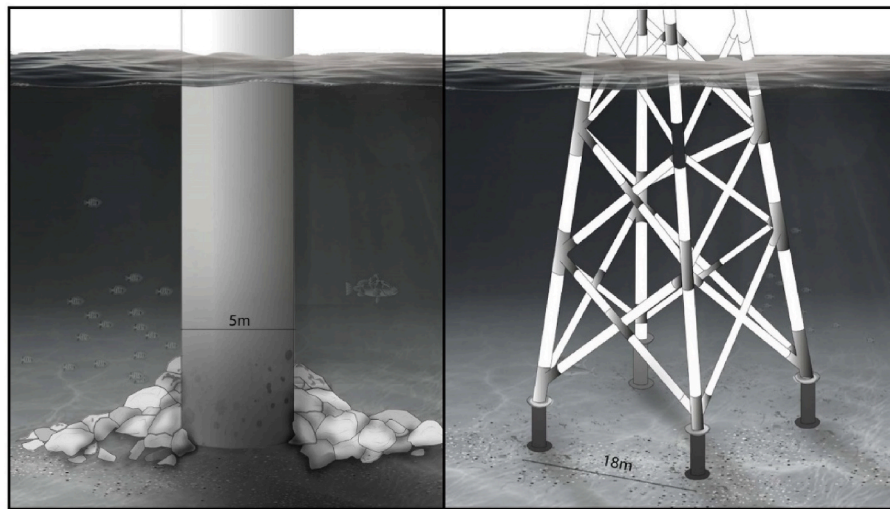
Fig. 2. Graphical representation of the subtidal part of the two types of foundations under study: monopiles situated in Belwind (left panel) and jackets situated in C-Power (right panel). Illustrations by Kasper Denayer.

study were located at varying water depths ranging from 15 to 29 m in Belwind and 11–24 m in C-Power.

Pre-impact sedimentary conditions in both areas were defined as medium-coarse sands (350–500 μm), with coarser grained sediments on the Bligh Bank compared to the Thornton Bank (average mean of 450 μm vs. 300 μm; extracted from Verfaillie et al., 2006). Sediments also contained low organic matter contents, ranging between 0.1 and 0.4%, with the majority of values < 0.3% (De Maersschalck et al., 2006; Reubens et al., 2009). Baseline studies (Van Veen grab sampling, surface area: 0.1m²) showed that infaunal communities mainly corresponded with the *Nephtys cirrosa* and *Hesionura elongata* or formerly called *Ophelia--Glycera* community (De Maersschalck et al., 2006; Van Hoey et al., 2004; Reubens et al., 2009; Breine et al., 2018). These communities are characterized by relatively low abundances (100–700 ind. m^{-2}), species richness (<15 spp. sample^{-1}) and a community structure dominated by polychaetes (e.g., *Nephtys cirrosa*, *Spio* spp., *Hesionura elongata*, *Ophelia borealis* and *Glycera* spp.) and mobile amphipods such as *Bathyporeia elegans* and *Urothoe brevicornis* (De Maersschalck et al., 2006; Van Hoey et al., 2004; Reubens et al., 2009; Breine et al., 2018).

2.2. Sample collection and processing

Throughout a period of three consecutive years (2017–2019), Van Veen grab samples (surface area: 0.1 m²) were collected during the autumn period (October–November) at two sampling positions (i.e., distances from the structures) from the studied turbines within both OWFs. Nearby samples were taken at 37.5 m from the centre of the turbines, which is the closest distance from the turbine that can be sampled from a vessel without entering the safety zone around the turbine. Sample direction relative to the turbines was located on the dominant current axis (SW-NE), but avoiding sub-bottom electric cables (i.e., SW-orientation for the monopiles in Belwind, NE-orientation for the jackets in C-Power). Distant samples were collected in the middle between four surrounding wind turbines (i.e., at the farthest possible distance from the nearest turbines), at 500 m (Belwind) and 350 m (C-Power) approximately. During each sampling year, a total of 28 turbines were studied that were spread over the entire concession zones. For the Belwind OWF, one sample was collected at both sampling positions around 15 monopile foundations, but due to maintenance works at the time of sampling, three turbines could not be sampled (1 turbine in 2018, 2 turbines in 2019), leading to a total of 84 samples (2017: n = 30, 2018: n = 28 and 2019: n = 26, Table 1). For the C-Power OWF, one sample was collected from all sampling positions each year (n = 26),

Table 1
Overview table of the sample collection with the period of sampling, the sampling location (i.e., OWF), years since construction, turbine foundation type, sampling position (i.e., distance from turbine) and the number of analysed samples. Throughout the sampling period, a total of n = 162 samples was collected within both OWFs (Belwind: n = 84 and C-Power: n = 78).

Period of sampling	Sampling location (OWF)	Years since construction	Turbine foundation type	Sampling position	Number of samples
Autumn 2017	Belwind	7 years	Monopile	Nearby (37.5 m)	15
				Distant (500 m)	15
	C-Power	5 years	Jacket	Nearby (37.5 m)	13
				Distant (350 m)	13
Autumn 2018	Belwind	8 years	Monopile	Nearby (37.5 m)	14[a]
				Distant (500 m)	14[a]
	C-Power	6 years	Jacket	Nearby (37.5 m)	13
				Distant (350 m)	13
Autumn 2019	Belwind	9 years	Monopile	Nearby (37.5 m)	13[a]
				Distant (500 m)	13[a]
	C-Power	7 years	Jacket	Nearby (37.5 m)	13
				Distant (350 m)	13

[a] due to maintenance works, three turbines were not sampled (BB10 in 2018 and BB08/BB09 in 2019).

resulting in a total of 78 samples within this OWF (Table 1).

2.2.1. Biotic samples

Macrobenthic samples were obtained by means of a 0.1 m² Van Veen grab and were immediately sieved on board over a 1 mm mesh-sized sieve. The remaining macrofauna was collected, preserved in a 4% formaldehyde-seawater solution and stained with Rose Bengal. Afterwards, these samples were further processed in the laboratory which included sorting, counting and identification to the lowest possible taxonomic level, using a stereo microscope.

2.2.2. Abiotic samples

Each Van Veen grab sample was subsampled with an additional plexiglass core (Ø 3.6 cm) for further environmental analyses (i.e., sediment grain size distribution and total sediment organic matter content). In the laboratory, sediment from these subsamples was dried at 60 °C and the grain size distribution was measured using laser diffraction on a Malvern Mastersizer 2000G, hydro version 5.40. Next to the median grain size (MGS, μm), the grain size distributions were also used to determine the fine sand fraction (<250 μm, %) for each sample. Total organic matter (TOM, %) content was calculated per sample from the difference between dry weight (determined after drying for 48 h at 60 °C) and ash-free dry weight (2 h at 500 °C).

2.3. Data analysis

The total abundance (TN, ind. m^{-2}) and species richness (S, spp. sample^{-1}) were calculated for each sample for the univariate datasets, while the individual abundances of the detected species within a sample were all compiled into multivariate community datasets. Corresponding values of abiotic predictor variables (MGS, fine sand fraction, water depth and TOM) and the "age" of the OWFs at the time of sampling (i.e., years since construction, corresponding to the difference between year since start of operational phase and year of sampling) were also included in the final selected datasets for the Belwind (n = 84) and C-Power (n = 78) OWF. The subsequent analyses were performed separately for each OWF and conducted using RStudio (v 1.2.5001, R v4.0.3).

2.3.1. Univariate analysis

A thorough data exploration was performed for each dataset according to Zuur et al. (2010) included boxplots and Cleveland plots to assess potential outliers together with pairwise scatterplots, Pearson correlation coefficients and variance inflation factors (VIFs) to look for multicollinearity. Moreover, potential interactions between the continuous predictor variables (MGS, fine sand fraction, water depth and TOM) and discrete predictor variables (sampling position, year since construction) were explored through coplots. Data exploration revealed the presence of two outliers for the total densities (TN > 10.000 ind. m^{-2}) and one outlier in terms of species richness (S > 45) within C-Power dataset. In addition, the predictor variable MGS showed strong collinearity with the fine sand fraction for both datasets and was therefore excluded for further analyses. For the species richness analysis within the Belwind OWF, data exploration (i.e., coplots) further suggested two potential interactions for TOM with the factors sampling position and years since construction. Co-plots constructed for the C-Power dataset also indicated potential interactions for three environmental variables (water depth, fine sand fraction, TOM) and the factor sampling position.

Generalized additive models (GAMs) were used to investigate the influence of the predictor variables (water depth, fine sand fraction, TOM, sampling position and years since construction) on the response variables (TN, S) within each OWF by means of the "gam" function of the "mgcv" package (Wood, 2017). Continuous environmental variables were included as smoothed terms to detect potential non-linear relationships and the data was modelled with a negative binomial distribution and a log link function. Models were built following a manual backward stepwise method, starting from the most complex model including interactions by means of the Aikaike's Information Criteria (AIC, ΔAIC ≥2) values to select the best-fitting models, resulting in a total of four end models (Table 2). End models were validated by means of the residual plots produced by the "gam.check" function to assess the assumptions of homogeneity of variances and normality. The effective degrees of freedom (edf) values of the smoothed terms were used to assess the type of relationship of the variables (i.e., linear or non-linear). Predicted values for the outcome variables were obtained through the "predict" function according to all the combinations of terms in the end model. This dataset was then used to plot the patterns along the entire

Table 2
End models for total abundances (TN, ind. m^{-2}) and species richness (S, spp. sample^{-1}) within the Belwind and C-Power OWF.

Sampling location (OWF)	Response variable	Predictor variables included in end model
Belwind	TN	Water depth + fine sand fraction
	S	Water depth + fine sand fraction
C-Power	TN	TOM + s(water depth, by = sampling position) + s(fine sand fraction, by = sampling position) + sampling position
	S	Water depth*sampling position + s(fine sand fraction, by = sampling position) + s(TOM, by = sampling position)

Smoothed terms (edf >1) are indicated with s() and interactions between parametric parameters and sampling position are represented by a an "*" or "by = " for interactions of smoothed terms with sampling position.

range of a specific predictor variable for an average level of the remaining predictor variables.

2.3.2. Multivariate analyses

Potential spatial and/or temporal differences in terms of macrobenthic community composition were investigated with a Permutational Multivariate Analysis of Variance (Permanova: fixed effects "sampling position" and "years since construction"), based on a Bray Curtis dissimilarity matrix. The homogeneity of multivariate dispersions was tested using the PERMDISP routine (distances among centroids). A Species Indicator Analysis (SIA, package "indicspecies") was performed to test which species were most responsible for the differences in community composition. All the multivariate analyses were performed on relative abundance data, to exclude effects of differences in total abundances between samples.

2.3.3. Biofouling drop-off expansion

The potential presence of bio-fouling (*Mytilus edulis*) drop-off products within the surrounding soft-sediments was explored through a descriptive analysis for both OWFs (Belwind: n = 13 samples, C-Power: n = 13 samples). Sediment residues (i.e., after initial sieving) of the nearby macrofaunal samples (Van Veen grab with surface area: 0.1 m^2) collected during the last sampling campaign (2019) were placed in a 0.30 × 0.25 m sorting tray and photographs were taken for each sample. Subsequently, the blue mussel associated material (i.e., empty shells, live organisms) was counted per sample and further categorized into four distinct groups based on predetermined threshold values: "none" (no shells), "low" (<5 shells per sample), "moderate" (5–15 shells per sample) and "high" (>15 shells per sample or presence of live organisms). If there was evidence for biofouling presence, these categories were further described based on their corresponding abiotic properties, biotic structural parameters (average values per group) and community composition (descriptive analysis based on abundances).

3. Results

3.1. Belwind OWF

3.1.1. GAMs

Total macrofaunal abundances within the Belwind OWF varied between 20 and 1080 ind. m^{-2}, while species richness ranged between 1 and 23. Water depth varied between 15 and 29 m and considerable variation was found in terms of fine sand fraction (0–24%) and TOM (0.3–1.4%). The range and average values of the studied variables were rather comparable between both sampling positions (Appendix Table 1). The final GAM models for both biotic indices included the predictor variables fine sand fraction and water depth, and explained 41% and 34% of the variation in total macrofaunal abundance and species richness, respectively (Table 3). Each of these predictor variables had a

Table 3

Summary statistics of all model components for the end models of total abundances (ind. m^{-2}) and species richness (spp. sample^{-1}) within the Belwind OWF. Estimate values are given for each parametric (i.e., linear) term, with corresponding significance (P) and the total deviance explained (DE, %) for the end model.

Total macrofaunal abundances (ind. m^{-2})			Species richness (spp. sample^{-1})		
Parametric terms	Estimate	P	Parametric terms	Estimate	P
Fine sand	0.06609	***	Fine sand	0.038054	***
Water depth	0.04930	***	Water depth	0.036838	***
Total DE: 41.1%			Total DE: 33.9%		

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

significant relationship (edf = 1) with the total abundances and species richness (p < 0.05, Table 3). Both response variables showed similar patterns, in which macrofaunal abundances and species richness increase with increasing fine sand fraction and water depth (Table 3, Fig. 3, panel a & c).

3.1.2. Multivariate results

Within the Belwind study site, a total of 66 species were recorded and significant differences were found between the nearby and distant samples with regards to community composition (Permanova, factor "Position": p = 0.006), but these results should be interpreted with caution due to the significant dispersion effect (Permdisp, p = 0.02). Results from the Indicator Species Analysis showed that only one genus, namely *Glycera* spp. (p < 0.05), was associated with the distant sediment samples. For the nearby samples, three amphipod species were characteristic, with strongest associations found for *Urothoe brevicornis* (p < 0.01), *Bathyporeia guilliamsoniana* (p < 0.01), followed by *Monocorophium* spp. (p < 0.05).

3.1.3. Biofouling drop-off expansion

Within the Belwind OWF, no evidence for the presence of biofouling drop-off products was found through the photographic analysis. Only one of the 13 samples in 2019 contained a low amount of *Mytilus edulis*

shells (<5 empty shells, Appendix Fig. 1), while the remaining samples were all devoid of any blue mussel material and corresponded with the medium-coarse sediments that are typically found within these areas (Appendix Fig. 1).

3.2. C-Power OWF

3.2.1. GAMs

Total macrofaunal abundances in C-Power ranged between 40 and 6020 ind. m^{-2} and species richness also showed considerable variation (3–47). Water depth varied between 11 and 24 m, while find sand fraction and TOM ranged between 2-31% and 0.3–1.1%, respectively. Maximum and average values for the fine sand fraction were higher for the nearby samples (>30%, 19 ± 6%) compared to the distant samples (22%, 13 ± 7%) (Appendix Table 2). A similar trend was also found for the total macrofaunal abundances (nearby: 6020 ind. m^{-2}, 925 ± 1243 ind. m^{-2} vs. distant: 830 ind. m^{-2}, 279 ± 189 ind. m^{-2}) and species richness (nearby: 47, 16 ± 8 vs. distant: 24, 9 ± 4), while other studied variables showed comparable values for both sampling positions (Appendix Table 2). The final GAM models for both biotic indices were more complex compared to the Belwind OWF and explained a higher amount of variation (TN: 75%, S: 78%, Table 4).

Macrofaunal abundances at the C-Power OWF were significantly affected by position (highest abundances at nearby samples) and generally increased with TOM, with highest predicted abundances for TOM values between 0.7 and 1% (p < 0.05, Table 4, Fig. 4). Both water depth and fine sand fraction had a stronger, non-linear effect on abundance in the nearby samples, where increasing predictor values lead to a higher increase in predicted macrofaunal abundances compared to the distant samples (p < 0.05, Table 4, Fig. 4). While predicted abundances enhanced rather gradually with water depth and fine sand fraction for the distant samples, a very strong increase was observed for the nearby samples at water depths between 20 and 24 m and fine sand fractions between 20 and 30%, albeit with larger confidence intervals (Fig. 4). Comparable to the findings for macrofaunal abundances, predicted species richness was higher for the nearby samples compared to the distant samples along the entire water depth and fine sand fraction
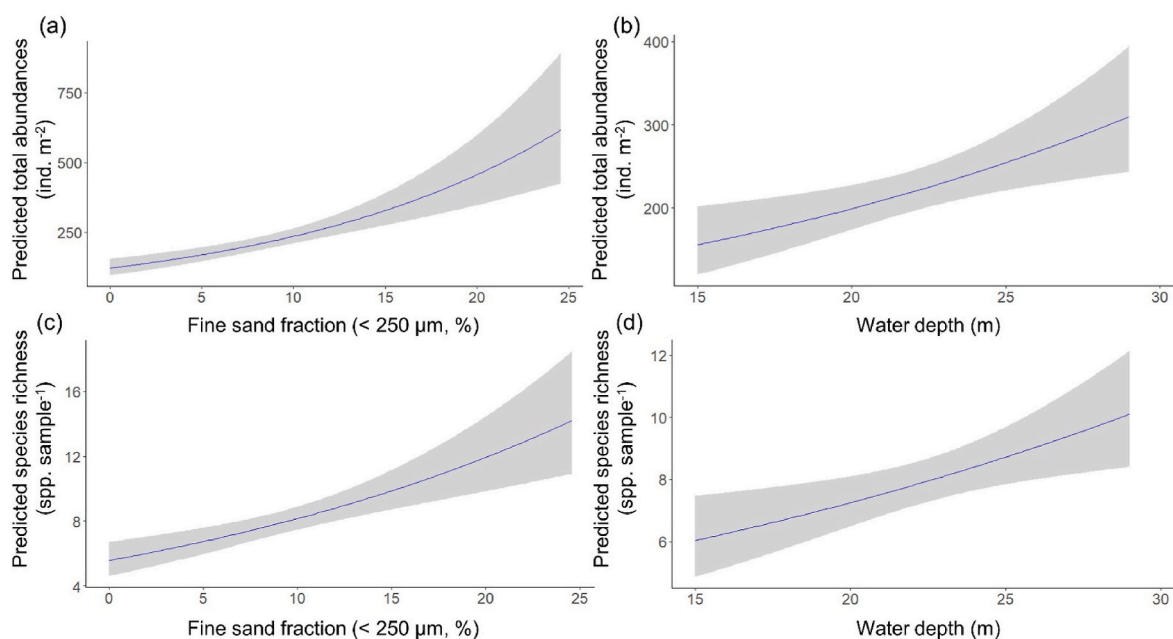

Fig. 3. Predicted total abundances (ind. m^{-2}, panel a & b) and species richness (spp. sample^{-1}, panel c & d) for the selected explanatory variables fine sand fraction (<250 μm, %) and water depth (m) within the Belwind OWF. Panels a and c represent the results for the fine sand fraction range at an average water depth of 22m, while panels b and d represent the results for the water depth ranges for an average fine sand fraction of 9%. The shaded, grey areas display the 95% confidence intervals.

Table 4

Summary statistics of all model components for the end models of total abundances (ind. m^{-2}) and species richness (spp. sample^{-1}) within the C-Power OWF. Estimate values and effective degrees of freedom (edf) are given for each parametric (i.e., linear) and smoothed term (i.e., non-linear), respectively, together with corresponding significance (P) and the total deviance explained (DE, %) for the end model.

Total macrofaunal abundances (ind. m^{-2})			Species richness (spp. sample^{-1})		
Parametric terms	Estimate	P	Parametric terms	Estimate	P
TOM	1.1913	***	Water depth: distant	0.04790	***
Sampling Position: nearby	0.4990	***	Water depth: nearby	0.06118	***
Smoothed terms	Edf	P	Smoothed terms	Edf	P
s(Water depth): distant	1.001	***	s(Fine sand): distant	1.000	***
s(Water depth): nearby	2.664	***	s(Fine sand): nearby	3.154	***
s(Fine sand): distant	1.465	***	s(TOM): distant	2.639	*
s(Fine sand): nearby	1.103	***	s(TOM): nearby	2.170	*
Total DE: 75.1%			Total DE: 78.2%		

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

gradient (p < 0.05, Table 4, Fig. 5). In addition, predicted values within the nearby samples showed a stronger relationship with water depth and had a small elevation ("hump" shape) at fine sand fraction around 15% and a very strong increase at fine sand fractions >30% together with enhancing confidence intervals (Fig. 5). Furthermore, a divergent pattern was found in terms of TOM, where predicted species richness nearby the jackets "peaked" at OM levels between 0.4 and 0.9% and showed a gradual decline from 0.9% onwards, while an opposite trend was found for the distant samples (p < 0.05, Table 4, Fig. 5).

3.2.2. Multivariate results

A total of 100 species were detected within the C-Power dataset and significant dissimilarities were found in terms of macrofaunal community composition between the sampling positions (Permanova, factor "Position": p = 0.001, Permdisp: p > 0.05) and years since construction (Permanova, factor "Age": p = 0.001, Permdisp: p > 0.05). Pairwise post-hoc tests further revealed that temporal differences were significant between the 7th year since construction and the other two sampling years (Post-hoc tests: 5 years *vs.* 7 years: p = 0.021 and 6 years *vs.* 7 years: p = 0.009). Indicator Species Analysis revealed that distant samples contained three associated polychaete species, namely, *Nephtys cirrosa* (p < 0.001), *Ophelia borealis* (p < 0.01) and *Glycera* sp. (p < 0.05).

This analysis further showed that a total of 14 species were associated with the nearby samples. Species that contributed the most to spatial differences (p < 0.01) were the polychaetes *Lanice conchilega*, Terebellidae juveniles, *Eumida sanguinea* and *Phyllodoce* spp. together with the echinoid *Echinocyamus pusillus* and the amphipod *Abludomelita obtusata*. Other important species (p < 0.05) included *Actinaria* spp., *Mytilus edulis*, together with two amphipod species (*Nototropis falcatus*, *Urothoe poseidonis*) and several polychaete species (*Nereis* spp., *Polynoinea* spp., *Travisia forbesii* and *Myrianida prolifera*). With regards to the temporal differences, the ISA indicated that the 5th and 6th year since construction were both characterized by the amphipod *Urothoe brevicornis* (p < 0.01). The last sampling year (2019), corresponding with the 7th year since construction, was mainly associated with the species *Pseudocuma* spp. (p < 0.001), together with *Ophiura ophiura* and *Nototropis falcatus* (p < 0.01). Other important species (p < 0.05) were Bivalvia juveniles, *Spisula* spp., *Aonides* spp. and *Nototropis swammerdamei*.

3.2.3. Biofouling drop-off expansion

In contrast to the findings for the Belwind OWF, photograph analysis within the nearby sediments of the C-Power OWF revealed the presence
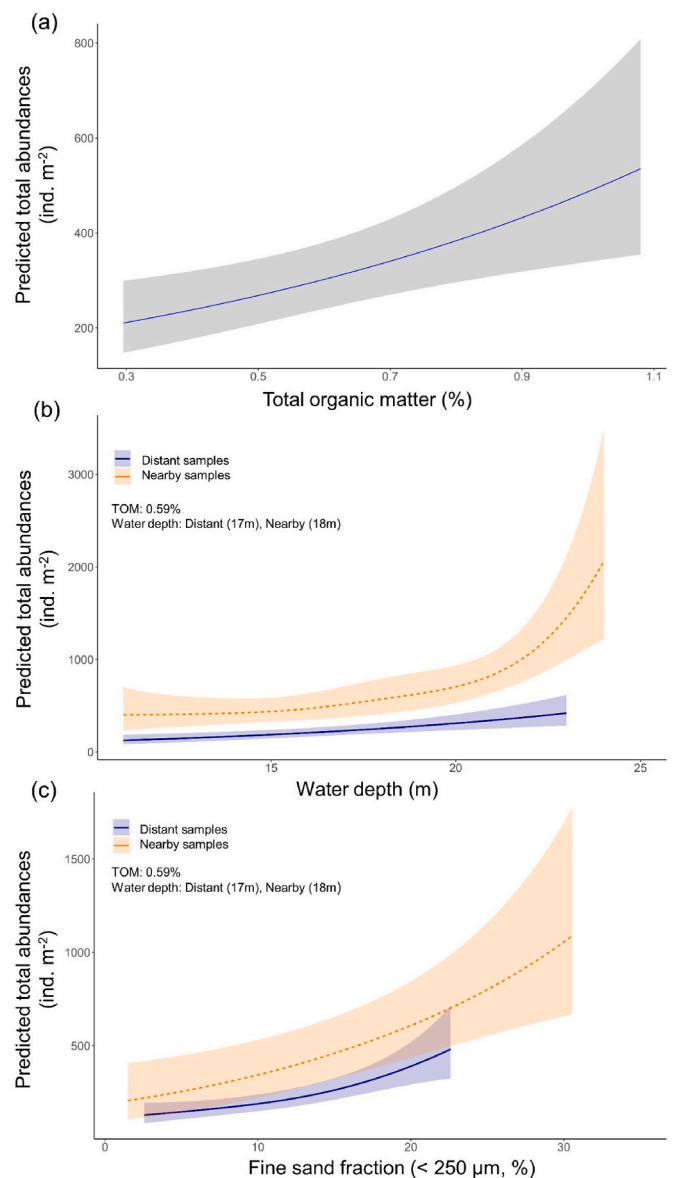

Fig. 4. Predicted total abundances (TN, ind. m^{-2}) for the selected explanatory variable Total Organic Matter (TOM, %, panel a) and smoothed terms water depth (m, panel b) and fine sand fraction (<250 μm, %, panel c) within the C-Power OWF. Panel a represents predicted TN as a function of TOM at an average value of water depth (18m) and fine sand fraction (16%). Panels b and c display the predicted TN as a function of the different water depth and fine sand fraction ranges for average values of the other predictor terms in the models (depicted on graphs). Blue, full lines are used for the distant samples and orange, dashed lines represent the nearby samples, while the shaded (grey, blue and orange) areas display the 95% confidence intervals.

of significant *Mytilus edulis* drop-off products (i.e., empty shells, alive individuals) around the jacket foundations. The amount of blue mussel associated material did however show considerable variation and ranged from low (<5 empty shells, n = 5 samples) to moderate (5–15 empty shells, n = 3 samples, Fig. 6a) to high (>15 empty shells, n = 5 samples, Fig. 6b). Moreover, three samples from the latter category also contained alive individuals, varying from a few specimens (3–5 individuals, Fig. 6c) to a true *Mytilus edulis* complex (>25 individuals, Fig. 6d). The moderate blue mussel habitat category contained sediments with an average fine sand fraction of 19% and average TOM values of 0.51%. These sediment patches consisted of an infaunal community with moderate average abundances (487 ind. m^{-2}), species
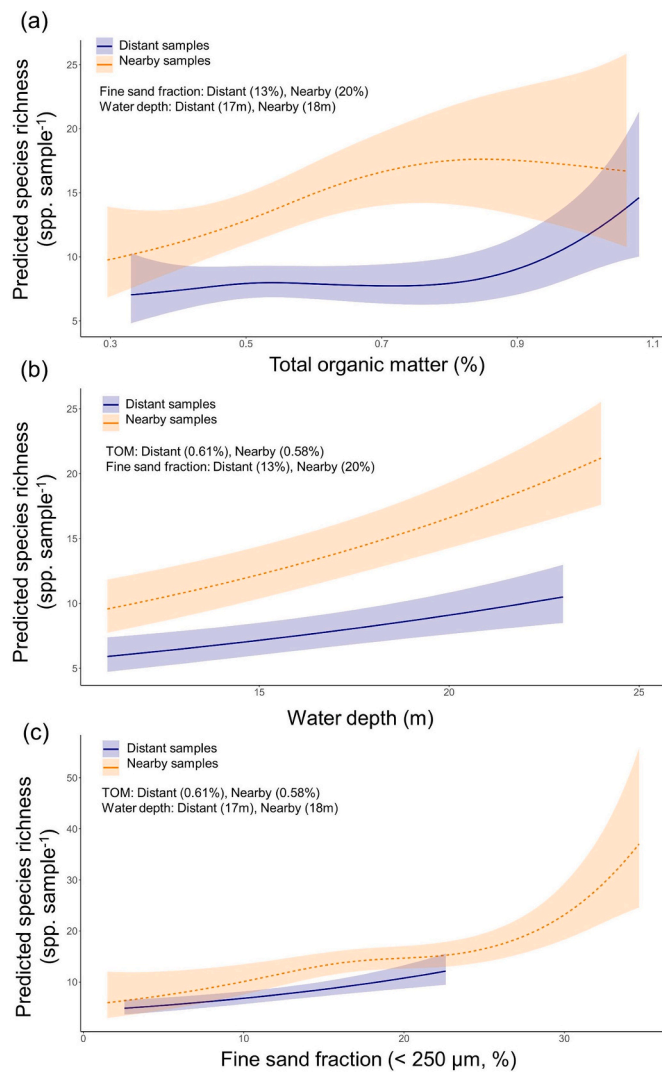
Fig. 5. Predicted species richness (S, spp. sample^{-1}) for the selected explanatory variable water depth (m, panel a) and smoothed terms fine sand fraction (<250 μm, %, panel b) and Total Organic Matter (TOM, %, panel c) within the C-Power OWF. Predicted S are visualized as a function of different water depth (panel a), fine sand fraction (panel b) and TOM (panel c) ranges for average values of the other predictor terms in the models (depicted on graphs). Blue, full lines are used for the distant samples and orange, dashed lines represent the nearby samples, while the shaded (grey, blue and orange) areas display the 95% confidence intervals.

richness (S = 14) and a polychaete-amphipod dominated community structure (*Nephtys cirrosa, Bathyporeia elegans, Urothoe brevicornis, Spiophanes bombyx, Spio* spp.). The high *Mytilus edulis* habitat category harboured sediments with an average fine sand fraction of 21%) and average TOM contents of 0.56%. Macrobenthic communities showed relatively high average abundances (937 ind. m^{-2}), species richness (S = 19) and a community composition that was clearly distinct due to the rather low abundances of the typical *Nephtys cirrosa, Bathyporeia elegans* and *Urothoe brevicornis* species. In contrast, macrofaunal communities in these sediments were characterized by a wide range of different polychaete species (*Eumida sanguinea, Lanice conchilega, Terebellidae* juveniles and *Nephtys* juveniles), amphipods (*Ablomelita obtusa, Nototropis swammerdamei*), cumaceans (*Bodotria* spp., *Pseudocuma* spp., *Diastylis* spp.) and the occurrence of horseshoe worms (Phoronida).

Within the high habitat category, the three samples that contained alive blue mussel individuals could be further distinguished into sub habitats due to the dominance of two habitat-forming species: *Lanice*

conchilega and *Mytilus edulis*. The *Lanice conchilega*-associated samples (n = 2) were found in finer sediments (average fine sand fraction: 33%) with an average TOM content of 0.82%. Next to the high occurrences of the tube-building polychaete, a wide variety of other species were abundant (Appendix Table 3), resulting in very rich infaunal communities in terms of abundance and diversity (average TN: 11795 ind. m^{-2} and average S: 42). The *Mytilus edulis*-associated sample was also characterized by finer sediments (fine sand fraction: 29%) and higher TOM content (1.05%). Infaunal abundances were high (4790 ind. m^{-2}) and a combination of hard and soft-substrate species was found (Appendix Table 3), resulting in the highest species richness (S: 47) recorded in the entire dataset.

4. Discussion

The findings within this study clearly show that impacts related to the "artificial reef" effect can influence the surrounding soft-sediments. However, the nature and extent of these pressures do seem to be site dependent as different results were found for the C-Power (jackets) and Belwind (monopiles) OWFs. First we will elaborate on the detailed patterns found around the jacket foundations, after which we discuss the differences in effects between sites.

4.1. Ecological changes occur around jacket foundations

Submerged vertical structures in dynamic environments generate complex three-dimensional local flow patterns, which largely determine the sediment biogeochemical properties around the turbines in an OWF (van Berkel et al., 2020). For example, one of the consequences is the formation of vortex shredding in the wake of a foundation, allowing the creation of downstream retention areas resulting in the increased deposition of finer sediment particles and facilitation of organic matter accumulation (Baeye and Fettweis, 2015; Rivier et al., 2016; Welzel et al., 2020). Moreover, these changes may be amplified by the presence of colonizing epifaunal species through their associated bio-depositional flow (i.e., faecal pellets, detritus) which also increases food availability within the surrounding areas (Coates et al., 2014; Mavraki et al., 2022). Sediment fining and organic enrichment was already observed at 15 m distance from the scour protection layer of a gravity-based foundation within the C-Power OWF (Coates et al., 2014). Based on this knowledge, we proposed that nearby (i.e., 37.5 m) areas within these wake formations could also potentially shift from high-energy areas to lower-energy areas with the accumulation of finer-grained sediment particles and more organic matter (Coates et al., 2014). These changes in habitat properties near the artificial structures may also induce a shift in macrobenthos from typical offshore assemblages towards assemblages comparable to more onshore located communities within the BPNS such as the rich *Abra alba* community (Van Hoey et al., 2004; Coates et al., 2014; Breine et al., 2018; Dannheim et al., 2020). While no indications of this shift were detected for the monopiles in the Belwind OWF in this study, macrobenthic enrichment (i.e., higher total abundances and species richness) and an altered community composition at the sediments located nearby jacket foundations within C-Power proved to be a consistent finding.

4.1.1. The more the merrier: abundant and diverse infaunal communities

In general, macrofaunal abundances and species richness were higher with increasing water depth and fine sand fraction which corresponds to the natural patterns that are found within these shallow (<50 m) coastal areas (Armonies et al., 2014; Coolen et al., 2022; Armonies, 2021; Cheng et al., 2021). With increasing water depth, macrobenthic communities are less affected by wave and sediment disturbance (e.g., turbulence, sediment mobility) allowing the establishment of more abundant and diverse benthic communities within deeper sediments such as sandbank gullies (Van Lancker et al., 2012; Armonies et al., 2014; Armonies, 2021). Nevertheless, predicted

Fig. 6. Example photographs of the nearby sediments sampled in 2019 (i.e., 7 years since construction) within the C-Power OWF: (a) represents a sample that contained a moderate amount of *Mytilus edulis* associated material (5–15 empty shells), (b) corresponds to a sample with a high amount of *Mytilus edulis* empty shells (>15), while (c) and (d) are examples of samples that contained alive individuals varying from 3 to 5 specimens (c) to > 25 specimens (d).

abundance and species richness were consistently higher nearby compared to the distant samples along the entire water depth and fine sand fraction ranges. Nearby sediments were also generally composed of higher fine sand fractions (≥30%) compared to the distant sediments (≤22%). This difference in sedimentary properties between both sampling positions is in line with the proposed "blockage effect" of the submerged structures on currents and concomitant alterations in near-bed flow velocity and sediment deposition (Vanhellemont and Ruddick, 2014; Welzel et al., 2020). Moreover, both biotic indices and especially species richness showed a non-linear relationship with the amount of fine sand, with intense benthic enrichment linked to values surpassing 20%.

While these results confirm that sedimentary changes and benthic enrichment are occurring closer to the jackets, our study also showed that these spatial differences were stronger in deeper sediments (water depth >20 m). Subtidal sandbank systems are highly complex bedforms with fine-scale geomorphic features such as crests, slopes and troughs (Van Lancker et al., 2012; Cheng et al., 2020). The deeper sediments in our study correspond with the sandbank troughs or gullies, which show strong spatial variability in sediment composition but generally contain finer and less permeable sediments compared to the shallower crests of a sandbank (Van Lancker et al., 2012; Cheng et al., 2020). As such, ecological changes related to turbine presence might be limited for the shallower, wave-exposed crests, while AR-effects such as the accumulation of finer sediments and benthic enrichment are more pronounced within these troughs due to the initial sediment conditions. Overall, AR-induced biotic-sediment relationships nearby jackets appear to be rather complex and fluctuating, with benthic responses to sediment fining that act on small and patchy spatial scales. This could be attributed to the strong natural spatial variability within these sandbank systems and sediment dispersal patterns around jacket structures, which are thought to be more convoluted compared to cylindrical piles such as

gravity-based foundations and monopiles, probably resulting in more widespread but scattered areas of water flow retention (Welzel et al., 2020).

Whereas OM contents at both distances were higher compared to the values within the baseline study (≤0.3%) (De Maersschalck et al., 2006), our findings do not indicate that organic matter accumulation is enhanced nearby the jackets compared to distant positions. Moreover, different relationships were found between OM and macrofaunal abundances and species richness within C-Power. As such, our results do not support the proposed "organic enrichment hypothesis. This might be partially explained by the water-flow regime in which the C-Power OWF is located. Previous studies have already shown that observing and quantifying organic enrichment at intermediate distances (30–100 m) from hard structures and aquaculture sites is challenging within dynamic, offshore areas (Keeley et al., 2013; Jak and Glorius, 2017; Methratta, 2021). Compared to finer, low-energy sites where organic enrichment effects are often more severe but spatially limited, high-energy sites are believed to have larger but more diffuse depositional footprints which makes it difficult to detect enrichment effects relative to ambient conditions (Keeley et al., 2013).

4.1.2. A shift in community composition: rise of the sand mason

Significant spatial differences were also evident in terms of community composition close to the jacket foundations of the C-Power OWF. Distant sediments harboured polychaete-dominated (e.g., *Nephtys cirrosa, Ophelia borealis, Glycera* spp.) infaunal communities which corresponded with the typical, offshore communities that were observed during the pre-construction monitoring studies (De Maersschalck et al., 2006). Whereas infaunal communities nearby the turbines also comprised indicator species of coarser grained sediments, these species were often more abundant and co-occurred with several additional species which are not typical for these areas (Van Hoey et al., 2004;

Degraer et al., 2006; Breine et al., 2018). A clear offshore-onshore gradient can be observed within the BPNS in terms of macrofaunal distributions and the coastal *Abra alba* community is considered as one of the richest benthic assemblages (Van Hoey et al., 2004; Breine et al., 2018). Some of the species associated with the nearby sediments such as *Abludomelita obtusata*, *Phyllodoce* spp. and *Eumida sanguinea* are also commonly found within the *Abra alba* community and have a strong preference for finer-grained sediments (Degraer et al., 2006; Breine et al., 2018). Moreover, the presence of adult individuals of the sand mason, *Lanice conchilega*, and its early life stages (*Terebellidae* juveniles) characterized the sediments nearby jacket turbines, which represents a strong deviation from the baseline assessment (De Maersschalck et al., 2006). Whereas this tube-building polychaete occurs over a wide range of sediment types within the BPNS at relatively low densities (<20 ind. m^{-2}), highest occurrences or so called *Lanice conchilega* aggregations are mainly found along the coast in fine sandy sediments and its presence is considered as a key feature of the *Abra alba* community (Van Hoey et al., 2004, Van Hoey et al., 2208; Breine et al., 2018). These results and the significantly higher abundances and species richness adjacent to jackets compared to distant samples do indicate a shift from typical offshore communities found in permeable, coarser sediments towards richer communities associated with near-shore, finer sediments around the jackets. This trend is, however, partial as the nearby infaunal communities around the jackets exhibit characteristics of both the transitional *Nephtys cirrosa* and coastal *Abra alba* community (Van Hoey et al., 2004; Breine et al., 2018).

4.1.3. Biofouling drop-off material promotes habitat diversification

Increased habitat heterogeneity and biodiversity through the provision of hard substrates and concomitant establishment of mature epifouling communities, represent two of the most profound impacts of OWF development (Degraer et al., 2020). This aspect of the AR effect not only affects areas in the immediate vicinity of the turbines, but can also induce secondary effects such as the introduction of habitat-forming species, enhanced habitat complexity and other habitat modifications (e.g., sediment stabilization, lower current velocities) further away through the process of "biofouling drop-off" (Callaway, 2018; Keeley et al., 2013; Degraer et al., 2020; Mascorda Cabre et al., 2021). Significant mussel shell aggregations were observed within the footprint of three jacket foundations on the East coast of the U.S. (Hutchison et al., 2020). Changes in benthic habitats were also found at larger spatial scales (>50 m), and were linked to the mussel-dominated colonization of the structures (Hutchison et al., 2020). In offshore longline mussel farms, considerable fall-offs of mussels and their shells introduced physical structure on the seabed underneath the ropes, accompanied by shifts in macroinvertebrate community structure (Mascorda Cabre et al., 2021). Similar trends were detected in our study, as notable but variable amounts of empty blue mussel shells were found exclusively nearby the jackets in C-Power. These shell-debris habitat patches were characterized by finer sediments and supported an assemblage of species not typically found in offshore soft-sediments. Certain nearby samples also contained alive *Mytilus edulis* individuals, always in co-occurrence with very high densities of *Lanice conchilega* and many other species typically associated with subtidal mussel beds. This confirms that habitat-forming species can be introduced around the foundations, creating sediments with unique abiotic conditions and diverse benthic communities (Norling and Kautsky, 2008; Bertolini et al., 2018; Callaway, 2018; Hutchison et al., 2020; Mascorda Cabre et al., 2021; Rabaut et al., 2007; Van Hoey et al., 2008). We conclude that "biofouling drop-off" products (i.e., blue mussel shell debris and alive individuals) originating from the jacket foundations have led to significant habitat diversification within the nearby sediments (Fig. 7). It does remain uncertain whether these biofouling effects are ephemeral or permanent, especially with regards to the introduction of habitat-forming species.
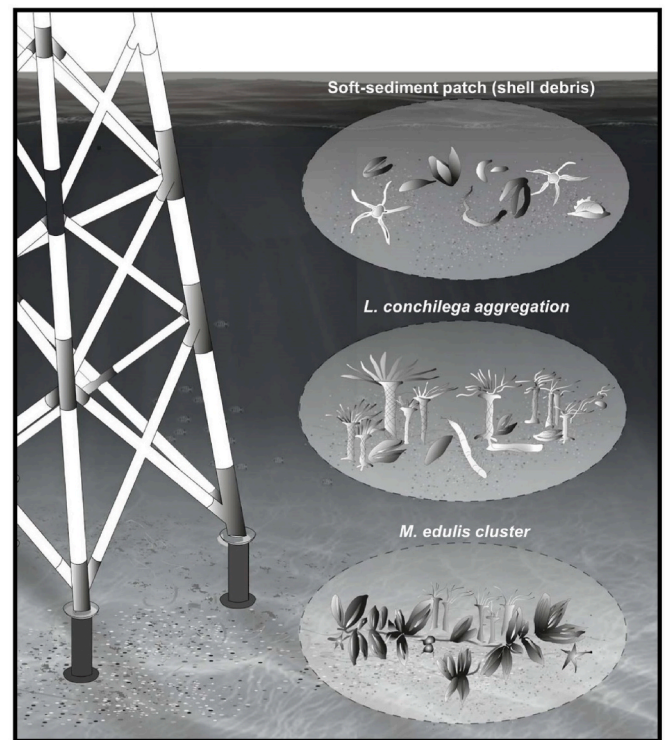

Fig. 7. Visual representation of the habitat diversification found nearby the jacket foundations, with soft-sediment patches containing various amounts of *Mytilus edulis* shell debris (top), *Lanice conchilega* aggregations (middle) and *Mytilus edulis* clusters (bottom). Illustration by Kasper Denayer.

4.2. AR effects around offshore monopiles: nearby but too far?

In contrast to the results at the C-Power study site, no clear AR effects were found for the nearby located sediments around the monopile turbines within the Belwind OWF. However, other studies already showed that physical and biological aspects can indeed be affected by the presence of monopile foundations. In particular, altered flow patterns and the presence of "sediment plumes" have been detected in the wake of monopile foundations (Vanhellemont and Ruddick, 2014; Baeye and Fettweis, 2015; Rivier et al., 2016; Forster, 2018). Furthermore, it is known that this foundation type is rapidly colonized by epifauna and supports the establishment of mature biofouling communities (Coolen et al., 2020, 2022; Zupan et al., 2023). In addition, the samples nearby the turbine are taken relatively close to the hard substrate of the erosion protection layer (~18.5m). Consequently, the question arises which factors might be responsible for this lack of effects on sediment composition and macrobenthos assemblages around monopiles and large variability in effects at the OWF-level?

4.2.1. Differences between foundation types: Monopiles vs. Jackets

Contrasts in technical attributes between foundation types will differently affect the nature and extent of hydrological changes and sediment deposition around the structures (Keeley et al., 2013; Rivier et al., 2016; Schultze et al., 2020). Previous observational and modelling studies have indicated that the originating downstream wake around monopiles can be relatively narrow and unsteady, composed of swirling vortices (Baeye and Fettweis, 2015 Rivier et al., 2016; Floeter et al., 2017; Schultze et al., 2020). In addition, much ambiguity exists with regards to the actual length of these wakes ranging from tens of meters to up to several kilometres (Forster, 2018). Far fewer studies are available about turbine-water flow interactions for jacket foundations, but it is suggested that the additional vortex shredding and streamline contraction caused by the diagonal braces of the structure leads more

widespread and larger sediment depositional patterns (Welzel et al., 2020). As a result, obtaining benthic samples accurately within the depositional footprint of monopiles might be more difficult compared to jacket foundations. Moreover, jacket-like structures (e.g., oil rigs, offshore platforms) are known to be true *Mytilus edulis* "hotspots", where they dominate epifaunal communities up to depths of 20 m (Whomersley and Picken, 2003; Krone et al., 2013; Hutchison et al., 2020). In contrast, the dominance of *Mytilus edulis* is restricted to the upper parts (0–5m depth) of cylindrical structures such as gravity-based foundations and monopiles (Coolen et al., 2022). This, together with the presence of a scour protection layer around monopile structures which can trap and limit biofouling expansion (i.e., drop-offs) to immediate areas around the monopiles, could therefore result in a lower "fouling impact potential" at the Belwind study site.

4.2.2. Differences between site-specific baseline conditions

As mentioned earlier in this study, it can be expected that the actual spatial extent of AR-related effects on seabed conditions such as sedimentation rates and accumulation of organic matter will also depend on local resuspension and dispersion processes (Keeley et al., 2013). Although both OWFs under study are situated in high-energy environments, subtle differences in terms of physical conditions could therefore result in different dispersive capacities and AR footprints (Keeley et al., 2013). The Belwind OWF is situated ca. 10 km further off the coastline than the C-Power OWF. As a result, Belwind receives no coastal influence and is mainly affected by clear (i.e., low turbidity) and saline water masses from the English Channel (Vlaeminck et al., 1989). In addition, this area also has stronger bottom current velocities (20–30%) and coarser-grained sediments compared to C-Power (Verfaillie et al., 2006; Legrand and Baetens, 2021). Moreover, the extension of depositional patterns is also believed to be affected by the preceding hydro-meteorological conditions and more specifically the wave vs. current dominance (Ivanov et al., 2020; Welzel et al., 2020). Considering that the prevailing wind direction within the BPNS is (W)-SW oriented, with stronger wind speeds at Belwind (Van Hulle et al., 2004), sediment plume propagation might have been inhibited along the SW-axis of the structures (i.e., sampling orientation for nearby samples Belwind). In contrast, wind-induced waves/currents could have stimulated the spatial extent of the sediment plume along the NE-axis, which corresponds with the orientation of the nearby samples for the jacket foundations within this study. As such, the lack of detectable AR effects within this study for the Belwind OWF may also be attributed to the stronger hydrological forcing compared to the more transitionally located C-Power study site.

5. Conclusions and future recommendations

This study revealed that AR associated ecological changes are occurring nearby the jacket foundations within the C-Power OWF, but not nearby the monopiles of Belwind. The benthic enrichment hypothesis was confirmed as total macrofaunal abundances and species richness were consistently higher within nearby sediments relative to distant positions, especially for deeper sediments (>20 m, sandbank gullies) at intermediate levels of fine sand (10–20%) and organic matter (0.5–0.9%). Intense benthic enrichment was also linked with the observed sediment fining at nearby sampling positions, albeit with considerable variability. These results and the significant distance-based differences in terms of community composition indicate a shift from typical offshore communities found in permeable, coarser sediments towards richer communities associated with near-shore, finer sediments around the jackets. Moreover, the substantial amount of observed drop-off material from the dominant turbine foundation colonizer *Mytilus edulis* (i.e., shell debris and alive individuals) was found to result in more heterogenous sediment patches nearby the jackets. It is proposed that the lack of ecological changes at nearby distances within the Belwind study site may be related to interlinked foundation-specific (i.e., turbine

shape and biofouling community composition) and site-specific (i.e., hydro-meteorological conditions, water-flow regimes and native infaunal community composition) factors.

Our findings further indicate that certain aspects of the AR mechanism still need further investigation. Quantifying impacts of OWFs on sediment resuspension and organic enrichment remains challenging, especially in high-energy sites where effects are less pronounced compared to nearshore sites (Keeley et al., 2013). It is therefore strongly recommended to include a numerical modelling approach within future OWF impact assessments to determine the propagation of site-specific and even turbine-specific sediment depositional patterns that will allow a more accurate *in-situ* benthic sampling strategy. Additional research with appropriate sampling gear such as high-resolution mapping techniques (e.g., video surveys, side scan sonar and multibeam) is also needed to determine the actual spatial range of biofouling drop-off expansion and monitor the temporal development of this specific AR effect. Integrating these modelling and visualisation approaches will better delineate areas of interest to study the effects of turbine-related OM deposition on sediment biogeochemistry and relationships with infauna. Lastly, it is known that future OWFs will be constructed in deeper, more offshore located areas such as Belwind, with monopiles as the most common turbine type (WindEurope, 2020). As such, follow-up studies are urgently needed to understand the sphere of influence of this specific foundation type on the surrounding benthic communities.

Authorship statements

NL: conceptualization, data collection, analyses, writing; UB: analyses, review, editing; JV: analyses, review, editing; SD and TM: review, editing. This manuscript was read and approved by all the authors.

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2023.106009.

References

Armonies, W., 2021. Who lives where? Macrobenthic species distribution over sediment types and depth classes in the eastern North Sea. Helgol. Mar. Res. 75, 4–9. https://doi.org/10.1186/s10152-021-00552-1.

Armonies, W., Buschbaum, C., Hellwig-Armonies, M., 2014. The seaward limit of wave effects on coastal macrobenthos. Helgol. Mar. Res. 68, 1–16. https://doi.org/10.1007/s10152-013-0364-1.

Baeye, M., Fettweis, M., 2015. In situ observations of suspended particulate matter plumes at an offshore windfarm, southern North Sea. Geo Mar. Lett. 35, 247–255.

Bertolini, C., Montgomery, W.I., O'Connor, N.E., 2018. Habitat with small inter-structural spaces promotes mussel survival and reef generation. Mar. Biol. 165 (10), 1–11.

Breine, N.T., De Backer, A., Van Colen, C., Moens, T., Hostens, K., Van Hoey, G., 2018. Structural and functional diversity of soft bottom macrobenthic communities in the Southern North Sea. Estuarine. Coast. Shelf Sci. 214, 173–184.

Buyse, J., Hostens, K., Degraer, S., De Backer, A., 2022. Offshore wind farms affect the spatial distribution pattern of plaice Pleuronectes platessa at both the turbine and wind farm scale. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 79, 1777–1786. https://doi.org/10.1093/icesjms/fsac107.

Callaway, R., 2018. Interstitial space and trapped sediment drive benthic communities in artificial shell and rock reefs. Front. Mar. Sci. 5, 288.

Cheng, C.H., Soetaert, K., Borsje, B.W., 2020. Sediment characteristics over asymmetrical tidal sand waves in the Dutch north sea. J. Mar. Sci. Eng. 8, 1–16.

Cheng, C.H., Borsje, B.W., Beauchard, O., O'Flynn, S., Ysebaert, T., Soetaert, K., 2021. Small-scale macrobenthic community structure along asymmetrical sand waves in an underwater seascape. Mar. Ecol. 42, 1–15. https://doi.org/10.1111/maec.12657.

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.

Coolen, J.W.P., Van Der Weide, B., Cuperus, J., Blomberg, M., Van Moorsel, G.W.N.M., Faasse, M.A., et al., 2020. Benthic biodiversity on old platforms, young wind farms, and rocky reefs. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 77, 1250–1265. https://doi.org/10.1093/icesjms/fsy092.

Coolen, J.W.P., Vanaverbeke, J., Dannheim, J., Garcia, C., Birchenough, S.N.R., Krone, R., et al., 2022. Generalized changes of benthic communities after construction of wind farms in the southern. North J. Environ. Manag. 315, 115173 https://doi.org/10.1016/j.jenvman.2022.115173.

Couce, E., Engelhard, G.H., Schratzberger, M., 2020. Capturing threshold responses of marine benthos along gradients of natural and anthropogenic change. J. Appl. Ecol. 57, 1137–1148. https://doi.org/10.1111/1365-2664.13604.

Dannheim, J., Bergström, L., Birchenough, S.N., Brzana, R., Boon, A.R., Coolen, J.W., Degraer, S., 2020. Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 77 (3), 1092–1108.

De Backer, A., Van Hoey, G., Coates, D., Vanaverbeke, J., Hostens, K., 2014. Similar diversity-disturbance responses to different physical impacts: three cases of small-scale biodiversity increase in the Belgian part of the North Sea. Mar. Pollut. Bull. 84, 251–262.

De Maersschalck, V., Hostens, K., Wittoeck, J., Cooreman, K., Vincx, M., Degraer, S., 2006. Monitoring van de effecten van het Thornton windmolenpark op de benthische macro-invertebraten en de visfauna van zachte substraten-Referentietoestand. Rapport ILVO-Visserij/Monitoring/2006-01,, p. 142.

Degraer, S., Carey, D.A., Coolen, J.W., Hutchison, Z.L., Kerckhof, F., Rumes, B., Vanaverbeke, J., 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning. Oceanography 33 (4), 48–57.

Degraer, S., Wittoeck, J., Appeltans, W., Cooreman, K., Deprez, T., Hillewaert, H., Hostens, et al., 2006. The Macrobenthos Atlas of the Belgian Part of the North Sea. Belgian Science Policy, Brussel, p. 164.

Floeter, J., van Beusekom, J.E., Auch, D., Callies, U., Carpenter, J., Dudeck, T., Möllmann, C., 2017. Pelagic effects of offshore wind farm foundations in the stratified North Sea. Prog. Oceanogr. 156, 154–173.

Forster, R.M., 2018. The effect of monopile-induced turbulence on local suspended sediment patterns around UK wind farms: field survey report. An IECS report to The Crown Estate 88. ISBN 978-1-906410-77-3; November 2018.

Gill, A.B., Degraer, S., Lipsky, A., Mavraki, N., Methratta, E., Brabant, R., 2020. Setting the context for offshore wind development effects on fish and fisheries. Oceanography 33, 118–127. https://doi.org/10.5670/oceanog.2020.411.

Glarou, M., Zrust, M., Svendsen, J.C., 2020. Using artificial-reef knowledge to enhance the ecological function of offshore wind turbine foundations: implications for fish abundance and diversity. J. Mar. Sci. Eng. 8 https://doi.org/10.3390/JMSE8050332.

Hutchison, Z.L., Bartley, M.L., Degraer, S., English, P., Khan, A., Livermore, J., King, J.W., 2020. Offshore wind energy and benthic habitat changes. Oceanography 33 (4), 58–69.

ICES (International Council for the Exploration of the Sea), 2018. Greater North sea ecoregion – ecosystem overview. https://doi.org/10.17895/ices.pub.4670.

Ivanov, E., Capet, A., Barth, A., Delhez, E.J., Soetaert, K., Grégoire, M., 2020. Hydrodynamic variability in the Southern Bight of the North Sea in response to typical atmospheric and tidal regimes. Benefit of using a high resolution model. Ocean Model. 154, 101682.

Jak, R., Glorius, S.T., 2017. Marcobenthos in Offshore Wind Farms; A Review of Research, Results, and Relevance for Future Developments. Wageningen Marine Research (University & Research centre), p. 477. Wageningen Marine Research report C043/17.

Karlsson, R., Tivefälth, M., Duranović, I., Martinsson, S., Kjølhamar, A., Murvoll, K.M., 2022. Artificial hard-substrate colonisation in the offshore hywind scotland pilot park. Wind Energy Sci. 7, 801–814.

Keeley, N.B., Forrest, B.M., Macleod, C.K., 2013. Novel observations of benthic enrichment in contrasting flow regimes with implications for marine farm monitoring and management. Mar. Pollut. Bull. 66 (1–2), 105–116.

Krone, R., Gutow, L., Joschko, T.J., Schröder, A., 2013. Epifauna dynamics at an offshore foundation – implications for future wind power farming in the North Sea. Mar. Environ. Res. 85, 1–12.

Lacroix, G., Ruddick, K., Ozer, J., Lancelot, C., 2004. Modelling the impact of the Scheldt and Rhine/Meuse plumes on the salinity distribution in Belgian waters (southern North Sea). J. Sea Res. 52 (3), 149–163. https://doi.org/10.1016/j.seares.2004.01.003.

Legrand, S., Baetens, K., 2021. Dataset : Hydrodynamic Forecast for the Belgian Coastal Zone. Royal Belgian Institute of Natural Sciences. https://metadata.naturalsciences.be/geonetwork/srv/eng/catalog.search#/metadata/BCZ_HydroState_V1.

Lindeboom, H., Degraer, S., Dannheim, J., Gill, A.B., Wilhelmsson, D., 2015. Offshore wind park monitoring programmes, lessons learned and recommendations for the future. Hydrobiologia 756 (1), 169–180.

Maar, M., Bolding, K., Petersen, J.K., Hansen, J.L., Timmermann, K., 2009. Local effects of blue mussels around turbine foundations in an ecosystem model of Nysted off-shore wind farm. J. Sea Res. 62, 159–174.

Mascorda Cabre, L., Hosegood, P., Attrill, M.J., Bridger, D., Sheehan, E.V., 2021. Offshore longline mussel farms: a review of oceanographic and ecological interactions to inform future research needs, policy and management. Rev. Aquacult. 13 (4), 1864–1887.

Mavraki, N., Coolen, J.W.P., Kapasakali, D.A., Degraer, S., Vanaverbeke, J., Beermann, J., 2022. Small suspension-feeding amphipods play a pivotal role in carbon dynamics around offshore man-made structures. Mar. Environ. Res. 178, 105664.

Methratta, E.T., 2021. Distance-based sampling methods for assessing the ecological effects of offshore wind farms: synthesis and application to fisheries resource studies. Front. Mar. Sci. 8, 1062.

Norling, P., Kautsky, N., 2008. Patches of the mussel Mytilus sp. are islands of high biodiversity in subtidal sediment habitats in the Baltic Sea. Aquat. Biol. 4 (1), 75–87.

Papalexandrou, M., 2021. Offshore wind: staying ahead of the curve. In: Mathioulakis, M. (Ed.), Aspects of the Energy Union: Application and Effects of European Energy Policies in SE Europe and Eastern Mediterranean. Palgrave Macmillan, Cham, pp. 277–295. https://doi.org/10.1007/978-3-030-55981-6_13.

Rabaut, M., Guilini, K., Van Hoey, G., Vincx, M., Degraer, S., 2007. A bio-engineered soft-bottom environment: the impact of Lanice conchilega on the benthic species-specific densities and community structure. Estuarine. Coast. Shelf Sci. 75, 525–536.

Reubens, J., Eede, S.V., Vincx, M., 2009. Monitoring of the effects of offshore wind farms on the endobenthos of soft substrates: year-0 Bligh Bank and Year-1 Thorntonbank. In: Degraer, S., Brabant, R., Royal, B. (Eds.), Offshore Wind Farms in the Belgian Part of the North Sea: State of the Art after Two Years of Environmental Monitoring, Pp. 59-9. Belgian Institute of Natural Sciences. Management Unit of the North Sea Mathematical Models. Marine ecosystem management unit, Brussels, p. 327.

Rivier, A., Bennis, A.C., Pinon, G., Magar, V., Gross, M., 2016. Parameterization of wind turbine impacts on hydrodynamics and sediment transport. Ocean Dynam. 66 (10), 1285–1299.

Schultze, L.K.P., Merckelbach, L.M., Horstmann, J., Raasch, S., Carpenter, J.R., 2020. Increased mixing and turbulence in the wake of offshore wind farm foundations. J. Geophys. Res.: Oceans 125, e2019JC015858.

Sverker, E., Kautsky, N., 1987. Role of biodeposition by Mytilus edulis in the circulation of matter and nutrients in a Baltic coastal ecosystem. Mar. Ecol. Prog. Ser. 38, 201–212.

van Berkel, J., Burchard, H., Christensen, A., Mortensen, L.O., Petersen, O.S., Thomsen, F., 2020. The effects of offshore wind farms on hydrodynamics and implications for fishes. Oceanography 33 (4), 108–117.

Van Hoey, G., Degraer, S., Vincx, M., 2004. Macrobenthic community structure of soft bottom sediments at the Belgian Continental Shelf. Estuarine. Coast. Shelf Sci. 59, 599–613.

Van Hoey, G., Guilini, K., Rabaut, M., Vincx, M., Degraer, S., 2008. Ecological implications of the presence of the tube-building polychaete Lanice conchilega on soft-bottom benthic ecosystems. Mar. Biol. 154 (6), 1009–1019.

Van Hulle, F., Le Bot, S., Cabooter, Y., Soens, J., Van Lancker, V., Deleu, S., Henriet, J.P., et al., 2004. Optimal Offshore Wind Energy Developments in Belgium. Project Report CP/21: SPSD II. Belgian Science Policy, Brussels, p. 154.

Van Lancker, V., Moerkerke, G., Du Four, I., Verfaillie, E., Rabaut, M., Degraer, S., 2012. Fine-scale geomorphological mapping of sandbank environments for the prediction of macrobenthic occurrences, Belgian Part of the North Sea. In: Harris, P., Baker, E.K. (Eds.), Seafloor Geomorphology as Benthic Habitat: GeoHab Atlas of Seafloor Geomorphic Features and Benthic Habitats. Elsevier, Amsterdam, pp. 251–260, p. 936.

Vanhellemont, Q., Ruddick, K., 2014. Turbid wakes associated with offshore wind turbines observed with Landsat 8. Remote Sens. Environ. 145, 105–115.

Verfaillie, E., Van Lancker, V., Van Meirvenne, M., 2006. Multivariate geostatistics for the predictive modelling of the surficial sand distribution in shelf seas. Continent. Shelf Res. 26 (19), 2454–2468.

Vlaeminck, I., Houthuys, R., Gullentops, F., 1989. A morphological study of sandbanks off the Belgian Coast. In: Pichot, G. (Ed.), Progress in Belgian Oceanographic Research 1989: Proceedings of the North Sea Symposium Held in Ghent, 14 February 1989. Management Unit of the Mathematical Model of the North Sea and Scheldt Estuary, Brussel, pp. 179–195, p. 451.

Welzel, M., Schendel, A., Goseberg, N., Hildebrandt, A., Schlurmann, T., 2020. Influence of structural elements on the spatial sediment displacement around a jacket-type offshore foundation. Water 12 (6), 1651.

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

Wilding, T.A., Cromey, C.J., Nickell, T.D., Hughes, D.J., 2012. Salmon farm impacts on muddy-sediment megabenthic assemblages on the west coast of Scotland. Aquacult. Environ. Interact. 2 (2), 145–156.

WindEurope, 2020. Offshore Wind in Europe, Key Trends and Statistics 2019, p. 40. Brussels, Belgium.

Wood, S.N., 2017. Generalized Additive Models: an Introduction with R, second ed. (second ed. Chapman and Hall/CRC. https://doi.org/10.1201/9781315370279.

Zucco, C., Wende, W., Merck, T., Köchling, I., Köppel, J., 2006. Ecological Research on Offshore Wind Farms: International Exchange of Experiences (Part B Literature Review of Ecological Impacts), p. 290. Project No: 804 46 001.

Zupan, M., Rumes, B., Vanaverbeke, J., Degraer, S., Kerckhof, F., 2023. Long-term succession on offshore wind farms and the role of species interactions. Diversity 15, 288. https://doi.org/10.3390/d15020288.

Zuur, A.F., Ieno, E.N., Elphick, C.S., 2010. A protocol for data exploration to avoid common statistical problems. Methods Ecol. Evol. 1, 3–14.