

CHAPTER 5

EVALUATION OF TURBINE-RELATED IMPACTS ON MACROBENTHIC COMMUNITIES WITHIN TWO OFFSHORE WIND FARMS DURING THE OPERATIONAL PHASE

LEFAIBLE Nene, COLSON Liesbet, BRAECKMAN Ulrike & MOENS Tom

Ghent University, Biology Department, Marine Biology Research Group, Krijgslaan 281, Campus Sterre – S8, 9000 Ghent, Belgium

Corresponding author: Nene.Lefaible@UGent.be

Abstract

Two consecutive years of monitoring at different distances (far: 350-500 m *vs.* very close: 37.5 m) within the offshore wind farms at Thornton Bank (TB; jacket foundations) and Bligh Bank (BB; monopile foundations) revealed consistent turbine-related impacts on the surrounding sediments and macrobenthic communities. Sediment fining was only observed around the jacket foundations at TB, while no conclusive results were found in terms of organic enrichment. General trends of benthic responses included higher densities and diversity (species richness) in closer vicinity of the turbines, but effects were most pronounced at TB. Community composition differed consistently at both banks and several recurring species were responsible for between-group (far *vs.* very close samples) differences during both years. Macrobenthic assemblages closer to the turbines showed similarities with communities that are associated with lower-energy environments. An in-depth community analysis was used to describe the typical within-group assemblages, but also revealed some small-scale variation in terms of densities, richness and

community composition. At last, the recurrent trend of more pronounced results at TB confirm the hypothesis that impacts are site-specific (dispersive capacities, turbine-type) and can vary over different spatial scales, which highlights the importance of a targeted monitoring at the three different turbine types (gravity-based, jackets and monopiles) found in the Belgian part of the North Sea.

1. Introduction

Considering the 2020 Belgian targets for renewable energy, there has been an expansion of offshore wind farms (OWFs) and licences in the Belgian part of the North Sea (BPNS) since 2008 (Rumes *et al.* 2017). Several projects are currently at different stages of development (planned construction, under construction or operational), but it is expected that by 2020 a total of nine OWFs will be operational within the eastern area (Rumes *et al.* 2018). In addition, the government aims to double the capacity of electricity outputs from wind energy and has planned to designate a new concession area after 2020 (Rumes & Brabant 2018).

Because every stage (pre-construction, construction, operational and decommissioning phase) of development has the potential to influence the surrounding macrobenthic communities, consistent monitoring remains of high importance (Gill *et al.* 2018). Specific impacts will, however, depend on the local habitat type and community characteristics in which the OWFs are constructed (Byers *et al.* 2013; Gill *et al.* 2018).

The OWFs under study (C-power and Belwind) are situated offshore and the naturally occurring habitats can be categorised as high-energy environments. The seafloor within these areas is usually devoid of topographic structures with mobile, medium-coarse sediments and low organic matter content (Van Hoey *et al.* 2004; Byers *et al.* 2013). Macrobenthic communities within these rather homogenous soft sediments are mainly dominated by relatively “poor” assemblages (densities and diversity) with high resilience such as the *Nephtys cirrosa* assemblage (Van Hoey *et al.* 2004; Reubens *et al.* 2009; Coates *et al.* 2014; Breine *et al.* 2018). However, a recent study by Breine *et al.* (2018) revealed that assemblages with moderate densities and high diversity (*Hesionura elongata* community) are also found in this dynamic area. The permanent presence of the turbines during the operational phase results in a modification of the habitat, by means of altered local environmental conditions (hydrology, sediment type, water column stratification) and infaunal community structures (De Backer *et al.* 2014; Maar *et al.* 2009; Danheim *et al.* 2019; Gill *et al.* 2018; Coates *et al.* 2014). In addition, these vertical structures provide surface area for colonising epifaunal communities, which in turn might intensify these changes by influencing particle and organic matter fluxes and local biodiversity (De De Backer *et al.* 2014; Maar *et al.* 2009).

These predictions, together with the results from a targeted study around one gravity-based foundation at TB, led to the

hypothesis that in closer vicinity of the turbines, sediment fining and organic matter enrichment could result in a shift towards richer macrobenthic assemblages that are associated with finer sediments (Coates *et al.* 2014; Wilding *et al.* 2012). Testing this hypothesis was implemented within the large scale monitoring from 2015 onwards by sampling at two distances (close: 50 m; far: 350-500 m) from the turbines to allow a spatial comparison within the OWFs under study. Findings from the first years of monitoring (2015-2016) did, however, not coincide with the expected results. It was proposed that effects could be restricted to distances closer (< 50 m) to the turbines and that impacts might differ between turbine types (gravity-based, jacket, monopiles). Consequently, the sampling strategy was adjusted by comparing far (350-500 m) to very close (37.5 m) locations, while also taking into account differences between turbine foundations.

Results from the 2017 monitoring campaign indeed revealed sediment fining, organic enrichment and changes in macrobenthic communities (higher densities, diversity and different compositions) at very close distances around the jacket-based foundations at TB (Lefaible *et al.* 2018). Impacts were less pronounced around the monopiles at BB, where only a difference in community composition was detected between both distances from the turbines (Lefaible *et al.* 2018). It was suggested that these contrasting results could be related to a combination of the site’s flushing potential (dispersive capacity) and structural differences between foundation types and the associated “epifaunal capacity” (Lefaible *et al.* 2018). While these findings confirm the “positive” effects of turbine presence on nearby local macrobenthic communities, it also highlights that these impacts appear to be site-specific and can vary over different spatial scales, which partially explains the discrepancy that is found in current literature in terms of effects of OWFs on benthos (Danheim *et al.*

2019; Jak & Glorius 2017). Moreover, a recurrent finding is that within the same wind park, there appears to be a high inter-turbine variability both in terms of epifaunal communities and infaunal benthic communities (Jak & Glorius 2017). As a result, describing general conclusions on turbine-related impacts remains a challenge within ongoing monitoring programs.

During the 2018 campaign, a similar sampling strategy as in 2017 (far samples: 350-500 m vs. very close samples: 37.5 m) was applied and results within this report were used to assess the strength and consistency of the distance-based differences that were observed in 2017. In addition, an in-depth community analysis was performed to

determine the small-scale variability within the communities living very close to and far from the turbine foundations.

2. Material and methods

2.1. Study area

Sampling was conducted in the concession area of two wind farms within the BPNS: C-Power and Belwind (fig. 1). Both parks are built offshore on naturally occurring sandbanks, but they differ in terms of distance from the coastline, timing of construction and turbine type. C-power is situated on the Thornton Bank (TB) at approximately 30 km from the coastline. The park became fully operational in 2013 and is

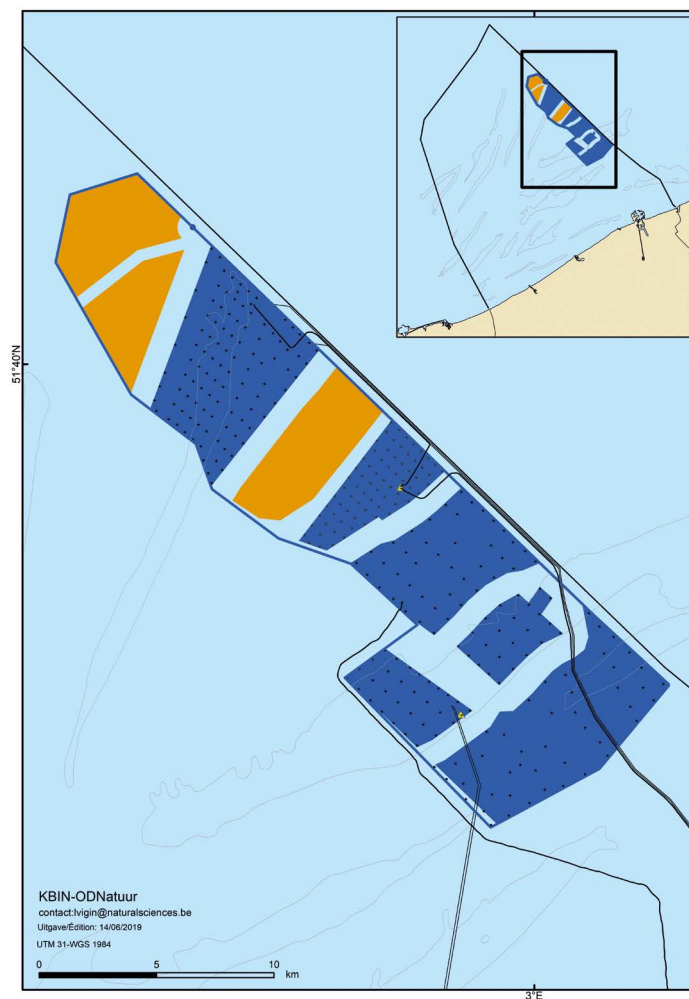


Figure 1. Wind farm concession area in the Belgian part of the North Sea. Blue areas represent operational offshore windfarms, while orange areas are domains for which concessions have been granted and building is expected to start in 2019.

composed of six gravity-based foundations and 48 jacket foundations (Rumes *et al.* 2017). Belwind was constructed on the Bligh Bank (BB), which currently represents the most offshore wind park at 46 km from the port of Zeebrugge and consists of 55 monopile foundations which have been operational since 2010 (Rumes *et al.* 2017).

2.2. Sampling design, sample collection and treatment

The potential effects of turbine presence on macrobenthic communities were tested by conducting spatial comparisons. Therefore, samples were collected at two distances from the turbines in autumn 2018 on board the vessels Aquatrot and RV Belgica. Very close samples (TB:16, BB:15) were taken at approximately 37.5 m from the centre of the turbine, whereas far samples (TB:32, BB:31) were collected in the middle between the four wind turbines (*i.e.*, farthest possible distance), *i.e.*, at distances between 350 and 500 m from any wind turbine (fig. 2).

The samples were collected from the vessels by means of a 0.1 m² Van Veen grab. A Plexiglass core (Ø 3.6 cm) was taken from

each Van Veen grab sample to collect the environmental data which include: grain size distribution (reported: median grain size [MGS]), total organic matter content (TOM) and sediment fraction larger than 2 mm (> 2 mm). After drying at 60°C, the grain size distribution was measured using laser diffraction on a Malvern Mastersizer 2000G, hydro version 5.40. Sediment fractions larger than 2 mm were quantified using a 2 mm sieve. In addition, results from the grain size distributions were also used to determine the fine sand fraction (125-250 µm) within each sample. Total organic matter (TOM) content was calculated per sample from the difference between dry weight (48 h at 60°C) and ash-free dry weight (2 h at 500°C).

The rest of the sample was sieved on board (1 mm mesh-sized sieve), and the macrofauna was preserved in a 4% formaldehyde-seawater solution and stained with Rose Bengal. In the laboratory, organisms were sorted, counted and identified to the lowest possible taxonomic level. Biomass was also determined for each taxon level as blotted wet weight (mg). Within this report these taxa are further referred to as species.

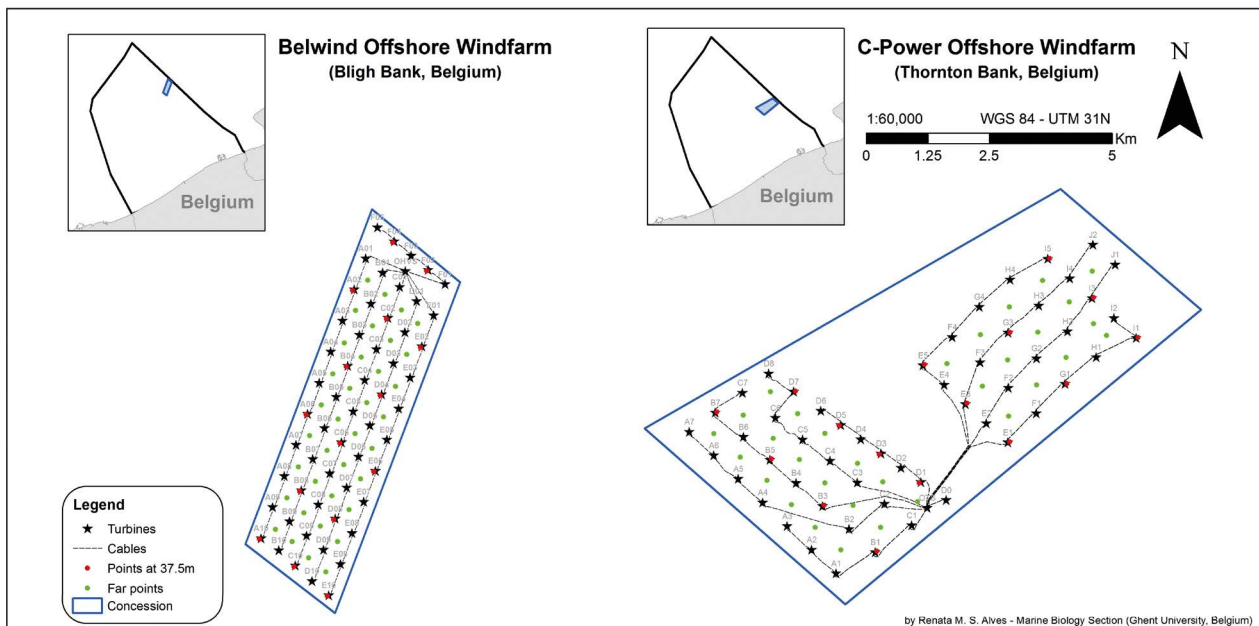


Figure 2. Overview of far and close samples at the Bligh Bank (left) and Thornton Bank (right).

2.3. Data analysis

Prior to statistical analysis, the total abundance (ind. m⁻²), biomass (mg WW m⁻²), number of species (S), Shannon-Wiener diversity index (H') and Pielou's evenness (J') were calculated from the dataset. Univariate analysis (1 way ANOVA) was performed in R (version 3.2.2) to assess differences between distances from the turbines (far *vs.* very close) in terms of the above-mentioned biological parameters and the sediment parameters MGS, fine sand fraction, fraction > 2 mm and TOM. Assumptions of normality and homogeneity of variances were tested by Shapiro-Wilk and Levene tests respectively, and log transformations were performed if these assumptions were not met. If after transformation the assumptions were still not fulfilled, a PERMANOVA (Permutational Anova, based on Euclidean distance matrix) was performed, allowing us to perform univariate ANOVAs with p-values obtained by permutation (Anderson *et al.* 2008), thus avoiding the assumption of normality. Additionally, multiple linear regression analysis was used to develop a model to predict the biotic variables that showed significant differences after univariate analysis from MGS, the fine sand fraction, sediment fraction > 2 mm and TOM. Potential multicollinearity was verified using a Variance Inflation Factor (VIF). When the final model was found, residuals were inspected to detect outliers, which were subsequently removed from the models. Shapiro-Wilk tests were used to verify whether residuals were normally distributed.

Multivariate analysis was performed in PRIMER (version 6.1.11) with PERMANOVA add-on to investigate the potential effects of distance on macrobenthic community structure. These tests were based on a Bray-Curtis resemblance matrix (fourth-root transformed data) and were performed by using a fixed one-factor design (distance, levels: far *vs.* very close). Homogeneity of multivariate dispersions was tested using

the PERMDISP routine (distances among centroids). Principal coordinates analysis (PCO) was used to visualise the data with additional vector overlay that was based on multiple correlations (Spearman correlation, $R > 0.65$). Similarity percentages (SIMPER) routine analysis was done to specify the contributions of individual species to the distinction between groups of samples and/or to the similarity of samples within a group (Clarke & Gorley 2006). These SIMPER results together with CLUSTER analysis were also used to describe the assemblages within each group (far and very close samples). Finally, a distance-based linear model (DistLM, adjusted R² with stepwise criterion) was run to investigate the potential relationship between biological and environmental variables (Anderson *et al.* 2008).

Due to the unbalanced sampling design, type "III" sums of squares were used for every analysis of variance test, and a significance level of $p < 0.05$ was applied. Quantitative results are expressed as mean values and corresponding standard error (mean \pm SE).

3. Results

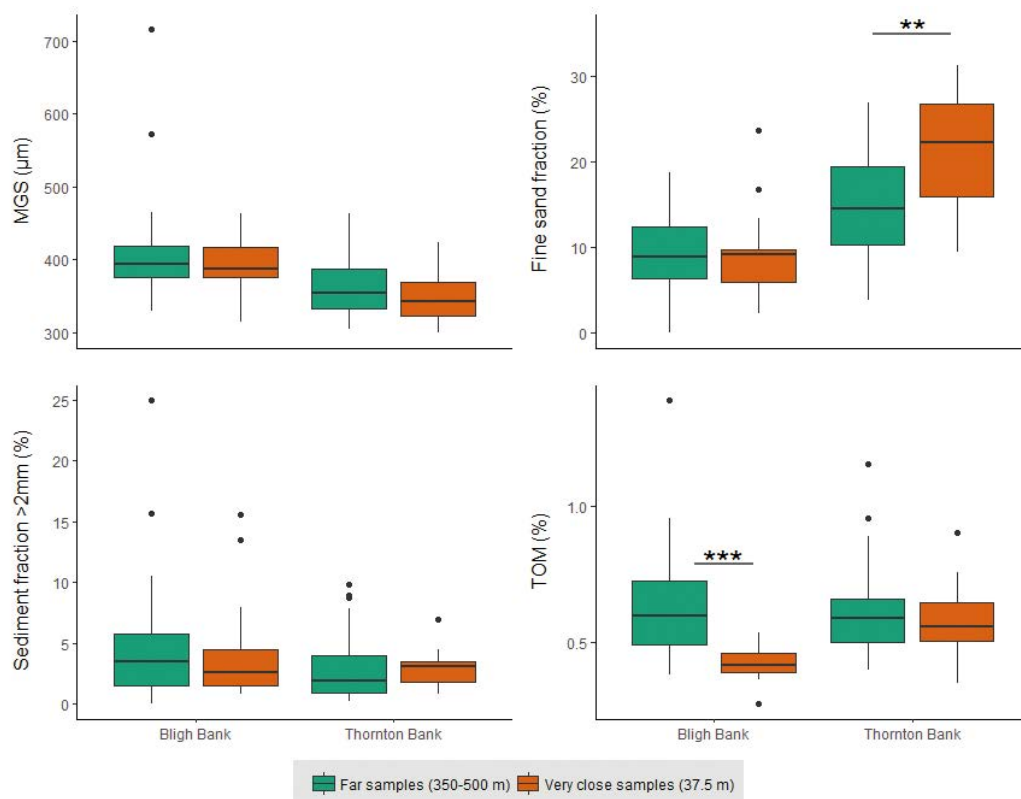
3.1. Effects of turbine presence

Quantitative results for the spatial comparison between both distances are summarised in table 1, fig. 3 and fig. 4. Sediments within both sandbanks consisted of medium sands (250-500 μ m), except for two far samples at BB with very coarse sands (BB17_Far: 572 μ m, BB22_Far: 715 μ m). Median grain size was on average lower in the very close samples at both sites, but no significant difference with the far samples was found. The average percentage of fine sand (125-250 μ m) was, however, significantly higher (table 1, $p < 0.01$) within the very close samples ($21 \pm 2\%$) compared to the far samples ($15 \pm 1\%$) at TB, whereas it was generally lower ($\sim 9\%$) and comparable for both distances at BB (table 1). Sediment

Table 1. Overview of calculated environmental and community descriptors (mean \pm SE) for the spatial comparison between both distances from a turbine in two operational wind farms at TB and BB

| Univariate results | TB Very Close | TB Far | BB Very Close | BB Far |
|--|--|-----------------------------------|------------------------------------|--|
| Median grain size (MGS, μm) | 346 \pm 10 | 362 \pm 7 | 394 \pm 11 | 410 \pm 13 |
| Fine sand fraction (125-250 μm , %) | 21 \pm 2 ** | 15 \pm 1 | 9 \pm 1 | 9 \pm 1 |
| Total organic matter (TOM, %) | 0.58 \pm 0.04 | 0.63 \pm 0.03 | 0.42 \pm 0.02 | 0.63 \pm 0.04 *** |
| Sed. fraction > 2 mm (> 2 mm, %) | 3 \pm 0 | 3 \pm 0 | 4 \pm 1 | 5 \pm 1 |
| Total abundance (N, ind. m^{-2}) | 6955 \pm 5888 *** | 334 \pm 42 | 351 \pm 86 | 205 \pm 24 |
| Biomass (BM, mg WW m^{-2}) | 265 \pm 95 ** | 134 \pm 54 | 34 \pm 19 * | 7 \pm 2 |
| Number of species S | 15 \pm 2 ** | 9 \pm 1 | 11 \pm 2 | 8 \pm 1 |
| Shannon-Wiener H' | 1.74 \pm 0.17 | 1.71 \pm 0.08 | 1.92 \pm 0.15 | 1.76 \pm 0.09 |
| Evenness J' | 0.68 \pm 0.06 ** | 0.82 \pm 0.02 | 0.86 \pm 0.02 | 0.90 \pm 0.02 |
| Multivariate results | TB Very Close | TB Far | BB Very Close | BB Far |
| Community composition | | *** | | ** |
| Permdisp analysis | | NS | | NS |

Signif. codes: “***” 0.001; “**” 0.01; “*” 0.05; NS = not significant. “*” represents significant differences that were also found in 2017.

**Figure 3.** Overview boxplots of the abiotic variables: median grain size (MGS), fine sand fraction (125-250 μm , %), sediment fraction above 2 mm (> 2 mm) and total organic matter (TOM) per sampling site (TB and BB) for the very close and far samples. Black dots represent outliers.

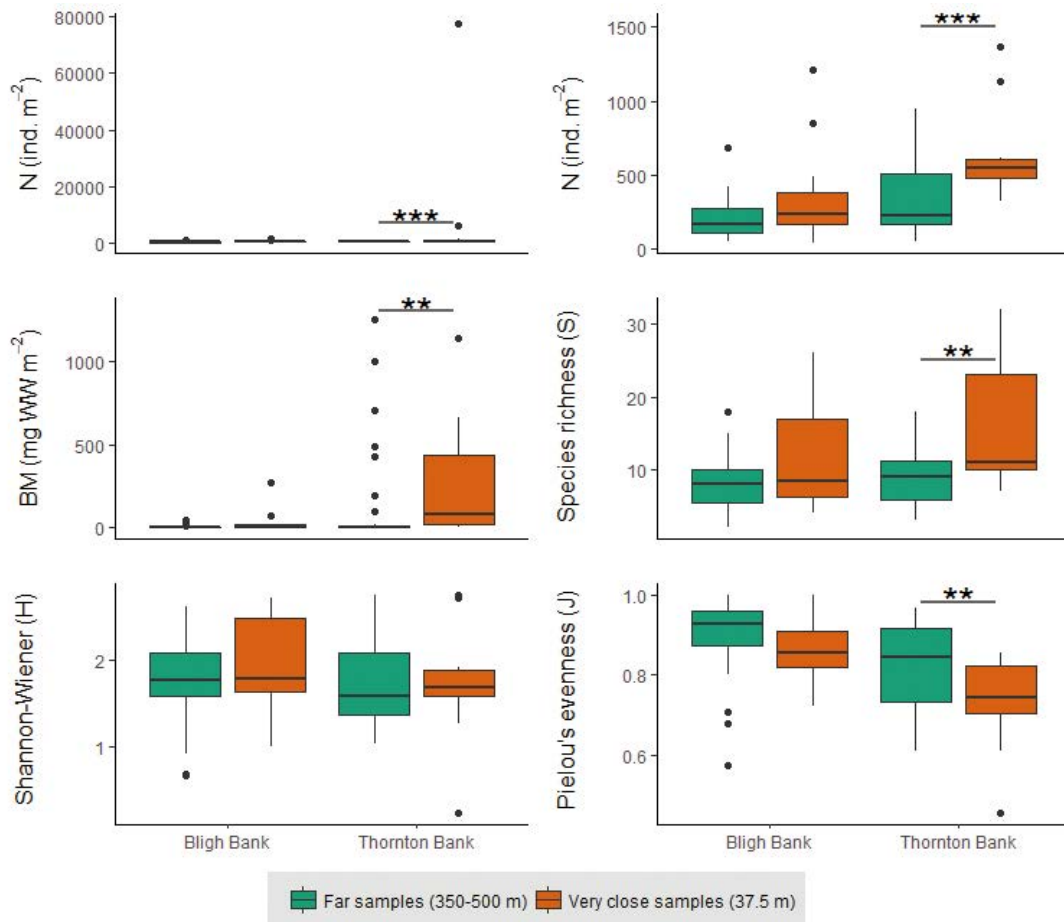


Figure 4. Overview boxplots of the biotic variables: abundance (N), abundance (N) without extreme values TB13_VC and TB16_VC, biomass (BM), Species richness (S), Shannon-wiener diversity (H'), Pielou's evenness (J') per sampling site (TB and BB) for the very close and far samples. Black dots represent outliers.

fractions > 2 mm were around 3% at TB and 4.5% at BB but within each sand bank, values proved similar at both distances from the turbines (table 1). Average total organic matter contents varied around 0.60% for all the samples at TB. A similar average value was found for the far samples ($0.63 \pm 0.04\%$) at BB, while the average TOM was only $0.42 \pm 0.02\%$ at very close samples at BB and this difference proved to be significant (table 1; $p < 0.001$).

At TB, samples closer to the turbines displayed significantly higher macrobenthic densities and biomass (1 way-Anova, $p < 0.001$ and $p < 0.05$). Two very close samples showed extremely high total densities (TB13_VC: 6020 ind.m^{-2} , TB16_VC: 77430 ind.m^{-2}) due to the dominant presence

of the amphipod *Monocorophium acherusicum*. When these samples were removed from the analysis, macrobenthic densities remained significantly higher within very close samples. In terms of diversity indices, species richness and Shannon-Wiener diversity tended to be higher at the very close samples, along with a lower evenness closer to the turbines. Except for the Shannon-Wiener diversity, all these differences proved to be significant (table 1). Multiple regression showed that only certain granulometric descriptors (MGS, fine sand fraction and > 2 mm fraction) were significant predictors for the univariate macrobenthic community descriptors at TB, while TOM was never included in the best models. The fine sand fraction was the only significant

predictor ($R^2_{adj} = 0.10$) for macrobenthic densities. In terms of macrobenthic biomass, a model containing only the > 2 mm fraction explained about 8% of the variation ($R^2_{adj} = 0.08$). Both MGS and the fine sand fraction were significant predictors for species richness ($R^2_{adj} = 0.42$), while Pielou's evenness was only explained by the fine sand fraction and the > 2 mm fraction ($R^2_{adj} = 0.19$).

At BB, density, biomass and diversity indices (S , H' and J') exhibited similar trends with distance from the turbine, but only macrobenthic biomass differed significantly between both distances. Very close samples had a 5 times higher average biomass (34 ± 19 mg WW m^{-2}) compared to the far samples (7 ± 2 mg WW m^{-2}). This difference was attributed to the high biomass of *Echinocardium cordatum* in the samples BBVC_01, BBVC_12 and BBVC_14, a species that was only found at very close distances. When these samples were removed from the dataset, average biomass was no longer significantly different between distances.

Macrobenthic community structure differed significantly between distances at both banks (table 1, fig. 5), but these

differences were more pronounced at TB (Permanova, $p < 0.001$, fig. 5) compared to BB (Permanova, $p < 0.01$, fig. 5). Permdisp tests were not significant, indicating true turbine distance effects. SIMPER analysis showed that within TB, the average dissimilarity between both distances was 62.54%. *Urothoe brevicornis* (6.67%), *Spiophanes bombyx* (5.48%), *Monocorophium acherusicum* (4.56%), *Ophiura* juv. (4.35%) and *Nemertea* sp. (4.31%) together contributed more than 25% to this dissimilarity and all these species were more abundant in the very close samples. Many other species contributed to a lesser extent (table 2). Within BB, the average dissimilarity between both distances was slightly higher (65.27%). *Bathyporeia elegans* (6.27%), *Nemertea* sp. (6.07%), *Urothoe brevicornis* (5.94%) and *Ophelia borealis* (5.38%) together contributed almost 25% of this dissimilarity. All these species, except for *Ophelia borealis*, were more abundant in the very close samples. Comparable to the results at TB, many other species contributed to a lesser extent (table 2). A DistLM was carried out to investigate the relationship between the macrobenthic community and the environmental variables. At the TB, MGS, the fine sand fraction and TOM had a significant

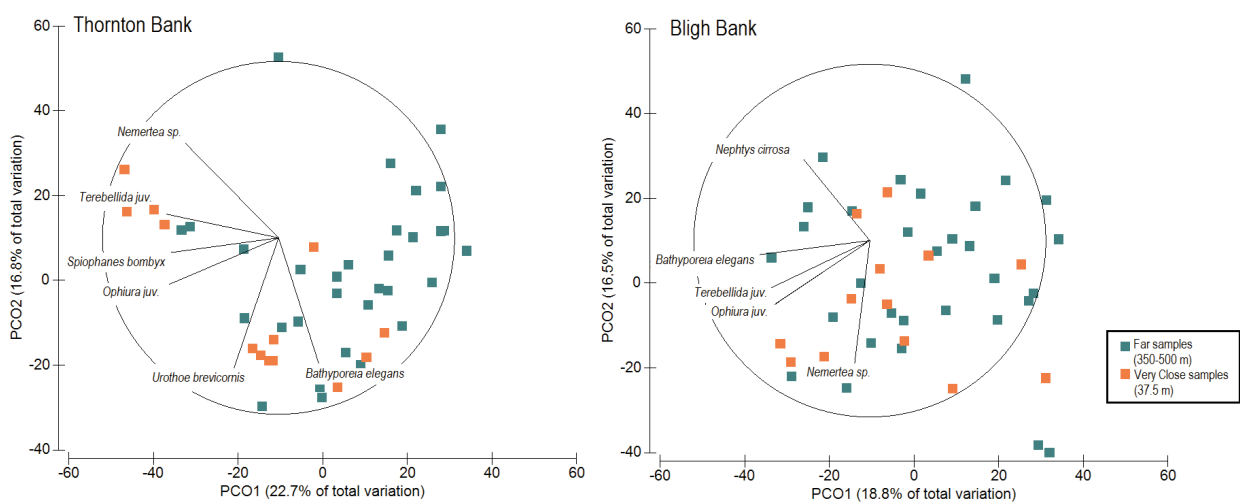


Figure 5. PCO (Principal coordinates analysis) plots based on Bray-Curtis resemblance matrix of fourth root transformed macrobenthic density data at two sandbanks (TB and BB) at two distances from the turbines (very close – far). Vector overlay was based on Pearson correlations (> 0.65).

Table 2. SIMPER results with species that contributed to the difference in community composition between the very close and far samples up to a cumulative value of approximately 50% for both sandbanks (TB and BB)

| Thornton Bank | Group Far | Group Very close | Average dissimilarity between groups 62.54% | |
|------------------------------------|-----------------------|-------------------------|--|------------------------------|
| Species | Avg. abundance | Avg. abundance | Contribution (%) | Cumulative contr. (%) |
| <i>Urothoe brevicornis</i> | 2.11 | 3.38 | 6.67 | 6.67 |
| <i>Spiophanes bombyx</i> | 0.72 | 2.33 | 5.48 | 12.15 |
| <i>Monocorophium acherusicum</i> | 0.41 | 2.26 | 4.56 | 16.72 |
| <i>Ophiura</i> juv. | 0.79 | 1.64 | 4.35 | 21.06 |
| <i>Nemertea</i> sp. | 0.98 | 1.60 | 4.31 | 25.37 |
| <i>Bathyporeia elegans</i> | 1.99 | 1.37 | 4.18 | 29.55 |
| <i>Lanice conchilega</i> | 0.41 | 1.30 | 3.73 | 33.28 |
| <i>Terebellida</i> juv. | 0.37 | 1.39 | 3.48 | 36.76 |
| <i>Nephtys</i> juv. | 2.16 | 2.37 | 3.06 | 39.83 |
| <i>Spisula</i> sp. | 0.35 | 0.74 | 2.97 | 42.80 |
| <i>Echinocardium cordatum</i> | 0.38 | 0.96 | 2.95 | 45.75 |
| <i>Bathyporeia guilliamsoniana</i> | 0.48 | 0.57 | 2.61 | 48.35 |
| <i>Spio</i> sp. | 0.76 | 0.27 | 2.52 | 50.88 |

| Bligh Bank | Group Far | Group Very close | Average dissimilarity between groups 65.27% | |
|------------------------------|-----------------------|-------------------------|--|------------------------------|
| Species | Avg. abundance | Avg. abundance | Contribution (%) | Cumulative contr. (%) |
| <i>Bathyporeia elegans</i> | 1.51 | 1.70 | 6.27 | 6.27 |
| <i>Nemertea</i> sp. | 1.04 | 1.92 | 6.07 | 12.34 |
| <i>Urothoe brevicornis</i> | 0.16 | 1.55 | 5.94 | 18.27 |
| <i>Ophelia borealis</i> | 1.78 | 1.29 | 5.38 | 23.65 |
| <i>Glycera</i> sp. | 0.88 | 1.14 | 4.62 | 28.27 |
| <i>Nephtys cirrosa</i> | 1.79 | 1.79 | 4.58 | 32.85 |
| <i>Terebellida</i> juv. | 0.55 | 1.19 | 4.42 | 37.27 |
| <i>Nephtys</i> juv. | 2.05 | 2.08 | 4.09 | 41.36 |
| <i>Spisula</i> juv. | 0.95 | 0.29 | 3.80 | 45.16 |
| <i>Spio</i> sp. | 0.54 | 0.25 | 2.90 | 48.07 |
| <i>Echinocyamus pusillus</i> | 0.39 | 0.60 | 2.84 | 50.91 |

relationship with the multivariate data structure and together explained about 16% of the total variation. All abiotic variables (MGS, fine sand fraction, TOM and > 2 mm fraction) together explained 13% of the total variation in the macrobenthic community structure of BB.

3.2. In-depth analysis of community composition

Multivariate analysis of the macrobenthic community structure revealed significant differences between distances at both banks, but high residual variances and trends on the PCO (fig. 5) also suggest some variability within groups (far and very close samples). Therefore, we conduct a more in-depth analysis of the small-scale variability within the communities living very close to, and far from the turbine foundations. Results from the CLUSTER and SIMPER analysis revealed that for both banks, a typical assemblage could be identified within each distance group (table 3). These assemblage descriptions were established by identifying the truly characterising species (~ 65% of total densities) and the supporting species that also contributed a significant part to the overall assemblage composition. While the communities in most of the samples were

similar to these typical assemblages, certain variations and distinctive assemblages were also found within each group.

3.2.1. TB (C-power)

Communities within the far group at TB had an average similarity of 40.62% and most of the samples were similar to the described typical assemblage, which can be regarded as a polychaete-amphipod dominated community. Within these samples, there was, however, a separation between poorer and richer assemblages. Poorer samples showed lower average densities for the truly characterising species and were devoid of some of the supporting species resulting in lower total densities and richness, while richer samples had occurrences (1-2 individuals) of some extra species in addition to the typical assemblage.

Four out of 32 far samples (TB04_Far, TB05_Far, TB22_Far, TB23_Far) were distinct from most of the samples due to their low species richness ($S = 4$) and low densities ($N = 50-70$ ind. m^{-2}). In addition, these “impoverished” assemblages usually lacked one or more of the truly characterising species (*Nephtys cirrosa*, *Bathyporeia elegans*). TB23_Far only consisted of *Ophelia borealis*, *Glycera* sp. and *Nemertea* sp. which separated this sample clearly from the others.

Table 3. Overview of the typical assemblage compositions (within group SIMPER analysis) for each group (far and very close) at both banks (TB and BB)

| Thornton Bank (C-power) | |
|--|--|
| Typical far assemblage | Typical very close assemblage |
| Characterising species: <i>Nephtys cirrosa</i> (+juv.), <i>Bathyporeia elegans</i> | Characterising species: <i>Urothoe brevicornis</i> , <i>Nephtys cirrosa</i> (+juv.), <i>Spiophanes bombyx</i> |
| Supporting species: <i>Urothoe brevicornis</i> , <i>Nemertea</i> sp., <i>Spio</i> sp. | Supporting species: <i>Bathyporeia elegans</i> , <i>Ophiura</i> juv., <i>Lanice conchilega</i> , <i>Nemertea</i> sp., <i>Terebellidae</i> juv. |
| Bligh Bank (Belwind) | |
| Typical far assemblage | Typical very close assemblage |
| Characterising species: <i>Nephtys cirrosa</i> (+juv.), <i>Ophelia borealis</i> | Characterising species: <i>Nephtys cirrosa</i> (+juv.), <i>Nemertea</i> sp., <i>Bathyporeia elegans</i> |
| Supporting species: <i>Bathyporeia elegans</i> , <i>Nemertea</i> sp., <i>Glycera</i> sp. | Supporting species: <i>Ophelia borealis</i> , <i>Urothoe brevicornis</i> , <i>Glycera</i> sp., <i>Terebellidae</i> juv. |

In contrast, two far samples (TB09_Far and TB17_Far) showed higher densities ($N = 500-950 \text{ ind. m}^{-2}$) and species richness ($S > 15$) than most of the samples and represented “enriched” typical far assemblages. While both samples had relatively high densities for *Nephtys cirrosa* and were devoid of *Bathyporeia elegans*, they revealed quite different compositions. TB09_Far had high densities of *Magelona* sp. and *Spiophanes bombyx*, while many other species contributed to a lesser extent (*Echinocardium cordatum*, *Tellimya ferruginosa* and *Urothoe brevicornis*). Within TB17_Far, high densities were found for *Monocorophium acherusicum*, *Lanice conchilega* and *Terebellidae* juv. together with the polychaetes *Eumida sanguinea* and *Spiophanes bombyx*.

Very close assemblages showed slightly higher average similarities (42.96%) compared to the far samples due to the fact that all three characterising species from the typical very close assemblage were found in almost every sample. In addition, no truly “impoverished” samples were found at very close distances, but some samples were also considered to be poorer due to lower densities of the characterising species and the absence of some supporting species. Comparable to the findings at far distances, four out of the 16 very close samples (TB04_VC, TB06_VC, TB13_VC and TB16_VC) showed very high densities ($N > 1000 \text{ ind. m}^{-2}$) and species richness ($S > 20$). These “enriched” assemblages were devoid of *Bathyporeia elegans* and had occurrences of *Monocorophium acherusicum* and *Actinaria* sp., two species that were not found in any other very close samples. Especially TB13_VC and TB16_VC were dominated by the amphipods *Monocorophium acherusicum* and *Jassa hermani* while many other species contributed to a lesser extent. During the processing of both samples, a high amount of medium-large blue mussels (*Mytilus edulis*) were encountered, with associated *Actinaria* growing on the mussel shells (personal observation). These samples are

therefore considered to represent hard substrate (“mussel-bed”) associated communities. TB04_VC and TB06_VC had lower amounts of *Mytilus edulis* and fewer individuals of *Monocorophium acherusicum* and *Actinaria* sp. were encountered. These samples were quite comparable to the “typical” assemblages found at very close distances but were distinct due to the relatively high amounts of *Lanice conchilega* and *Terebellidae* juv. and the recurring counts of *Tellimya ferruginosa* and *Urothoe poseidonis*.

3.2.2. BB (Belwind)

Far samples at BB revealed an average similarity of 40.14%, but SIMPER and CLUSTER analysis indicated that despite small differences in terms of supporting species and sporadic counts of additional species, the vast majority of the samples were relatively similar to the typical far assemblage described for sediments around the monopiles. Comparable to the results at TB, four out of 31 samples (BB02_Far, BB05_Far, BB17_Far, BB22_Far) were clearly “impoverished” due to the low amount of species ($S: 2-4 \text{ species/sample}$) and total densities ($N: 70-120 \text{ ind. m}^{-2}$), and these communities were mainly composed of polychaetes. Communities at BB02_Far and BB05_Far were dominated by *Nephtys cirrosa*, while BB17_Far and BB22_Far mainly consisted of *Nemertea* sp. and *Ophelia borealis*. The latter two samples also showed the highest MGS found across both banks (572 μm , 715 μm).

Very close samples had a lower average similarity (34.26%) compared to the far samples, but the majority of the 15 samples were composed of the four characterising species with some minor differentiations for the supporting species. BB14_VC and BB15_VC proved to be “impoverished” assemblages both in terms of density ($N: 40-90 \text{ ind. m}^{-2}$) and diversity ($S: 4 \text{ species/sample}$) and showed a completely different composition from the typical very close

assemblage. In contrast, four “enriched” samples (BB01_VC, BB02_VC, BB08_VC, BB13_VC) displayed high densities (N: 380-1210 ind. m⁻²) and diversity (S > 20 species/sample). Besides the truly characterising species, most of the supporting species were also found and especially *Terebellidae* juv. were encountered frequently within these samples. Additional recurrent species included: *Monocorophium acherusicum*, *Ophiura* juv., *Echinocyamus pusillus*, *Aora typica*, *Spisula* sp. and *Spiophanes bombyx*.

4. Discussion

Changes in soft sediment macrobenthic communities during the operational phase of OWFs are a result of complex interactions between the abiotic and biotic components that are being affected (Dannheim *et al.* 2019). In addition, feedback-loops between both components and the fact that effects might be restricted to different spatial scales, make it difficult to understand the true cause-effect relationships that drive these changes (Dannheim *et al.* 2019). In particular, the influence of the turbine-associated epifouling communities on the surrounding sediment composition and macrobenthic communities remains challenging to quantify within the current monitoring program. To address these impediments, findings from two consecutive years of monitoring are being used to describe general patterns that were observed and to assess certain hypothesis-based questions related to turbine presence.

4.1. Turbine-related impacts on habitat characteristics

Increasing evidence is emerging that the continual presence of wind turbines in naturally homogeneous soft sediments can affect local abiotic components and processes (Coates *et al.* 2014; Lefaible *et al.* 2018; Dannheim *et al.* 2019). The introduction of vertical structures in these well-flushed environments changes local hydrodynamics,

which largely determines the sediment composition around the turbines (Byers *et al.* 2004). The induced alterations of bottom currents and sedimentation rates might allow the creation of sheltered areas and the deposition of finer particles in the wake of the turbine (Leonard & Pedersen 2005). Consequently, the sediment refinement and associated decrease in permeability will facilitate the retention of deposited organic matter (De Backer *et al.* 2014), leading to a potential shift from high-energy areas with coarser sediments and low organic matter to lower-energy areas with the accumulation of fine sediment and higher organic content (Leonard & Pedersen 2005; Byers *et al.* 2004).

In 2017, refinement and increased food availability were clearly found around the jacket foundations at TB (Lefaible *et al.* 2018). Samples very close to the turbines displayed lower average median grain size, a higher fine sand fraction (125-250 µm) and higher organic matter content (Lefaible *et al.* 2018). While similar trends were found in 2018 for the median grain size and the fine sand fraction, only the latter proved to be significantly different between both distances in both years. Within the far samples at TB, a decrease in average MGS was observed compared to 2017, and this was also accompanied by an increase in average TOM leading to more similar values between distances in 2018. Comparable to last year’s results, turbine-related changes in sedimentology (grain size distributions) were not observed around the monopiles at BB, and TOM was even significantly lower at very close samples.

It can be concluded that results from the environmental parameters support the fining hypothesis to a certain degree (fine sand fraction) at TB. A potential explanation for the lack of significantly lower MGS at the very close samples in 2018 could be that around the jacket foundations, the spatial extent of refinement exceeds the distance

of 37.5 m, resulting in non-existent or only minor differences between both sampling locations. If true, a declining trend in MGS should also be observed at far samples since the installation of the turbines. However, a temporal comparison (since 2015) of the average MGS for the far samples at TB did not confirm this hypothesis. The absence of a consistent temporal trend in terms of MGS affirms that distant changes of altered current flow on particulate transport and organic enrichment might be difficult to measure, especially within dynamic environments subject to high natural variability (Wilding *et al.* 2014; Dannheim *et al.* 2019; Jak & Glorius 2017). Additionally, the complete lack of granulometric differences at BB reinforces the proposed hypothesis that impacts of artificial structures can vary over different spatial scales and might be dependent on local factors such as a site's flushing potential (dispersive capacities) and foundation type (Lefaible *et al.* 2018).

4.2. Turbine-related impacts on biodiversity and community structure

The areas in which TB and BB are located represent environments that are subject to strong physical disturbance where the seafloor typically consists of well-sorted, medium-coarse and mobile sediments (Van Hoey *et al.* 2004; Breine *et al.* 2018; Byers *et al.* 2004). Within these habitats, relatively “poor” communities such as the *Nephtys cirrosa* assemblage are usually found, which are dominated by mobile species with opportunistic life strategies (Van Hoey *et al.* 2004; Breine *et al.* 2018). Impacts from the presence of the wind turbines, such as the above-mentioned seafloor alterations, are likely to induce changes in the surrounding macrobenthic communities, which are strongly associated with local physical properties (Coates *et al.* 2014; Van Hoey *et al.* 2004). Within the BPNS, richer communities such as the *Abra alba* community, are generally found in coastal areas with fine to medium sandy (< 300 µm) sediments (Van Hoey *et al.* 2004). It was

therefore suggested that near the artificial structures, macrobenthic communities with a higher density, biomass and diversity could develop (Coates *et al.* 2014; Lefaible *et al.* 2018).

At TB, relatively similar results for the univariate biological parameters were found compared to 2017, which implies a consistent trend of higher densities (N), species richness (S') and lower evenness (J') at very close distances from the jacket foundations. Correspondingly, community composition also revealed persistent differences between both distances. The in-depth community and SIMPER analysis indicated that despite some divergent samples, most far samples within TB could be categorised as the widely occurring *Nephtys cirrosa* community. This assemblage is mainly composed of the polychaetes *Nephtys cirrosa*, *Nemertea* sp. and *Spio* sp. together with the amphipods *Urothoe brevicornis* and *Bathyporeia elegans* (Van Hoey *et al.* 2004; Breine *et al.* 2018). In general, very close samples were also composed of these species but showed higher relative abundances, especially for the species *Urothoe brevicornis* and *Nemertea* sp., whereas *Bathyporeia elegans* had lower average abundances. *Spiophanes bombyx* also proved to be a characterising species within the very close samples and consistently contributed to between-group differences. While this polychaete is commonly found within the BPNS, it also comprises a significant share of the *Abra alba* community along the Northern French and Belgian coast (Van Hoey *et al.* 2004; Van Hoey *et al.* 2005; Desroy *et al.* 2002). The occurrence of *Spiophanes bombyx* is also often positively associated with the habitat structuring polychaete *Lanice conchilega*, which has beneficial effects on local faunal abundance and richness (Rabaut *et al.* 2007; De Backer *et al.* 2014). In contrast with last year's results, *Lanice conchilega* was also frequently encountered closer to the jackets. The higher relative abundances of the sediment modifying polychaetes described

above and of species such as *Ophiura* juv. and the deep-burrowing *Echinocardium cordatum* confirm a shift towards richer assemblages that are usually found in lower-energy environments.

Trends for the univariate community descriptors were similar at BB with higher average densities, biomass, richness (S' , H') and a lower evenness at very close distances from the monopiles. However, comparable to the findings in 2017, none of these differences proved to be significant. Community composition did differ between distances, but dissimilarities were less pronounced compared to the results at TB. Whereas average densities were generally lower, assemblages at very close distances from the monopiles showed relatively similar compositions as the *Nephtys cirrosa* assemblages found at TB (far samples), except for the low occurrences of *Urothoe brevicornis* and the presence of the supporting species *Ophelia borealis*. The latter seems to be an indicator species of “poorer” communities (Van Hoey *et al.* 2004) and also contributed to between-group differences with higher relative abundance at far distances. While the expected turbine-related impacts seem to be less prominent at BB, SIMPER results did show some similarities with the findings at TB, and four very close samples showed considerably higher densities and diversity. Comparable to the results at TB, species such as *Terebellidae* juv., *Spiophanes bombyx*, *Ophiura* juv. and *Echinocyamus pusillus* were frequently encountered in these assemblages. This indicates that also at BB, turbine-based enrichment of infaunal communities is taking place, but on a smaller scale.

4.3. Artificial reef-effect and potential impacts of epifaunal communities

Besides the increased habitat complexity that is provided by the permanent presence of the wind turbines, the structures (and scour protection) are also rapidly colonised by hard-bottom assemblages with sessile – and

mobile fauna (Dannheim *et al.* 2019). These combined effects create so-called “artificial reefs” which are considered to increase overall biodiversity and have the potential to turn exposed soft bottom systems into rich ecosystems (De Backer *et al.* 2014; Maar *et al.* 2009; Dannheim *et al.* 2019). In addition, the epifaunal communities that establish on the turbines might indirectly intensify the described turbine-related impacts on local habitat characteristics by altering organic matter fluxes to the surrounding sediments (De Backer *et al.* 2014; Maar *et al.* 2009; Coates *et al.* 2014; Dannheim *et al.* 2019). *Mytilus edulis* is known to be a rapid coloniser of newly available surface-area and constitutes an important share of epifaunal biomass on wind turbines (Maar *et al.* 2009; Krone *et al.* 2013). These bivalves are strong habitat modifiers and their shells provide secondary hard substrate, thereby enhancing local spatial heterogeneity and associated biodiversity (Maar *et al.* 2009; Krone *et al.* 2014).

As stated in the beginning of the discussion section, the mechanisms by which the epifaunal communities might influence their environment remain challenging to quantify within the current monitoring program. However, the “enriched” assemblages (TB04_VC, TB06_VC, TB13_VC, TB16_VC) found at very close distances at TB could provide direct evidence of their potential effects. Wind turbines and especially, jacket-like foundations (oil rigs, gas platforms) seem to form a very favourable substrate for *Mytilus edulis* colonisation (Maar *et al.* 2009; Krone *et al.* 2014; Dannheim *et al.* 2019). In all four samples, significant amounts of blue mussels or their empty shells were found and they were clearly distinct from the majority of the very close samples due their high macrofaunal abundances and species richness. In addition, finer and organically enriched sediment was found at the very close distances. While these results confirm the proposed impacts of blue mussels, it also shows that the

presence of these organisms has the potential to expand the artificial reef-effect to areas beyond (> 30 m) the construction itself.

Bivalve shells can be knocked off from the structures by heavy weather or as a result of their own weight, thereby creating additional habitats or “secondary reefs” at close distances from the turbines (Krone *et al.* 2013). Krone *et al.* (2013) already described that around the piles of an oil-rig, high accumulations of deposited shells resulted in secondary hard substrate habitats (shell mounds) with high diversity and attachment sites for sessile reefs forming organisms. The samples TB04_VC and TB06_VC seem to concur with this description as they were characterised by high densities and diversity ($N > 1000$, $S > 20$) and contained significant amounts of the tube-building polychaete *Lanice conchilega*. In addition, complexes with many connected (abyssal threads) mussels were found in the samples TB13_VC and TB16_VC. Therefore, these samples might represent mussel-bed associated communities that occur around the turbines, where densities are dominated by smaller crustaceans such as the amphipods *Monocorophium acherusicum* and *Jassa herdmani*.

It is most likely that the described habitats (shell mounds and mussel-beds) were initially introduced as “drop-offs” from the turbines and impacts are therefore expected to act within an ephemeral time scale. Nevertheless, the abundant presence of *Mytilus edulis* on the turbines (source populations) and the altered seafloor conditions (sheltered areas) might allow these types of secondary/biogenic reefs to expand over time and establish permanently within the sediments surrounding the OWFs.

5. Conclusion and future perspectives

In two consecutive years of monitoring, turbine-related impacts on habitat characteristics

such as sediment refining were found, with higher fine sand fractions at very close distances (*i.e.* < 50 m) around the jacket foundations at TB. Organic enrichment was also observed around the jackets in 2017, but not in 2018. In contrast, an opposite trend of lower average organic matter content was observed at very close distances around the monopiles at BB. In terms of benthic responses, several analogies were found with last year’s results. General trends include higher densities and diversity in close vicinity of the turbines, where effects seem to be most pronounced around the jackets at TB, but there are indications that a similar process is taking place around the monopiles at BB. Furthermore, community composition between distances differed consistently at both sandbanks, with several recurring species that were responsible for between-group differences. While the hypothesis of a shift towards the *Abra alba* community could not be validated, assemblages closer to the turbines did show similarities with macrobenthic communities that are associated with finer sediment and low-energy environments (Breine *et al.* 2018; Byers *et al.* 2004). The observed changes in macrobenthic assemblage structure might in turn induce alterations in terms of functioning of the local ecosystem and a study by Breine *et al.* (2018) already revealed that physical factors such as grain size (coarse *vs.* fine sediment) were responsible for differences in trait modality compositions. It is therefore suggested that in addition to the structural biological changes that were found, functional properties might also be altered within the macrobenthic communities closer to the turbines. Consequently, results from 2017 and 2018 will be used to assess potential changes in functional diversity and trait modalities within the assemblages found around the turbines.

An in-depth community analysis provided valuable results to describe typical within-group (far and very close) assemblages.

However, considerable variation was also found in terms of densities, richness and assemblage structure. While this indicates that in these mobile sands assemblages can vary on a small spatial scale, it also emphasises that inter-turbine variability should be incorporated into future statistical analysis. Additionally, some hard substrate associated assemblages were found at very close distances around the jackets at TB, which provided insights in the potential effects of epifaunal communities on the surrounding infaunal macrobenthos.

Finally, the recurrent trend of more pronounced responses at TB confirms the hypothesis that impacts can be site-specific and may differ between turbine types (jackets vs. monopiles). These results highlight the importance of performing a targeted monitoring study that compares the effects of the three different turbine types (monopiles, jackets and gravity-based foundations) found in the BPNS.

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