CHAPTER 5

EFFECTS OF WIND TURBINE FOUNDATIONS ON SURROUNDING MACROBENTHIC COMMUNITIES

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Abstract

The installation of artificial hard substrates such as wind turbines is likely to affect the surrounding environment. Fining and organic matter enrichment were observed around one gravity-based foundation on the Thornton Bank, but subsequent basic monitoring did not reveal any of these effects in the vicinity of the turbine types at Thornton- and Bligh Bank. It was suggested that effects are restricted to close distances (< 50 m) from the turbines and that impacts could differ between turbine types. Therefore, the sampling strategy within this study was adjusted by comparing far with very close locations (37.5 m). Our results confirm turbine-related effects at very close distances around jacket-based foundations at the Thornton Bank. Within very close samples, fining and enrichment of the sediment was detected together with higher macrofaunal densities, diversity and shifts in communities. In contrast, effects around monopile-based foundations at the Bligh Bank were less pronounced and a significant difference in community composition only was found between both distances. We suggest that these contrasting results might be due to a combination of site-specific dispersive capacities and structural differences between foundation types (jackets *vs.* monopiles) and their associated epifouling communities. Consequently, we recommend performing a targeted monitoring study comparing the three different turbine foundation types (monopiles, jackets and gravity-based foundations) used in the BPNS.

1. Introduction

Currently, three offshore wind farms (OWF: C-Power, Belwind, Northwind) are operational within the concession zone for renewable energy in the eastern part of the Belgian part of the North Sea (BPNS) (Rumes & Brabant *et al.*2017). A fourth OWF will be constructed in close proximity to the coast in 2018-2019 by NV Norther.

The installation of artificial hard substrates in soft sediments could possibly affect the seafloor-inhabiting macrofauna communities. Macrobenthic communities play a crucial role in bentho-pelagic coupling and are considered an important food source for higher trophic species such as crabs and fish (Vandendriessche *et al.* 2015). Changes within these communities are therefore likely to alter overall food web energy flows (Colson *et al.* 2017; Danheim *et al.* 2014). Benthic communities are less sensitive to local-scale impacts in areas with high natural physical disturbance (Cooper *et al.* 2011). Therefore, short-term impacts through post-installation mortality are believed to be limited in the species-poor communities thriving in the

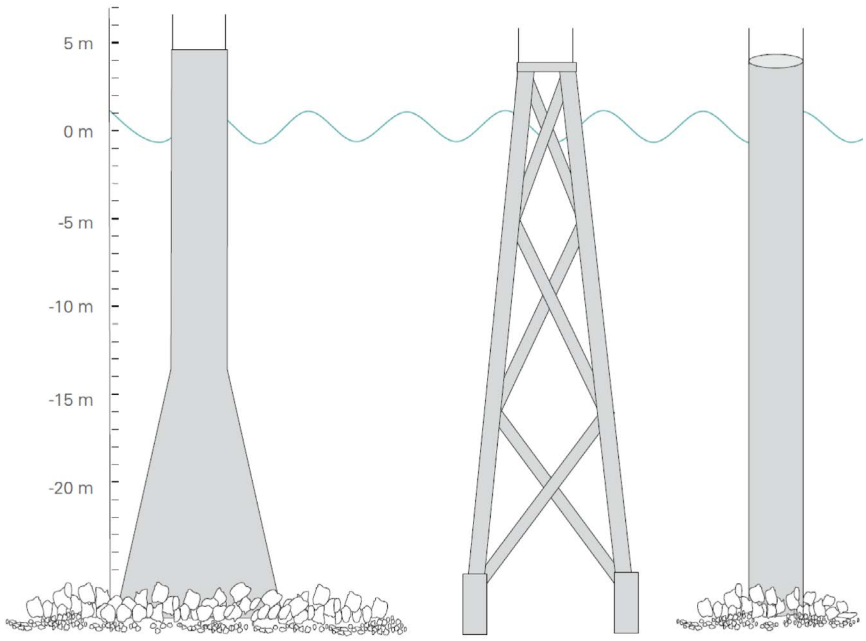

Figure 1. Three foundation types present in the Belgian part of the North Sea, from left to right: gravity based, jacket (both in C-Power) and monopile foundation (Belwind and planned in Norther) (Rumes *et al.* 2013).

highly dynamic offshore sediments of the BPNS (Van Hoey *et al.* 2004). Consecutive monitoring within two offshore wind farms (C-Power and Belwind) indeed demonstrated a relatively fast recovery (1-2 years) of the naturally occurring macrobenthic communities after wind farm construction (Reubens *et al.* 2009; Coates *et al.* 2014).

However, longer-term effects are expected. Fisheries exclusion in offshore wind farms may alter the marine environment at different levels (De Mesel *et al.* 2013; 2015; Reubens *et al.* 2013, 2014), including macrobenthic communities (Coates *et al.* 2016). In addition, the permanent presence of the wind turbines changes the physical properties of the surrounding habitat (De Backer *et al.* 2014). Vertical structures in the water column alter local hydrodynamics and sediment transport, and induce higher shear stress (Baeye *et al.* 2015; Barros *et al.* 2001). Abundant epifouling communities are known to colonize the foundations, thereby affecting the organic matter deposition to the sediment (De Mesel *et al.* 2013; Jak & Glorius 2017). Fining and organic matter enrichment of the sediment have indeed been observed in close vicinity of one gravity-based foundation on the Thornton Bank (Coates *et al.* 2013). In the macrobenthic communities within the 50 m surrounding this specific gravity-based foundation, some typical hard substrate fauna was found, next to suspension-deposit feeding species usually observed in fine sandy and organic matter-rich sediments. The subsequent basic monitoring studies (C-Power and Belwind) thereafter did not show evidence of this fining and organic enrichment in the vicinity (50 m) of any of the turbine foundation types (Reubens *et al.* 2016; Colson *et al.* 2017). Results found by Reubens *et al.* (2016) were based on samples in C-Power, which mostly consist of jacket-based turbines. Hence, a possible reason for the contrasting results with Coates *et al.* (2013) was attributed to the differences in turbine foundation types being studied. Foundation types are mainly selected according to the environmental conditions (*e.g.*, water depth and sediment type), together with production and installation costs, and other socio-economic considerations. OWF developers have hitherto used three different foundation types: gravity based, jacket and monopile foundations (fig. 1), each with different (pre-)construction-related activities such as dredging and pile driving (Coates 2014).

However, the main reason for the lack of fining and enrichment effect in the last basic monitoring studies (Reubens *et al.* 2016; Colson *et al.* 2017) may equally be the distance to the foundation at which the communities were sampled. The fining and enrichment effect is hypothesized to be restricted to very close distances (< 50 m) from the turbine foundation (Coates *et al.* 2013; Colson *et al.* 2017). For these reasons, the basic monitoring scheme comparing far (350-500 m distance from turbines) to close locations (50 m) was slightly altered in 2017 to a comparison of far with very close locations (37.5 m distance from turbine center, *i.e.*, the closest distance that is still feasible and safe to sample) within this study. In this report, we test whether a fining and enrichment effect is found at such a close distance to the turbine foundation, and whether this is reflected in the macrobenthic community structure. Furthermore, we verify whether this effect is present in the vicinity of both monopile and jacket foundation types.

A second part of the report assesses the before-impact (T0) communities in the NV Norther concession area and evaluates the suitability of the possible reference area. Conditions within the future Norther OWF differ from those already being monitored in C-Power and Belwind as this OWF is not located on a sandbank and is located very close to the coast (< 25 km). Due to the differences in sedimentology and the general distribution of macrobenthic communities along the onshore-offshore gradient described by Van Hoey *et al.* (2004), we expected to find different soft-sediment communities in this area.

2. Material and methods

2.1. Study area

Within the BPNS, sampling was conducted in the concession areas of two existing offshore wind farms (C-Power and Belwind) and one planned turbine park (Norther) (fig. 2). C-Power is located on the Thornton Bank (TB), situated approximately 30 km from the Belgian coastline. This park consists of 54 turbines with 2 types of foundations: 6 gravity-based (constructed in 2008) and 48 jacket foundations, which were built between 2011 and 2013 (Rumes*et al.* & Brabant 2017). Belwind is located at the Bligh Bank (BB) and represents the north western-most turbine park within this study (46 km from the port of Zeebrugge). Belwind contains a total of 55 monopile-based turbines that were constructed between 2009 and 2010 (Rumes & Brabant *et al.*2017). The concession for the Norther wind farm was granted in 2009 and the construction of 44 monopile-based turbines is expected to start in 2018-2019. The park will be situated 23 km from the Belgian coastline (port of Zeebrugge) and lies within the south eastern-most part of the concession area. The reference site (REF) was chosen directly beyond the south eastern border of the future wind park to correspond to the sediment characteristics found within the future Norther impact area (fig. 4).

2.2. Sample design, collection and treatment

By applying systematic stratified sampling designs, this study was able to conduct two one-way spatial comparisons as described in table 1. Within the first analysis, potential effects of turbine presence on macrobenthic communities were tested in two operational wind farms (C-Power and Belwind). Samples were collected at two distances from the turbines during autumn 2017 on board the vessels RV Simon Stevin and Aquatrot (fig. 3; table 1). ‘Very close’ samples were taken at approximately 37.5 m from the center of the

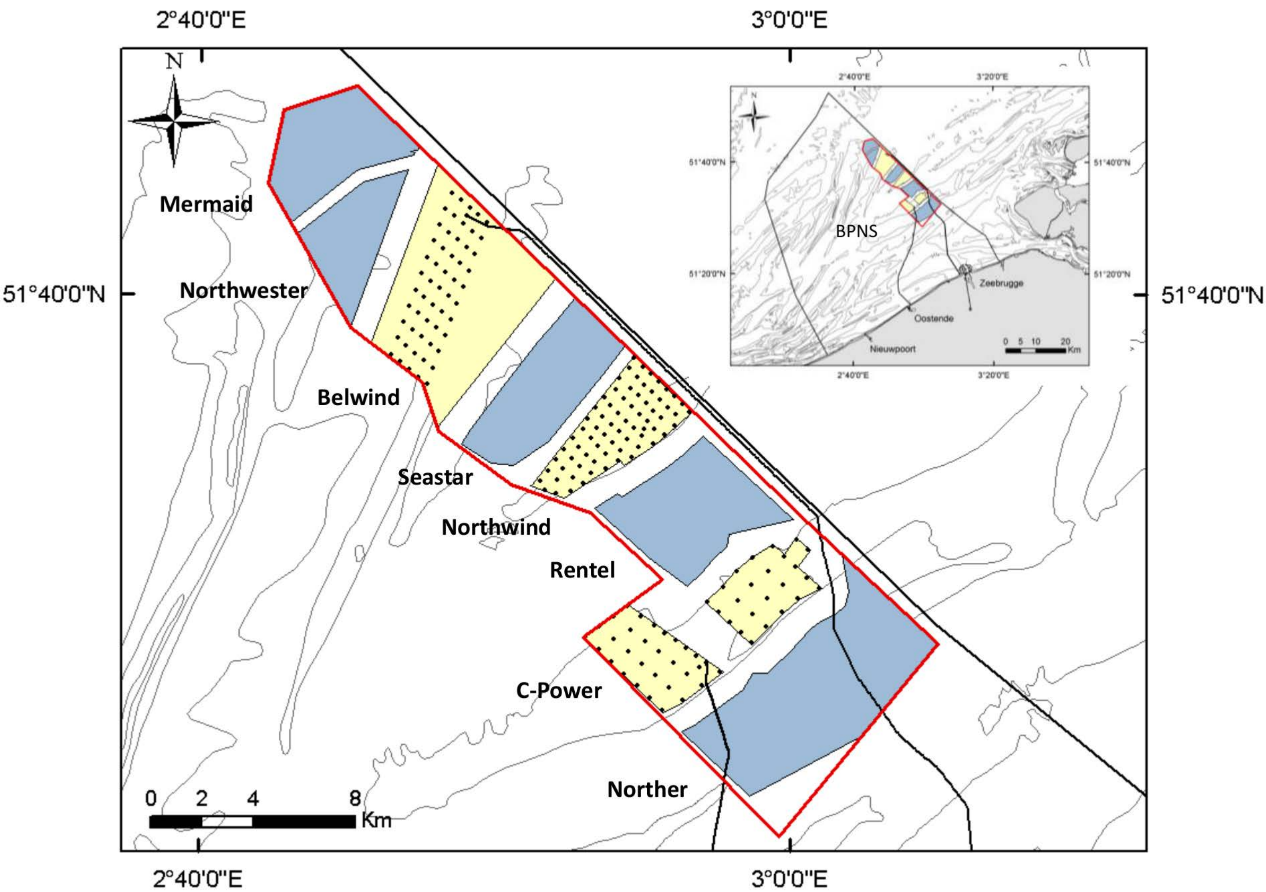

Figure 2. Wind farm concession area (red area) in the Belgian part of the North Sea. Yellow areas represent three operational offshore windfarms (C-Power, Northwind and Belwind), while blue areas are domains for which concessions have been granted (Norther, Rentel, Seastar, Northwester and Mermaid) (Coates, 2014).

Table 1. Overview of objectives and the number of samples taken at each location and sampling date

Type of analysis	Date of sampling	Vessels	Station	# samples
Effects of turbine presence (far *vs.* very close) within C-Power and Belwind windfarms	Autumn 2017 (Oct-Dec)	RV Simon Stevin, Aquatrot	TB_FAR	31
			BB_FAR	36
			TB_VERY_CLOSE	16
			BB_VERY_CLOSE	15
Baseline (T0) analysis for future offshore windfarm Norther	Autumn 2016 (Nov-Dec)	RV Simon Stevin, Stream	NORTHER_FAR	22
			Reference site (REF)	18

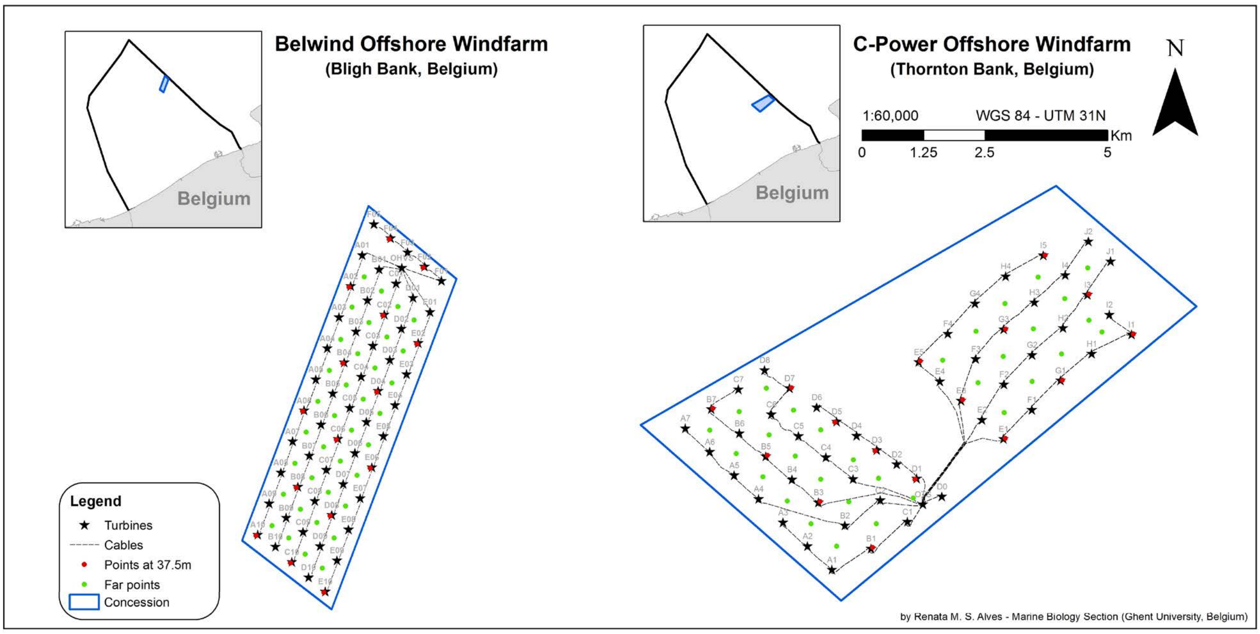

Figure 3. Overview of far and close samples at the Bligh Bank (left) and Thornton Bank (right).

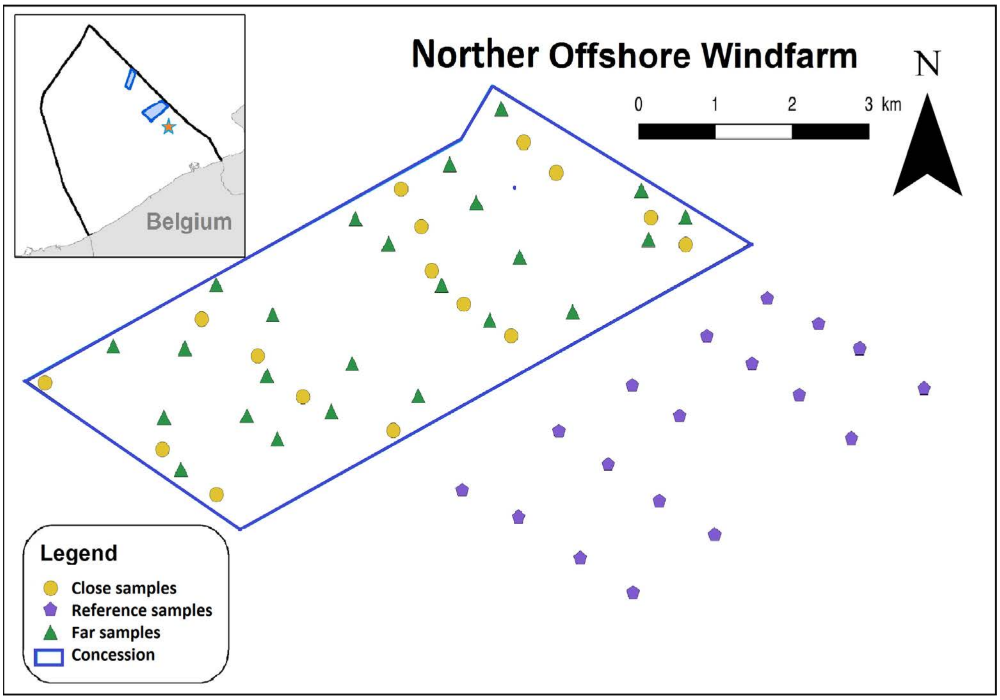

Figure 4. Overview of close and far samples (green triangles) and samples at the reference site (purple) for the future offshore wind farm Norther.

turbine, whereas far samples were collected in the middle between the four surrounding wind turbines (*i.e.*, farthest possible distance), *i.e.*, at distances between 350 and 500 m from any windmill. A second analysis was performed to establish the baseline (T0) for long-term monitoring within the future wind farm park Norther and test the validity of the proposed reference site. To this aim, samples were collected within the Norther area during autumn 2016. A similar sampling design was applied with close samples at approximately 50 m and far samples at least at 250 m from the future turbines (fig. 4; table 1). Within this study, only the far samples collected at Norther were used. In addition, 18 samples were also taken within the proposed reference area. Both the 'impact' site (Norther) and the reference site sampled in 2016 represent source samples of the area before the impact of wind turbine construction within the Before After Control Impact (BACI) design.

The samples were collected from the vessels by means of a 0.1 m^2 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 wamm). 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. The total organic matter (TOM) content was determined 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. From the obtained dataset, hyperbenthic species were excluded, and in case of uncertain identification, some taxa were lumped (*e.g.*, genus level: *Melitta* spp.).

2.3. Data Analysis

The samples collected at gravity based foundations were removed from the analyses (3 very close and 3 far samples) to test the effect of distance from the turbine, so that only samples at jacket foundations were included for the Thornton Bank. 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 Piélou'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) and location (Thornton Bank *vs.* Bligh Bank; Norther *vs.* reference site) in terms of the above-mentioned biological parameters and the sediment parameters MGS, fraction > 2 mm and TOM. Assumptions of normality and homogeneity of variances were tested by Shapiro-Wilk – and Levene's 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 & Millar 2004), 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 TOM, MGS and sediment fraction > 2 mm. Outliers were detected and removed from the models. Normal distribution of the residuals was tested

(Shapiro-Wilk) and potential multicollinearity was determined to use a Variance Inflation Factor (VIF).

Multivariate analysis was performed in PRIMER (version 6.1.11) with PERMANOVA add-on to investigate the potential effects of distance/location 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 and location, levels: Norther *vs.* reference site). Homogeneity of multivariate dispersions was tested using the PERMDISP routine (distances among centroids). Principal coordinate analysis (PCO) was used to visualize the data, while similarity percentages (SIMPER) analysis was performed to determine the contribution of species to the distinction between groups and/or to the similarity of samples within a group (Anderson *et al.* 2008; Clarke & Gorley 2006). Finally, a distance-based linear model (DistLM, adjusted R^2 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 (table 1), type 'III' sums of squares were used for every statistical test, and a significance level of $p < 0.05$ was applied. Quantitative results are expressed as mean values and corresponding standard deviation (mean ± SD). Permdisp results were only reported when significant.

3. Results

3.1. Effects of turbine presence

Thornton Bank (TB) and Bligh Bank (BB) displayed similar values in terms of TOM and sediment fraction > 2 mm. However, MGS was significantly higher at BB compared to TB (1 way ANOVA, $p < 0.01$). Higher macrobenthic densities and biomass were found at TB (1 way ANOVA, $p < 0.01$). In addition, multivariate analysis revealed that macrobenthic communities differed significantly between sandbanks (PERMANOVA, $p = 0.001$). Based on these results and to enable the comparison with the two previous reports (Colson *et al.* 2017; Reubens *et al.* 2016), it was decided to conduct further analyses testing potential effects of turbine presence for each sandbank separately.

3.1.1. Thornton Bank (C-Power)

Sediments within TB consisted of medium sands (250-500 µm), except for the sample TB28_FAR with an exceptionally high MGS (509 µm). MGS was significantly affected by distance from the turbines (1 way ANOVA, $p < 0.05$), with finer sands within the very close samples (342 ± 22 µm) compared to far samples (378 ± 49 µm). This refinement of the sediment with decreasing distance to the turbines was particularly found in the 125-250 µm fraction with the average percentage of fine sand being 20 ± 5% in very close samples, while this was only 13 ± 6% in the far samples (1 way ANOVA, $p < 0.01$). TOM content varied from 0.31%-1.86%, with significantly higher average values within the very close samples (0.72 ± 0.39%) compared to the far samples (0.53 ± 0.17%) (1 way ANOVA, $p < 0.05$). The sediment fraction > 2 mm within TB was variable and ranged from 0.04%-15.51% with higher average values within the very close samples, but no significant difference was found.

Samples closer to the turbines displayed significantly higher macrobenthic densities, species richness and Shannon-wiener diversity, whereas evenness was significantly lower (1 way ANOVA $p < 0.05$; fig. 5; table 2). No significant difference was found between both distances in terms of biomass.

Multivariate analysis on macrobenthic community structure revealed that within TB, different communities are found for both distances (PERMANOVA, $p < 0.001$; fig. 6). SIMPER results showed that very close samples had an average similarity of

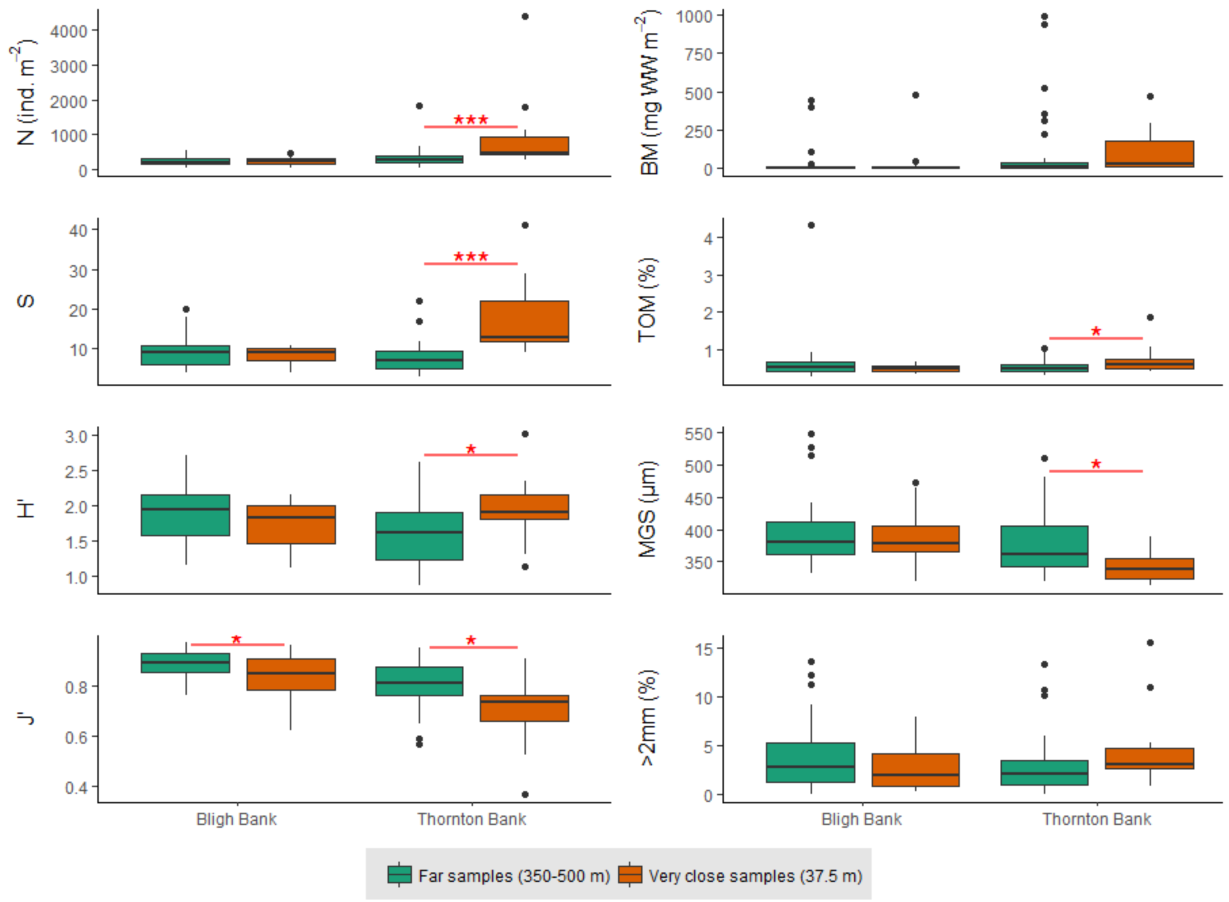

Figure 5. Overview boxplots of the biotic variables: abundance (N), biomass (BM), species richness (S), Shannon-wiener diversity (H'), evenness (J') and abiotic variables: total organic matter (TOM), median grain size (MGS), sediment fraction above 2 mm (> 2 mm) per sampling site for the very close and far samples. Black dots represent outliers.

37.25% with *Urothoe brevicornis* (22.68%), *Nephtys cirrosa* (17.45%), *Nephtys* juveniles (10.17%) and *Nemertea* sp. contributing about 60% to the total abundances. Far samples showed a higher average similarity (39.23%), but these communities were dominated by *Nephtys cirrosa* and *Nephtys* juveniles, which contributed 60% to the total abundances, while *Urothoe brevicornis* contributed another 17.45%. The average dissimilarity between communities at the two distances (far *vs*. very close) amounted to 67.33%. *Nemertea* sp. (5.58%), *Urothoe brevicornis* (5.27%), *Spiophanes bombyx* (4.17%), *Bathyporeia elegans* (4.05%), *Nephtys* juveniles (3.39%) and *Echinocardium cordatum* (3.13%) together explained about 25% of this dissimilarity and all six species showed higher average abundances in the very close samples. Many other species contributed to a lesser extent (contribution < 3%; table 3) indicating that differences between communities cannot be attributed to a few dominant species.

Multiple regression revealed that MGS and TOM were significant predictors of macrobenthic densities (N), species richness (S') and Shannon-wiener diversity (H'). This model best explained species richness (R^2_{adj} = 0.60) , followed by macrobenthic densities (R^2_{adj} = 0.41) and Shannon-Wiener diversity (R^2_{adj} = 0.17). TOM proved to be the only significant predictor (R^2_{adj} = 0.07) of Piélou's evenness (J'). All three abiotic variables (MGS, TOM and > 2 mm) had a significant relationship with the multivariate data and explained 22.83% of the total variation (DistLM analysis).

Table 2. Overview of calculated community descriptors (mean ± SD) for spatial comparisons: between both distances from a turbine in two operational wind farms at Thornton BankBank (TB) and Bligh Bank (BB), baseline analysis within a future wind farm (Norther – Reference site). Numbers that differ significantly are indicated in bold

Spatial analysis	Effects turbine presence				Baseline (T0) study	
	TB Very Close	TB Far	BB Very Close	BB Far	Norther	REF
Total abundance (N, ind. m^{-2})	**934 ± 1112** ***	343 ± 329	255 ± 118	239 ± 120	8855 ± 20612	2588 ± 2442
Biomass (BM, mg WW m^{-2})	110 ± 145	132 ± 274	39 ± 122	31 ± 99	164 ± 279	228 ± 263
Number of species S	**18 ± 9** ***	8 ± 4	8 ± 2	9 ± 4	30 ± 14	27 ± 11
Evenness J’	**0.71 ± 0.15** *	0.80 ± 0.10	**0.84 ± 0.09** *	0.89 ± 0.06	0.74 ± 0.11	0.69 ± 0.10
Shannon-Wiener H’	**1.92 ± 0.46** *	1.57 ± 0.44	1.74 ± 0.31	1.87 ± 0.42	2.40 ± 0.48	2.22 ± 0.35
Median grain size (MGS, µm)	**342 ± 22** *	378 ± 49	391 ± 42	392 ± 51	355 ± 89	334 ± 94
Total organic matter (TOM, %)	**0.72 ± 0.39** *	0.53 ± 0.17	0.50 ± 0.10	0.65 ± 0.64	**1.09 ± 0.49** ***	1.60 ± 0.50
Sed. fraction > 2 mm (> 2 mm, %)	4.68 ± 4.11	3.10 ± 3.38	2.93 ± 2.57	4.04 ± 3.76	11.45 ± 10.67	7.45 ± 9.21

Signif. codes: ‘***’ 0.001, ‘**’ 0.01, ‘*’ 0.05

3.1.2. Bligh Bank (Belwind)

In contrast to the results found within TB, all environmental variables were comparable between distances within BB. Sediments in BB were mainly composed of medium sands (250-500 µm), except for the samples: BB22_FAR (MGS: 547 µm), BB33_FAR (MGS: 514 µm) and BB36_FAR (MGS: 526 µm). The sediment fraction > 2 mm ranged from 0.07%-13.68% and TOM contents from 0.28%-4.31% with most values between 0.40% and 0.80%.

Average macrobenthic densities and biomass were slightly higher in samples closest to the turbines, while an opposite trend was found for all the diversity indices but none of these differences proved to be statistically significant. Only evenness was significantly lower (1 way ANOVA, $p < 0.05$) in the very close samples (0.84 ± 0.09) compared to far samples (0.89 ± 0.06).

Macrobenthic community structure did, however, differ between far and very close samples within BB (PERMANOVA, $p < 0.01$; fig. 6). The average similarity for the very close samples was 39.04% and communities were mainly composed (cumulative contribution of 57.26%) of the polychaetes *Nemertea* sp. (21.43%), *Nephtys cirrosa* (18.67%) and *Nephtys* juveniles (17.15%). Far samples had a higher average similarity (43.70%) with the species *Nephtys cirrosa* (24.42%), *Nephtys* juveniles (20.15%) and *Bathyporeia elegans* (13.81%) contributing approximately 60% to the difference in total abundances. Communities of far and very close samples had an average dissimilarity

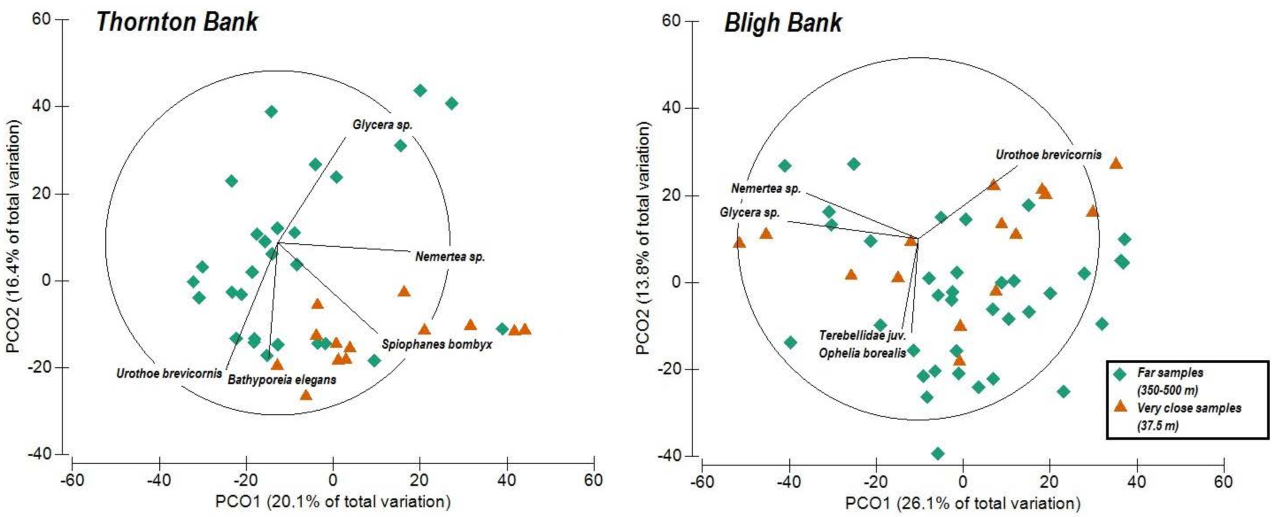

Figure 6. PCO (Principal coordinates analysis) plots based on Bray-Curtis resemblance matrix of fourth root transformed macrobenthic density data at two sandbanks (Thornton Bank and Bligh Bank) at two distances from the turbines (very close – far). Vector overlay was based on Pearson correlations (> 0.5).

of 61.19%. *Urothoe brevicornis* (7.25%), *Bathyporeia elegans* (5.93%), *Ophelia borealis* (5.47%), *Nemertea* sp. (5.46%) and *Glycera* sp. (5.24%) contributed almost 30% to this dissimilarity. Higher abundances of *Urothoe brevicornis* and *Nemertea* sp. were observed in the very close samples while the other three species were more abundant in the far samples. Comparable to the SIMPER results found at TB, many other species contributed to a lesser extent to the observed dissimilarity between distances (table 3).

Multiple regression revealed that only the sediment fraction > 2 mm was a significant predictor for Piélou's evenness, but the model showed a low fit ($R^2_{adj} = 0.08$). MGS and sediment fraction > 2 mm together explained 12.68% of the total variation in the macrobenthic community structure of BB.

3.2. Baseline analysis at Norther

Sediments found within the future impact area (Norther) and proposed reference area (REF) ranged from very fine sand to coarser sand (MGS: 96 µm-517 µm), but average values were comparable between both locations. The sediment fraction > 2 mm varied from 0.24%-39.46% with higher average values found within the Norther samples compared to the REF samples. Univariate analysis, however, revealed no significant differences in MGS and sediment fraction > 2 mm between locations. Organic matter content values were significantly higher (all > 1.00%) within REF (1.60 ± 0.50%) compared to samples of the future wind farm area (1.09 ± 0.49%; 1 way ANOVA, $p < 0.001$).

Relatively high macrofauna densities were found within both locations, and higher average densities were reported within the Norther samples compared to the REF samples (table 2). This tendency, albeit less pronounced, was also found for all the diversity indices (S, J', H'). In contrast, macrobenthos biomass showed a higher average value for the REF samples compared to the Norther samples. However, none of these differences proved to be significant (1 way ANOVA, $p > 0.05$; table 2).

Multivariate analysis of the macrobenthic community structure revealed significant differences between locations (Permanova, $p < 0.05$; fig. 8). Similarities within groups were higher for the REF sites (40.20%) compared to Norther sites (37.19%), but *Spiophanes bombyx* was the most dominant species within both locations (16.30% and 10.60% respectively, SIMPER). For the REF

Table 3. 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

Thornton Bank	**Group Far**	**Group Very close**	**Average dissimilarity between groups 66.17 %**	
Species	**Avg. abundance**	**Avg. abundance**	**Contribution (%)**	**Cumulative contr. (%)**
Nemertea sp.	1.08	2.63	5.58	5.58
Urothoe brevicornis	2.06	3.26	5.27	10.85
Spiophanes bombyx	0.51	1.74	4.17	15.2
Bathyporeia elegans	0.88	1.37	4.05	19.07
Nephtys juv.	2.04	1.70	3.39	22.46
Echinocardium cordatum	0.65	0.93	3.13	25.59
Nototropis swammerdamei	0.25	0.96	2.93	28.52
Terebellidae juv.	0.06	1.10	2.87	31.39
Spio sp.	0.35	0.86	2.46	33.85
Chaetognatha sp.	0.43	0.71	2.45	36.30
Gastrosaccus spinifer	0.43	0.59	2.45	38.75
Ophelia borealis	0.62	0.27	2.14	40.89
Urothoe poseidonis	0.27	0.62	2.00	42.89
Nephtys cirrosa	2.63	2.67	1.97	44.86
Glycera sp.	0.44	0.30	1.88	46.74
Thia scutellata	0.33	0.41	1.68	**48.42**

Bligh Bank	**Group Far**	**Group Very close**	**Average dissimilarity between groups 61.19 %**	
Species	**Avg. abundance**	**Avg. abundance**	**Contribution (%)**	**Cumulative contr. (%)**
Urothoe brevicornis	0.65	1.48	7.25	7.25
Bathyporeia elegans	1.86	1.79	5.93	13.18
Ophelia borealis	1.24	0.75	5.47	18.65
Nemertea sp.	1.53	2.06	5.46	24.11
Glycera sp.	1.09	0.80	5.24	29.35
Bathyporeia guilliamsoniana	0.00	1.17	5.04	34.39
Nephtys juv.	2.13	1.78	4.97	39.36
Nephtys cirrosa	2.27	0.30	4.59	43.95
Spio sp.	0.95	0.30	4.53	**48.48**

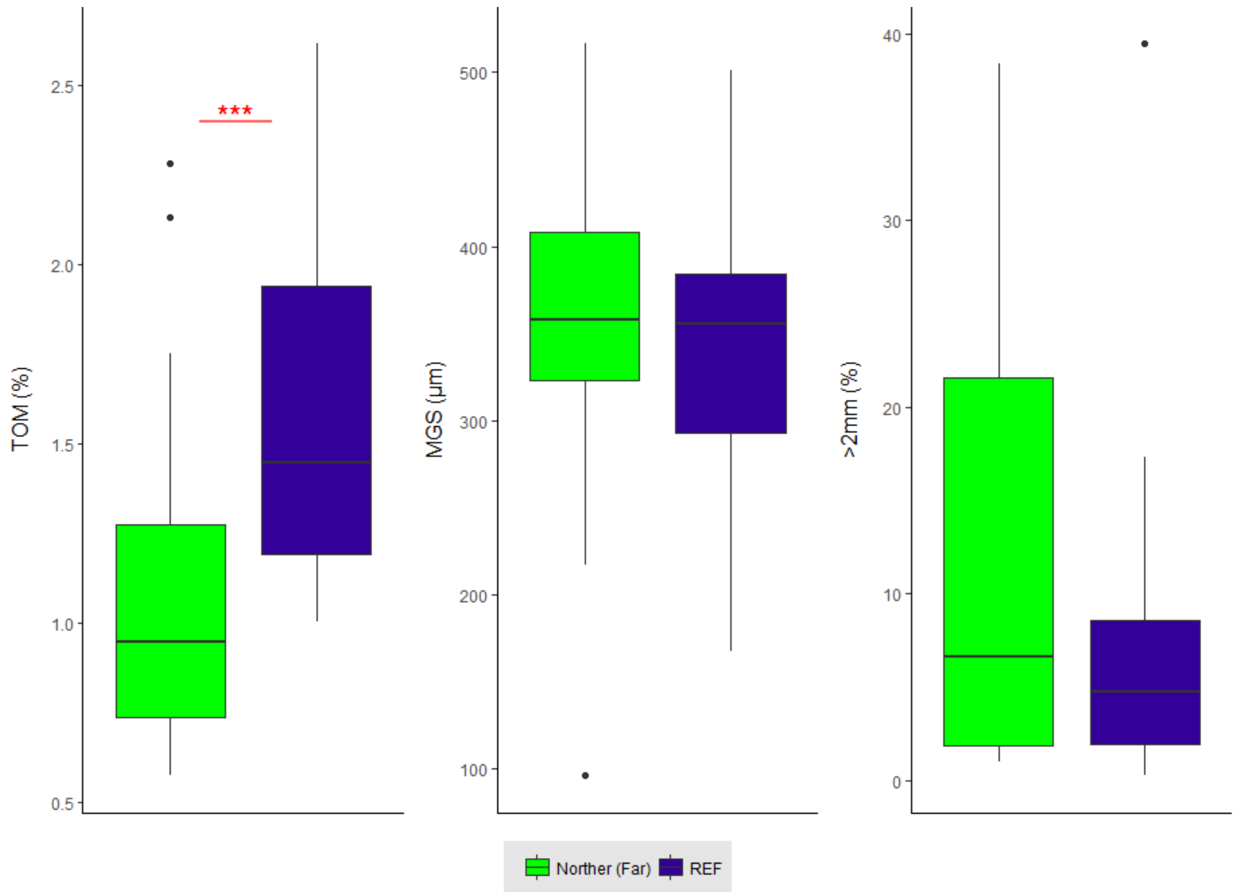

Figure 7. Overview boxplots of abiotic variables: total organic matter (TOM), median grain size (MGS), sediment fraction above 2 mm (> 2 mm) within each location (Norther vs. Reference site). Black dots represent outliers.

sites, the other two most abundant species were *Nemertea* sp. (14.30%) and *Nephtys cirrosa* (5.43%), while for the Norther samples these included *Urothoe breviconis* (9.49%) and *Nemertea* sp. (7.99%). The average dissimilarity between Norther and REF sites was 64.08%. The five most important species contributing over 10% of this differentiation included: *Urothoe brevicornis* (2.47%), *Spiophanes bombyx* (2.16%), *Edwardsia* sp. (2.14%), *Eumida sanguinea* (2.10%) and *Echinocyamus pusillus* (2.08%). All of these species showed higher average abundances in the Norther samples, except for the polychaete *Spiophanes bombyx* which was more abundant in the REF samples. It must be stated, however, that overall relative contributions were low and that many other species contributed to a lesser extent (relative contribution < 2%). A comparable analysis for multivariate biomass data revealed similar results (Permanova, $p < 0.05$). Similarities were again higher within the REF samples where biomass was dominated by *Spiophanes bombyx* (13.90%), *Nephtys cirrosa* (9.29%) and *Nemertea* sp. (8.46%). Within the Norther samples, *Nephtys cirrosa* (13.5%) contributed most to overall biomass followed by *Spiophanes bombyx* (9.22%) and *Urothoe breviconis* (8.90%). The average dissimilarity between locations was 68.54% and was mostly due to the species *Echinocardium cordatum* (5.22%), *Ophiura ophiura* (3.96%), *Spisula* sp. (3.46%), *Lanice conchilega* (2.84%) and *Ophiura albida* (2.73%), explaining approximately 20% of the dissimilarity. The first three species had higher average abundances in the REF samples, while the opposite was found for *Lanice conchilega* and *Ophiura albida*.

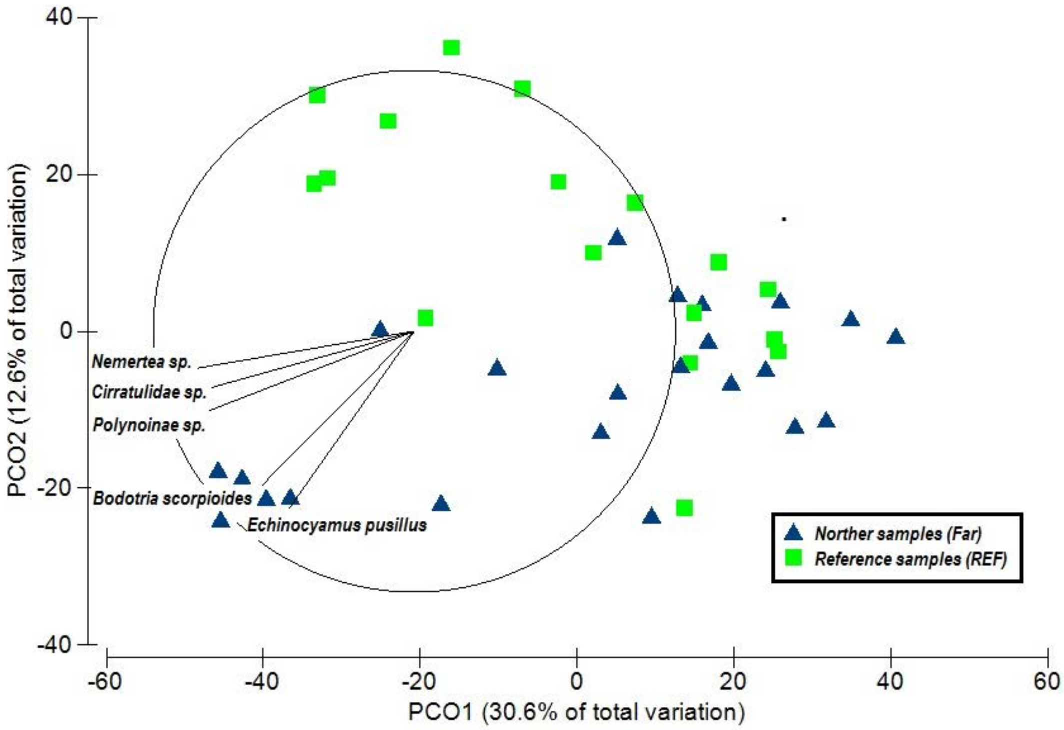

Figure 8. PCO (Principal coordinates analysis) plots based on Bray-Curtis resemblance matrix of fourth root transformed macrobenthic density data at two locations (Norther and reference site). Vector overlay was based on Pearson correlations (> 0.5).

The DistLM analyses showed that all environmental variables had a significant relationship with the multivariate abundance and biomass data, which explained 25.79% and 24.67% of the total variation, respectively.

4. Discussion

4.1. Effects turbine presence on soft sediment macrobenthic communities

The patterns observed on the Thornton Bank correspond to predictions and findings of earlier work describing the 'positive effects' of turbine presence and associated fouling communities on local macrobenthic communities (very) close to the structures (De Backer *et al.* 2014; Coates *et al.* 2014; Martin *et al.* 2005; Maar *et al.* 2009). Turbine foundations are known to change sediment characteristics by modifying local current flows and through the creation of sheltered areas (Leonard & Pedersen 2005). In this study, refinement of the sediment closer to the turbines is reflected both in terms of a smaller median grain size and an increased fine sand fraction (125-250 µm). The combined effects of these changes to the natural sediment and the local increase of biodiversity due to colonizing epifouling communities seem to have resulted in higher total organic matter concentrations in sediments closer to the turbines. The positive correlation between organic content and fine sediment fraction is a well-known phenomenon (Coates *et al.* 2014; Snelgrove & Butman 1994). Finer sediments have a lower permeability, which in turn facilitates the retention of deposited organic matter (De Backer *et al.* 2014; Janssen *et al.* 2005). Additionally, epifouling communities are known to increase local organic matter input through the deposition of faecal pellets and detritus (De Backer *et al.* 2014; Maar *et al.* 2009; Coates *et al.* 2014).

These changes in sedimentology (grain size and organic matter) also affected the surrounding soft-substrate macrobenthos as predicted by De Backer *et al.* (2014). The local increase in densities close to the turbines was accompanied by a higher diversity (S, H') and lower evenness (J'). Within the BPNS, abundance and species richness are highly correlated (Van Hoey *et al.* 2004) and rich communities such as the *Abra alba – Kurtiella bidentata* community are generally found in fine to medium sandy sediments (< 300 µm) with significant mud contents. A typical species for this community is the habitat structuring tube polychaete *Lanice conchilega*, which has positive effects on local faunal abundance and richness through its bioengineering capacities (Rabaut *et al.* 2007). Within TB, this species seems to be rare and was only found in one very close sample (TB_VC_16). Despite its cosmopolitan distribution and occurrence in sediments ranging from mud to coarse sands, highest *Lanice conchilega* densities are usually found in shallow muddy and fine sands in coastal areas (Van Hoey *et al.* 2008; Degraer *et al.* 2006). Additionally, Van Veen grabs have a low sampling efficiency for this species due to its rapid retracting ability (up to 20 cm), leading to a potential underestimation of actual densities (Van Hoey *et al.* 2006). SIMPER analysis, however, revealed that the opportunistic polychaete *Spiophanes bombyx* was almost completely absent from the samples far from the turbines. The occurrence of *Spiophanes bombyx* appears to be positively associated with *Lanice conchilega* (Rabaut *et al.* 2007; De Backer *et al.* 2014) and contributes a significant share of the described *Abra alba – Kurtiella bidentata* community along the Northern French and Belgian coast (Van Hoey *et al.* 2004; Van Hoey *et al.* 2005; Desroy *et al.* 2002). In addition, Coates *et al.* (2014) related the enrichment of macrofaunal abundances to the occurrence of *Asterias rubens*, *Lanice conchilega* and *Spiophanes bombyx* close to the studied GBF. Therefore, the higher relative abundances of this species together with other species (*Urothoe brevicornis*, B*athyporiea elegans* and *Nemertea* sp.) indicate a shift towards communities with higher density and diversity.

In contrast to the findings within the TB, no strong effects of turbine presence were found on the Bligh Bank as none of the studied univariate variables differed between distances, except for a lower evenness in very close samples. This is in accordance with a review paper by Jak & Glorius (2017) summarizing current research on macrobenthos in offshore wind farms within the North Sea. It was concluded that effects of turbine presence on soft sediment benthos are unclear and that if effects were found, they were either subtle, temporary or even opposite to expectations. It must be considered, however, that most of the studies were performed relatively shortly after constructions and that minimum distances from windmills were further (> 100 m) compared to our study. Nevertheless, Colson *et al.* (2017) also did not find any effects of turbine presence within BB at a distance of 50 m. In the present study, macrobenthic communities did differ between distances. However, compared to TB, communities from different distances showed lower dissimilarities and less pronounced differences. SIMPER results, however, did show some similarities with results at TB as very close samples showed higher abundances of *Nemertea* sp. and *Urothoe brevicornis*. In addition, very close to the turbines, we observed lower relative abundances of *Glycera* sp. and *Ophelia borealis*, both indicator species for the very low density and diversity *O. borealis-Glycera lapidum* community (Type I SA6; Van Hoey *et al.* 2004). This, together with a weak tendency of higher densities and lower evenness within very close samples, indicates a potential effect of turbine presence in very close vicinity of the structures.

The fact that somewhat different patterns are observed among both banks confirms the lack of consistent responses in current literature: impacts of artificial structures appear to be site-specific and can vary over different spatial scales (Martin *et al.* 2005). It also confirms that distant enrichment effects can be rather subtle and difficult to detect

(Keeley 2013; Jak & Glorius 2017). Changes in sediment type and food supply explained a substantial amount of the turbine-related increases in densities and diversity (S, H') at TB, but not at BB. Nevertheless, DistLM analyses revealed that the environmental variables used in this study did not seem to clarify macrobenthic community structure, especially within BB. This indicates that other local-scale factors may play an important role as well.

Difference in timing of construction between both OWFs might be a temporal factor driving the contrasting results. C-Power has been fully operational since 2013 (4 years), while Belwind since 2011 (6 years). This time-lag can have an impact on the state of the fouling communities on the actual structures, as species richness increases with age since installation (Van der Stap *et al.* 2016). Therefore, epifauna on the turbines might be in a different phase of succession (Colson *et al.* 2017; Leonard & Pedersen 2005). Studies on other artificial reefs (platforms, shipwrecks) do show a significant impact of time (Coolen *et al.* 2015; Van der Stap *et al.* 2016) and indicate that actual colonization with stable communities is attained after 5-6 years (Leeuwis *et al.* 2000; Hiscock 2010). As Belwind foundations have been installed for a longer time period, we would expect to find 'stable' epifouling communities with potentially stronger impacts on the environment surrounding the monopiles, but an opposite trend was found. However, offshore wind farm development is a 'young' industry in the North Sea, so long-term data on epifauna communities and studies on their dynamics within these OWFs are scarce. In addition, trends of fouling communities on artificial structures are less predictable than natural reefs and probably depend on several other abiotic factors such as depth, distance from the coast and water currents (Van der Stap *et al.* 2015).

An alternative explanation may be found in the difference in turbine foundation structure and its associated epifauna: Belwind consists of monopiles, while C-Power has constructed both gravity-based foundations and jackets (Colson *et al.* 2017; Reubens *et al.* 2016). Current literature demonstrates a clear vertical zonation on the turbines which appears to be consistently quite different between foundation types (Jak & Glorius 2017 and references therein; De Mesel *et al.* 2013). De Mesel *et al.* investigated subtidal fouling communities within TB and BB. Results showed that the *Mytilus*-zone was well developed (1 m width) on the concrete gravity based foundations on TB, while this zone was much narrower (50 cm) on the steel monopiles at BB. It was also found that communities in the subtidal zone are mostly the same, but that some species were only found on the GBFs and that overall, higher relative abundances were reached at TB. While epifaunal communities on jacket structures have not been studied in detail within TB, these turbines are fully covered with mussels (Reubens, pers. comm.). Krone *et al.* (2013) studied epifouling dynamics at an offshore platform (FINO-1) comparable to the jacket-based foundations at TB. While species composition on this structure was comparable to findings by De Mesel *et al.* (2013) and others, it was considered a 'biomass hotspot' with very high densities and biomass of the blue mussel *Mytilus edulis* ('Mytilisation'). Additionally, offshore oil rigs within the central and northern North Sea were dominated by *Mytilus edulis* up to depths of 20 m (Whomersby & Picken 2003). It appears that these jacket-like structures are extremely favourable for *Mytilus edulis* colonization. These bivalves are believed to have a strong impact on the surrounding environment (Krone *et al.* 2013; Maar *et al.* 2009). They affect biological activity by influencing particle and sediment fluxes and enrich surrounding sediments through their faeces/pseudo-faeces (Maar *et al.* 2009). Moreover, their shells provide secondary hard substrate enhancing spatial heterogeneity and associated local diversity (Maar *et al.* 2009; Krone *et al.* 2012; Svane *et al.* 2001). In addition, the amount of newly available substrate differs per foundation type (Rumes *et al.* 2013; Krone *et al.* 2013). Introduced surface area for epifouling colonization in the subtidal zone is highest for jackets (1280 m^2) followed by gravity based foundations (671 m^2) and monopiles (518 m^2) (Rumes *et al.* 2013). These combined effects of lower surface area and 'poorer' epifouling communities in terms of densities and richness may partially explain the contrasting results found in this study.

Finally, it can be expected that the spatial extent of enrichment effects will be dependent on local resuspension processes, transporting organic particles from the 'footprint' area to the adjacent sediments (Keeley 2013). Dispersive capacities of a site are determined by its physical properties such as sediment type, water masses, depth and current speed. Especially the latter two will determine the 'flushing' potential of a site, which affects the accumulation of TOM and nutrient mineralisation (Keeley 2013; Coates *et al.* 2004). With medium to coarse sediments, TB and BB can be considered as highly permeable areas. However, some differences could result in other dispersive properties between both sites. Firstly, both sandbanks are influenced by dissimilar water masses and differ in their relative position and distance from the coastline (Van Hoey *et al.* 2004; Lacroix *et al.* 2004). Secondly, the larger MGS suggests that stronger current velocities are present at BB compared to TB. Finally, regression analysis showed that TOM was not a significant predictor of abundance, diversity or community composition within BB. Therefore, an additional explanation for the lack of a significant enrichment effect at BB could be that BB represents a higher energy/flow system with intense resuspension and ephemeral organic enrichment, leading to no or at most very subtle effects at very close distances.

Previous studies have shown that monopiles are being colonized by epifauna (De Mesel *et al.* 2005) and that these structures alter local hydrodynamics (Leonard & Pederson 2005). The spatial extent of turbine-related effects, however, probably depends on interrelated factors such as a site's dispersive capacity and turbine-specific epifouling potential. As a result, impacts on local soft-sediment communities may only be detectable at distances even closer (< 37.5 m) from the monopile turbines at BB.

4.2. Baseline analysis

Whereas most wind farms are being constructed in more offshore areas, Norther will be situated in the coastal zone. A reference area was chosen directly below the future wind park (southeast border) and is thereby located even closer to the Belgian coastline. The median grain size in both reference and future impact area of Norther was variable, ranging from very fine to coarser sands. However, average values fell within the range of medium sands (250-500 µm), which are widely found within the BPNS (Van Hoey *et al.* 2004; Degraer *et al.* 1999). The higher total organic matter content in the more onshore reference area can be attributed to the onshore-offshore gradient that is established in terms of nutrient availability within the Southern North Sea (Brockemann *et al.* 1990). The higher TOM values within the reference area did, however, not result in notable differences between both areas in terms of macrobenthic diversity, biomass and densities.

While multivariate statistics revealed differences in community structure between the Norther site and the reference area, the PCO (fig. 8) also suggests strong variability within both locations and especially for samples in the future impact area. In addition, SIMPER results indicate that dissimilarities between locations are mostly due to subtle differences in less abundant species (low relative contribution, < 2%) and that true discriminating species are difficult to confirm. These findings corroborate the results of Van Hoey *et al.* (2004), who observed a high heterogeneity in granulometry and macrobenthic communities within the nearshore area of the BPNS.

Within the reference area, certain samples (REF_13, REF_17, REF_18) showed most similarities with the subtidal *Abra alba – Kurtiella bidentata* community (Type I, SA1). This community is found in nearshore areas with finer sands and high total organic matter content. This community is characterized by high densities (> 2000 ind. m^{-2}) and diversity (≥ 30 spp. $sample^{-1}$) and by the occurrence of species such as the amphipod *Parambius typicus* and habitat structuring species like *Lanice conchilega* and *Owenia fusiformis* (Rabaut *et al.* 2007; Ropert & Dauvin 2000; Van Hoey *et al.* 2004). Some samples within the future impact area (FAR_14, FAR_17, FAR_20 and FAR_23) were quite distinct and showed no similarity with previously described communities by Van Hoey *et al.* (2004). These samples consisted of finer sands and high gravel fractions (> 20%), indicating the presence of mixed sediment substrate with boulders. These communities had very high total abundances (> 10,000 ind. m^{-2}), high diversity (> 40 spp. $sample^{-1}$), and were dominated by hard substrate-associated taxa such as *Monocorophium acherusicum*, *Monocorophium insidiosum* and the tanaid *Apseudopsis latreilli* (pers. comm. Francis Kerckhof & Gert Van Hoey). The majority of samples, however, consisted of medium sands and had total abundances between 1000-2000 ind. m^{-2}, probably representing a transitional community (Type II, SA3) between the rich *Abra alba-Kurtiella bidentata* community (Type I, SA1) and more impoverished communities (Type I, SA4 & SA6) found in offshore areas (Van Hoey *et al.* 2004).

The results gave a first insight into the Norther future impact site and the reference area, that have both been used as control for BACI tests to evaluate the future impacts of human-induced perturbations on the benthic ecosystem. Being situated in the coastal zone, different communities were described, therefore the validity of the chosen reference area as a whole can be questioned. In order to reduce the effects of this natural variation, it is proposed to classify the Norther and reference area into different habitat types and corresponding communities. This will allow to perform more reliable comparisons when testing for potential turbine effects in future studies. Despite the variability that was found in terms of granulometry and macrobenthic communities, it can be stated that sediments within the region are mainly composed of medium sands and receive a high amount of organic matter. In addition, high densities and diversity were found and communities were dominated by the common polychaetes *Spiophanes bombyx* and *Nephtys cirrosa*, while many other species contributed to a lesser extent.

5. Conclusion and future perspectives

This study confirms the effects of turbine presence on the surrounding sediment and associated macrobenthos. Refinement and organic enrichment were detected at very close distances (37.5 m) around jacket-based foundations on the TB. While the communities currently found closer to the turbines within TB cannot be described as true *A. alba – K. bidentata* communities, the increase in densities, diversity and the trends in species composition indicate an ongoing shift towards this fine-sediment associated community. Impacts were less pronounced around the monopiles at the BB, where only a difference in communities was detected between both distances from turbines. These contrasting results indicate that turbine-related effects can be site-specific and probably depend on several local-scale factors and/or on turbine foundation type.

Monopiles and jackets are completely different structures with distinct construction activities (scouring protection), shape and subtidal surface area, which in turn affects the colonization patterns of the fouling communities. Differences in epifauna in terms of abundance, diversity and zonation patterns probably influence the distance from where turbine-related enrichment is found. Furthermore, a site's dispersive capacity might also influence the spatial extent of enrichment to nearby sediments.

As the development of offshore wind farms is expanding in the North Sea (Baeye *et al.* 2005), continued monitoring is recommended to understand the impacts that are being found and to fill the current gap of long-term studies. In addition, this study highlights 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. Results found in this study and Coates *et al.* (2013) show that the spatial extent of enrichment effects differs between foundation types. Therefore, it would be more accurate and informative to perform future monitoring at several distances (gradient) from the turbines, with closest samples even closer than the distance used in this study (< 37.5 m). In addition to the established environmental parameters (MGS, sediment fraction > 2 mm and TOM), we propose to also incorporate Chl-*a* measurements, such that food availability can be assessed both in terms of quantity and quality. Moreover, it would be interesting to investigate the macrobenthic communities through the combination of taxon composition (distribution of taxa) – and functional traits analysis to translate community shifts to changes in specific ecosystem functioning rates.

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