CHAPTER 4

EFFECT OF TURBINE PRESENCE AND TYPE ON MACROBENTHIC COMMUNITIES INSIDE AN OFFSHORE WINDFARM?

COLSON Liesbet, BRAECKMAN Ulrike & MOENS Tom

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

Abstract

At present, three offshore wind farms are operational in the Belgian part of the North Sea (BPNS) and five more will be built in the near future to meet Belgium's 2020 targets for renewable energy. Introducing these artificial hard substrates in a soft sediment habitat (*i.e.*, reef effect) is believed to cause the largest impact on the marine environment and at different scale. Many studies already demonstrated the reef effects on macrobenthos in the immediate vicinity of wind turbines. In this report we studied whether there is an effect of turbine presence on macrobenthic community structure and if so, if this effect differs between different types of foundations. Samples were taken at two distances from the turbines: far (350-500 m) and close (50 m). Our results show that the installation of offshore wind turbines can induce changes in the macrobenthos. This is mainly seen at the Thornton Bank, where communities of the far sites differ significantly from the close sites, with a higher Shannon-Wiener diversity and evenness at the far sites (respectively H' close: 1.62 ± 0.14; far: 1.93 ± 0.06; and J' close: 0.72 ± 0.04; far: 0.81 ± 0.02). These community changes occurred independently of the abiotic environment (measured variables: grainsize [µm], total organic matter [%] TOM and 2 mm sediment fraction), for which no differences were detected with respect to turbine presence. However, on the Bligh Bank, a higher organic matter content was found further from the turbines, but this did not result in differences between the communities of the two distances to the turbine. No differences were observed for both the abiotic and the biotic variables between jacket and gravity based foundations. This might be due to an unrepresentative sample size at the gravity based foundations. Alternatively, the effect of turbine presence and foundation type might manifest itself within close vicinity of the turbines (< 50 m) and as such remain unconcealed by the current sampling design. To tackle this, it is recommended to perform a targeted monitoring study to investigate potential changes in sedimentology and organic enrichment in the close vicinity (7-100 m) of the three turbine types present in the BPNS.

1. Introduction

At present, nine Belgian projects representing a total capacity of 2.2 GW were granted both a domain concession and an environmental permit to meet Belgium's 2020 targets for renewable energy: three projects are operational, one is under construction and at least five will be constructed in the near future in the Belgian part of the North Sea (BPNS) (Degraer *et al.* 2016). Introducing these artificial hard substrates in a soft sediment habitat (*i.e.*, reef effect) is believed to cause the largest impact on the marine environment and at different scale (Petersen & Malm, 2006) due to, for example, changes in hydrodynamics and presence of epifaunal coverage along the turbine. Additionally, fisheries exclusion in windmill parks may alter the marine environment at different scales (De Mesel *et al.* 2013; 2015; Reubens *et al.* 2013; 2014). Only when a monitoring program is conducted to assess the effects of the installation of artificial hard substrates on the marine environment, an environmental permit is received by the project developer (Brabant *et al.* 2013). In Belgium, this monitoring program is coordinated by the Operational Directorate Natural Environment (OD Nature) of the Royal Belgian Institute of Natural Sciences and targets physical, biological and socio-economical aspects of the marine environment (Degraer *et al.* 2016). In this report, we focus on the possible effects on the macrobenthic community in offshore windfarms (OWF). Many studies have already demonstrated reef effects on macrobenthos in the immediate vicinity of wind turbines (Barros *et al.* 2001; Coates 2013; 2014a; 2014b).

Sediment type and food supply are two of the main natural factors that structure macrobenthic communities, next to temperature and the influence of different water masses (Pearson & Rosenberg 1978; Wilhelmsson & Malm 2008; Kröncke 2011; Kröncke *et al.* 2011). Coates *et al.* (2013; 2014a) revealed changes in sedimentology up to a distance of 50 m from the turbines: grain size reduced significantly due to a decreased current flow in the wake of the turbines (15-50 m "behind" the turbines in comparison with larger distances of 100-200 m). In addition, organic matter content increased close to the turbines primarily as a result of the deposited faeces, pseudo-faeces and dead individuals of epifauna on the foundations (Barros *et al.*, 2001; Maar *et al.*, 2009; Kerckhof *et al.*, 2010, De Mesel *et al.*, 2013). These changes can trigger changes in macrobenthic community structure (Coates *et al.*, 2011, 2013; Ysebaert *et al.*, 2009). Coates *et al.* (2014a) revealed an increased macrobenthos density along with an enhanced diversity close to the windmill. At 1 and 7 m distance from the foundation, the dominance of two hard-substrate amphipods, *Monocorophium acherusicum* and *Jassa herdmani*, highlighted the direct effect of the presence of the wind turbine. At distances of 15-50 m, shifts in species dominance were detected, with an increased dominance of the amphipod *Urothoe brevicornis* and the tube building polychaetes *Lanice conchilega* and *Spiophanes bombyx* close to the foundation (Coates *et al.* 2013). As many macrobenthos species are an important food source for organisms higher in the food web (Vandendriessche *et al.* 2015), changes in macrobenthic communities have the potential to alter food web energy flows (Dannheim *et al.* 2014). Hence, effects of windmills can also be found higher up in the food web, resulting, for example, in the attraction of pouting *Trisopterus luscus* and Atlantic cod *Gadus morhua* inside the OWF (Vandendriessche & Reubens *et al.* 2013; Reubens *et al.* 2013).

Reubens *et al.* (2016) also revealed changes in macrobenthos community structure in the offshore windfarms. Differences were observed between samples close to (50 m) and further away from the turbine (350-500 m). However, the results of Reubens *et al.* (2016) were not consistent with those of Coates *et al.* (2014a), who found higher densities and species numbers in the far samples compared to the close samples. The latter were dominated by *Urothoe brevicornis* and *Gastrosaccus spinifer*, while *Bathyporeia elegans* and *Spiophanes bombyx* were more important in the far samples. As Reubens *et al.* (2016) did not observe differences in sedimentology between the close and far samples (in contrast with Coates *et al.* 2014a), it remains unclear which underlying ecological processes were responsible for the observed community changes. Reubens *et al.* (2016) suggested that this might be related to the turbine type used. Foundation types are mainly selected according to the environmental conditions (*e.g.*, water depth and sediment type) together with production and installation costs. With a water depth that ranges from 20-40 m at the BPNS, offshore windfarm (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 2014c). For a detailed description, see Coates (2014c) and Rumes *et al.* (2013).

The study of Reubens *et al.* (2016) was performed on a windmill farm dominated by jacket foundations, while the study of Coates *et al.* (2014a) focused on effects near a gravity based foundation. Jackets have an open structure, allowing the main current flow to

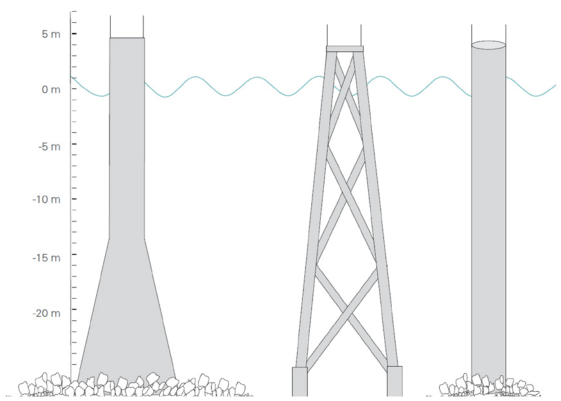

Figure 1. Three foundation types present in the Belgian part of the North Sea, from left to right: gravity based, jacket and monopile foundation (Rumes *et al.* 2013).

pass through. Gravity-based foundations, on the other hand, obstruct currents and areas with a lower current flow are generated in the wake of the turbine. These differences in flow velocity influence colonization potential of epifaunal species as well as sediment and TOM resuspension (Reubens *et al.* 2016).

In this report, we investigate whether there is an effect of turbine presence on macrobenthic community structure and if so, if this effect differs between different types of foundations.

2. Material and methods

2.1. Study area

Three projects are operational in the 238 km² area in the BPNS that was allocated to offshore renewable energy production (fig. 2). The current study was conducted in the concession area of two offshore wind farms: "C-Power", which is located on the Thornton bank (TB) sandbank, and Belwind, located at the Bligh Bank (BB). The C-Power wind farm consists of 54 turbines. The first six (constructed in 2008) were built on gravity-based foundations. The other 48 turbines have a jacket foundation and were constructed between 2011 and 2013 (Brabant *et al.* 2013). The 55 Belwind turbines are monopiles which were constructed in 2009-2010 and are operational since 2011.

2.2. Sample design, collection and treatment

A systematic stratified sampling design was adopted (fig. 3). Samples were collected in autumn 2016 at two distances, consistent with the sampling design of 2015 (Reubens *et al.* 2016), so a one-way spatial (close vs. far) comparison of samples can be conducted. Close samples were taken at approximately 50 m from the turbines on the South-West side. This is the smallest distance which is easily reached by a small vessel. If sampling in the South-West direction was not possible (to comply with a minimum distance of 50 m

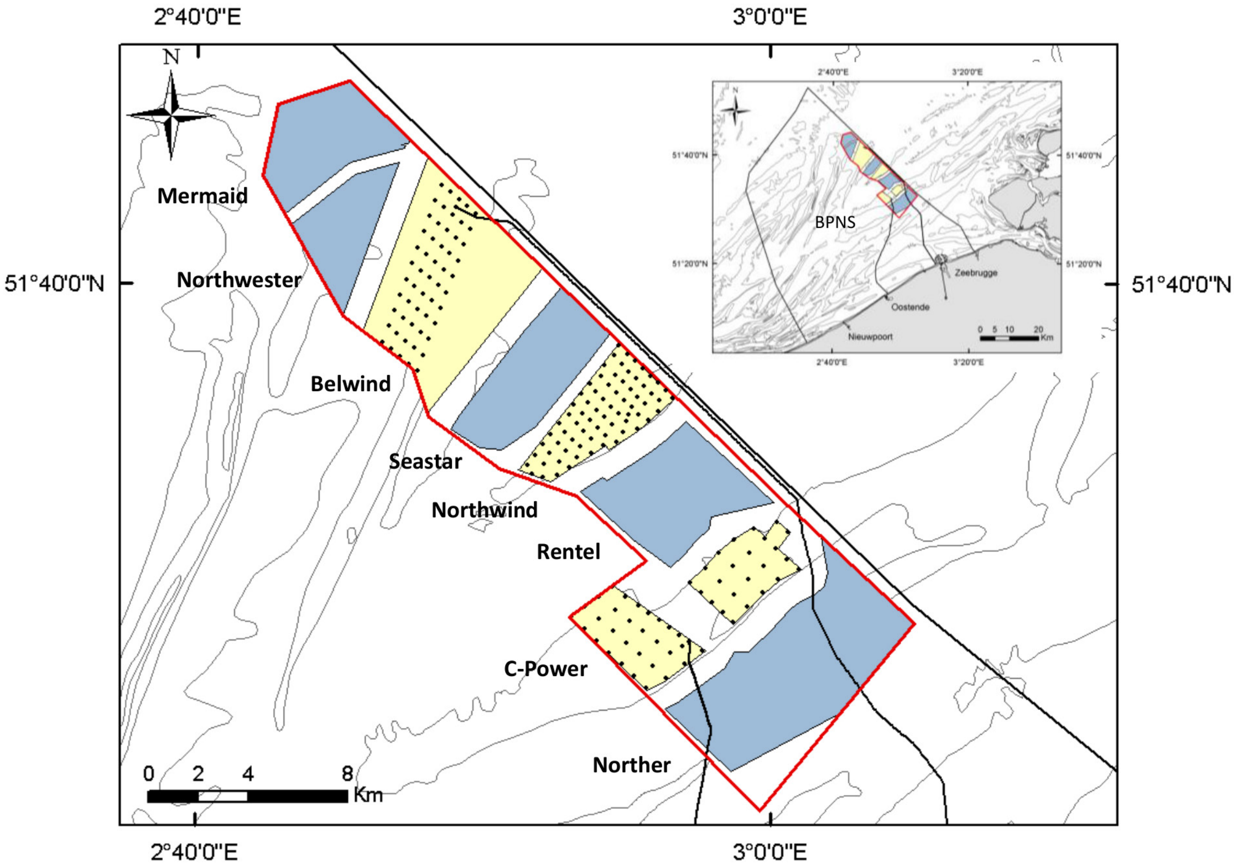

Figure 2. Wind farm concession area (red area) in the Belgian part of the North Sea. Three offshore wind farms have been constructed (yellow areas) on the Thorntonbank (C-Power), Bligh Bank (Belwind phase I) and Lodewijkbank (Northwind). Two power cables from C-Power and Belwind run to the port of Ostend and Zeebrugge, respectively (black lines). Five additional domain concessions have been granted to Norther, Rentel, Seastar, Northwester and Mermaid (blue areas). Wind turbines are marked as black dots (Coates 2014c).

from infield electricity cables), samples were taken at the North-East side of the turbine. The far samples were gathered in the middle between the four surrounding wind turbines (*i.e.*, the farthest possible distance). These distances ranged between 350 and 500 m from the turbines (fig. 3). Samples were collected on board the *RV* Simon Stevin and Aquatrot on 24, 25 and 29 October 2016. Table 1 shows when the different stations were sampled with which vessel and the number of samples.

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

Date	Vessel	Station	# Samples
24/10/2016	Simon Stevin	TB_far	32
25/10/2016	Simon Stevin	BB_far	24
25/10/2016	Aquatrot	BB_close	15
25 and 29/10/2016	Aquatrot	TB_close	16
29/10/2016	Aquatrot	GB	2
25/10/2016	Simon Stevin	GB	14

Samples were obtained by means of a 0.1 m² Van Veen grab, sieved alive onboard over a 1 mm mesh-sized sieve and preserved in a 4% formaldehyde-seawater solution. In the laboratory, samples were stained with rose Bengal. After rinsing over a 1 mm sieve and sorting, organisms were identified to species level whenever possible. Some organisms were identified at a higher taxa level because of the difficulty of identification or small size. Individuals were counted and biomass (blotted wet weight, mg) was determined for every species per sample.

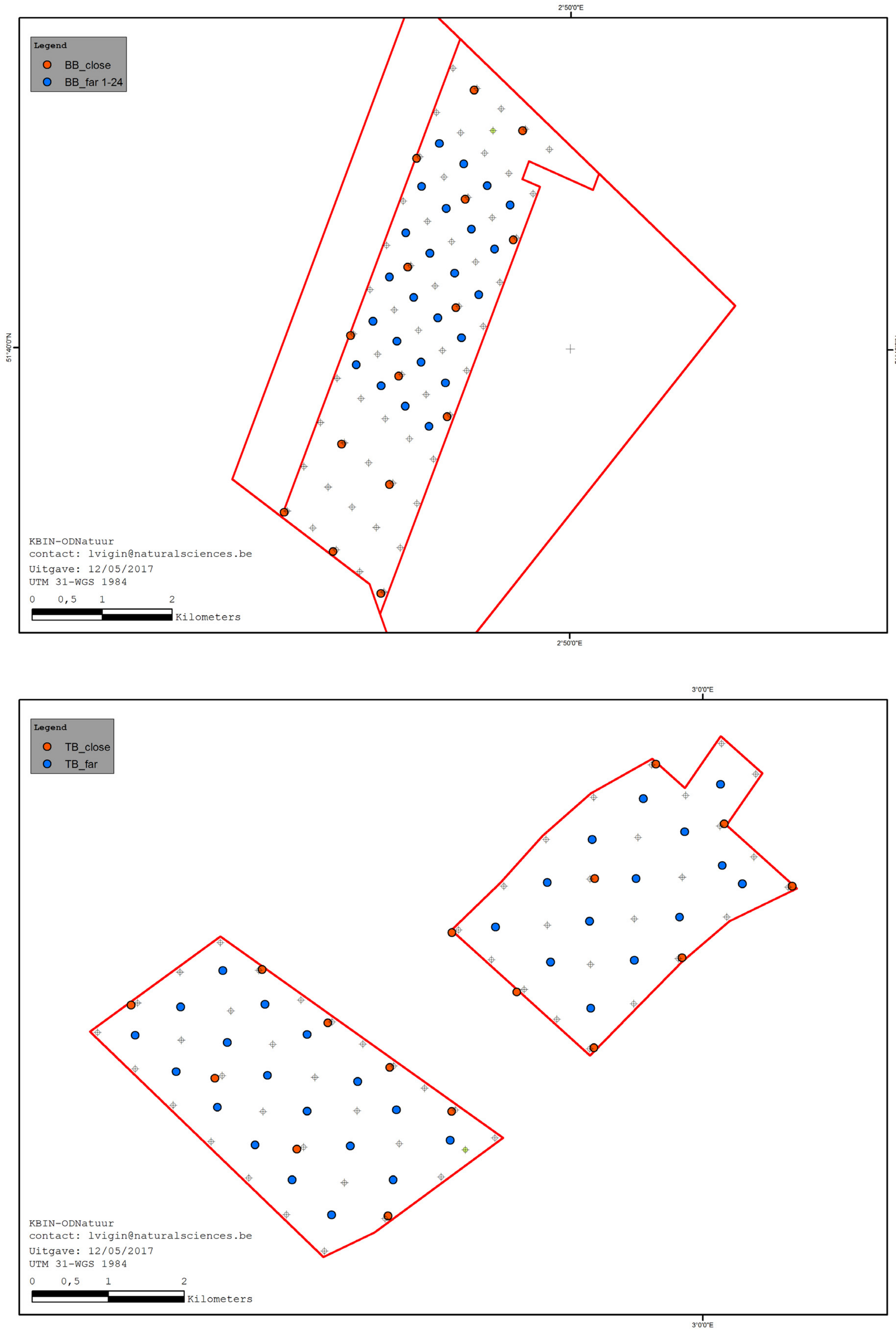

Figure 3. Overview of close and far samples at the Bligh Bank (up) and Thornton Bank (low). Black dots represent foundations, red and blue dots are sampling positions.

Environmental data such as grain size distribution (GS) and total organic matter content (TOM) were sampled parallel with the macrobenthos samples by means of a core (Ø 3.6 cm) taken from the Van Veen grab samples. After drying at 60 °C the grain size distribution was measured using laser diffraction on a Malvern Mastersizer 2000G, hydro version 5.40. Grain size fractions are given as volume percentages w ith a range from fine clay (max. 4 µm) to coarse gravel/shell material (max. 2 mm). 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 the dry weight (48 h at 60 °C) and the ash-free dry weight (2 h at 500 °C).

2.3. Data analysis

The three close samples at the Thornton Bank that were taken at gravity based foundations were removed from the analyses to test the effect of distance from the turbine, so that only samples at jacket foundations were included for the Thornton Bank. Also, two samples at the Thornton Bank were removed as they proved to be outliers: TB6_far with a much higher species number (36) and abundance (5070 ind. m^{-2}), and TB6_close with a very low species number (3) and abundance (30 ind. m^{-2}). Rare species were not removed from the dataset, as the presence of these species might be a first indication of changes in the macrobenthic community (not evaluated in this report). 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. One-way Anova (1 factor: position; two levels: close vs far) was performed to statistically investigate differences between the distances. Levene's test was used to verify homogeneity of variances, while the Shapiro-Wilk test was used to check for normality. In case assumptions were not met, data were (double) logarithmic transformed. If after transformation the assumptions were still not fulfilled, an assumption-free PERMANOVA (Permutational Analysis of Variance [Anderson *et al.* 2008] with the same design [1 factor: "position"]) was used, based on a Euclidean distance matrix.

Permutational Anova (PERMANOVA) with a fixed one-factor design (position) was also used to investigate the effect of distance on the macrobenthic community composition. PERMANOVA makes no explicit assumptions regarding the distribution of original variables (Anderson *et al.* 2008). As the design was unbalanced, it was decided to use Type III sums of squares. The number of permutations was set to 9999 and unrestricted permutation of raw data was performed as there was only one factor in the design. The multivariate analysis was based on a Bray-Curtis resemblance matrix and performed on fourth-root transformed abundance data. Homogeneity of multivariate dispersions was tested using the PERMDISP routine, using distances among centroids. Principal Coordinates Analysis (PCO) was run to visualize the data. Vector overlay was based on multiple correlations and only species with Spearman correlation $R > 0.6$ are shown. In addition, a 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).

Furthermore, a distance-based linear model (DistLM) based on Adjusted R^2 and stepwise criterion was carried out to investigate the relationship between the macrobenthic community and the environmental variables. Variables were tested for multi-collinearity (Anderson *et al.* 2008).

All analyses were performed in the Plymouth Routines in Multivariate Ecological Research (PRIMER) programme (version 6.1.11) with the PERMANOVA add-on software (Clarke & Gorley 2006; Anderson *et al.* 2008) and in R (version 3.2.2) (Team 2015). A type I error significance level of $p \leq 0.05$ was used in all tests. Results are expressed as means ± 1 standard error.

3. Results

The Thornton Bank (TB) and Bligh Bank (BB) contained a similar amount of TOM and had a comparable > 2 mm sediment fraction (1-way ANOVA, $p > 0.05$), but median grain size was significantly larger at the BB (1-way ANOVA, $p = 0.001$). Macrobenthic communities of both sandbanks differed strongly (1-way PERMANOVA $p = 0.0001$) (fig. 4), mainly due to higher macrobenthic densities at the TB than at the BB (1-way ANOVA, $p = 0.007$). For this reason, and to facilitate comparison with the results of Reubens *et al.* (2016), macrobenthic communities and the environment of both sandbanks were analyzed separately.

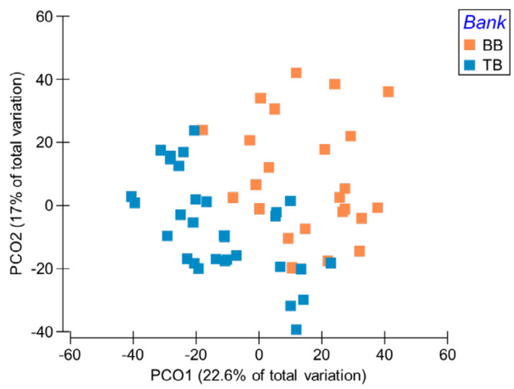

Figure 4. PCO (Principal Coordinates analysis) plot based on Bray-Curtis resemblance matrix of the fourth root transformed macrobenthic densities at the far sites from the two sandbanks (TB = Thornton Bank, BB = Bligh Bank).

3.1. Effect of distance from turbines

Almost all sediments consisted of coarse sands (median grain size between 300 and 500 µm) for both sandbanks (with the exception of 1 sample at TB_far [298 µm] and one at TB_close [649 µm]). TOM content remained low in all samples, around 0.5%, with slightly lower values at BB_close (0.37 ± 0.03%). The sediment fraction > 2 mm at the Thornton Bank ranged from 0.12 to 10.54% and at the Bligh Bank from 0.12 to 18.31% for the far samples (fig. 5 and table 2). A univariate analysis on the abiotic data revealed that there were no significant differences in grain size and in the 2-mm fraction between the samples close to and far from the turbines at both sandbanks. Only the far samples at the Bligh Bank had a higher organic matter content than the close samples (1-way ANOVA, $p = 0.020$). This pattern was not observed at the Thornton Bank (table 3).

At the Thornton Bank, far samples displayed higher macrobenthos biomass, species richness, Shannon-Wiener diversity and evenness but somewhat lower densities than the close samples (fig. 6 and table 2). Except for Shannon-Wiener diversity and evenness, these differences were not significant (table 3). At the Bligh Bank, results were less consistent. At the far samples, there was a tendency for a higher biomass and evenness and a lower number of species, abundance and Shannon-Wiener diversity (fig. 6 and table 2). None of these differences were, however, significant (table 3). As *E. cordatum* influenced biomass substantially, this species was removed from the analysis, but even then no significant differences in biomass were observed.

The multivariate analysis on the macrobenthic community structure at both sandbanks showed significant differences between the far and close samples at the Thornton bank (PERMANOVA, $p = 0.011$) but not at the Bligh Bank (PERMANOVA, $p = 0.167$) (fig. 7). Permdisps were not significant (TB: $p = 0.114$ – BB: $p = 0.349$), hence the significant differences between the two distances were not the result of a dispersion effect.

For the Thornton Bank, the dissimilarity between close and far sites was 54.41%. *Urothoe brevicornis* (13.91%), *Spiophanes bombyx* (7.35%) and *Bathyporeia elegans* (5.71%) together

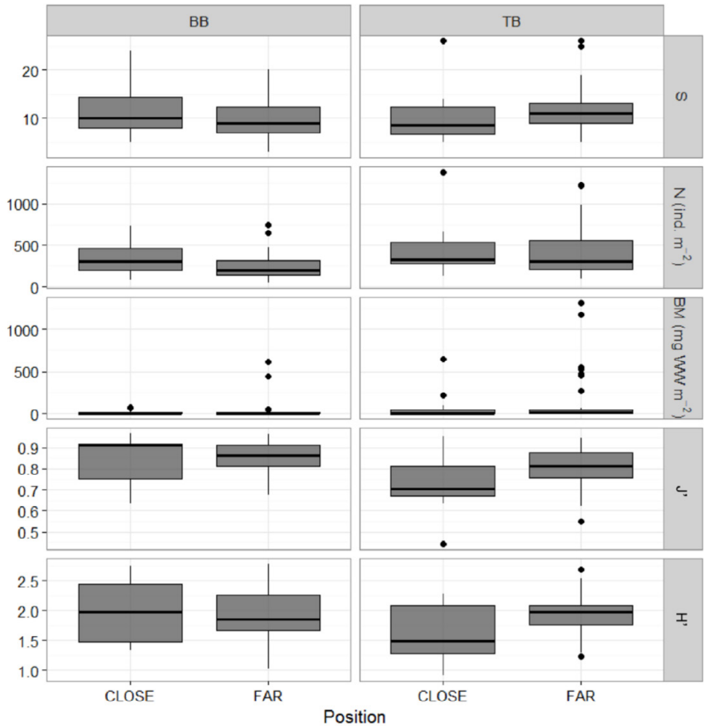

Figure 5. Box plots of the median grain size (GS [µm]), total organic matter (TOM [%]) and sediment fraction above 2 mm (> 2 mm %) per sampling site for the close and far samples (right: Thornton Bank, left: Bligh Bank). Black dots represent outliers.

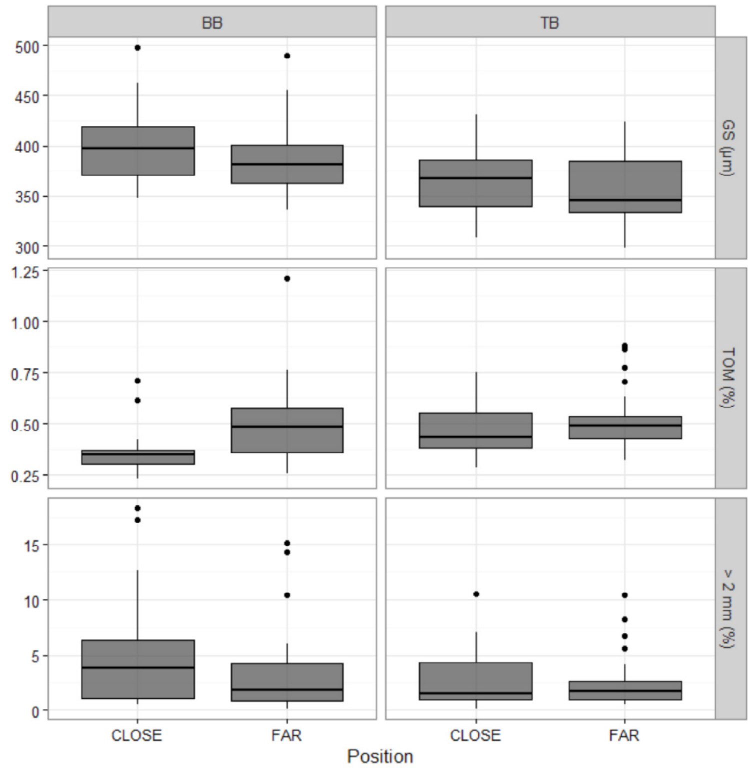

Figure 6. Box plots of the number of species (S), abundance (N), biomass (BM), evenness (J') and Shannon-Wiener diversity (H') per sampling site (right: Thornton Bank, left: Bligh Bank). Black dots represent outliers.

Table 2. Overview of number of stations and calculated community descriptors (mean ± SE) for the two distances (close-far) sampled at the Thornton Bank (TB – C-Power) and Bligh Bank (BB – Belwind) in 2016

	TB close	TB far	BB close	BB far
# Samples	12	31	15	24
Number of Species - S	10.25 ± 1.66	11.74 ± 0.91	11.60 ± 1.41	10.17 ± 0.94
Species abundance (ind. m^{-2}) - N	447.50 ± 96.05	440.65 ± 59.43	338.67 ± 50.09	260.42 ± 36.29
Biomass (mg WW m^{-2}) - BM	83.42 ± 53.80	162.88 ± 63.20	14.67 ± 5.95	53.18 ± 30.42
Evenness - J'	0.72 ± 0.04	0.81 ± 0.02	0.84 ± 0.03	0.86 ± 0.02
Shannon-Wiener - H'	1.62 ± 0.14	1.93 ± 0.06	1.98 ± 0.13	1.90 ± 0.09
Median grain size (µm) - GS	366.73 ± 11.39	355.48 ± 6.46	400.76 ± 10.66	387.96 ± 7.62
Total organic matter (%) - TOM	0.48 ± 0.04	0.51 ± 0.03	0.37 ± 0.03	0.50 ± 0.04
Sediment fraction > 2 mm (%) - > 2 mm	2.89 ± 0.94	2.48 ± 0.44	5.4 ± 1.54	3.41 ± 0.86

Table 3. Level of significance for all tests on the biotic and abiotic variables of the far versus the close samples at the two sandbanks (TB = Thornton Bank, BB = Bligh Bank)

BANK	GS	TOM	> 2 mm	S	N	BM	H'	J'
TB	0.359*	0.446*	0.662	0.200*	0.812*	0.486	0.020*	0.028*
BB	0.324*	0.020*	0.26	0.385*	0.186*	0.647*	0.603*	0.886*

* indicates that the analysis was performed with a one-way ANOVA, else PERMANOVA was used. Significant p-values are highlighted in red. GS = grain size, TOM = total organic matter content, > 2 mm is the sediment fraction larger than 2 mm, S = species richness, N = abundance, BM = biomass, H' = Shannon-Wiener diversity, J' = Pielou's evenness.

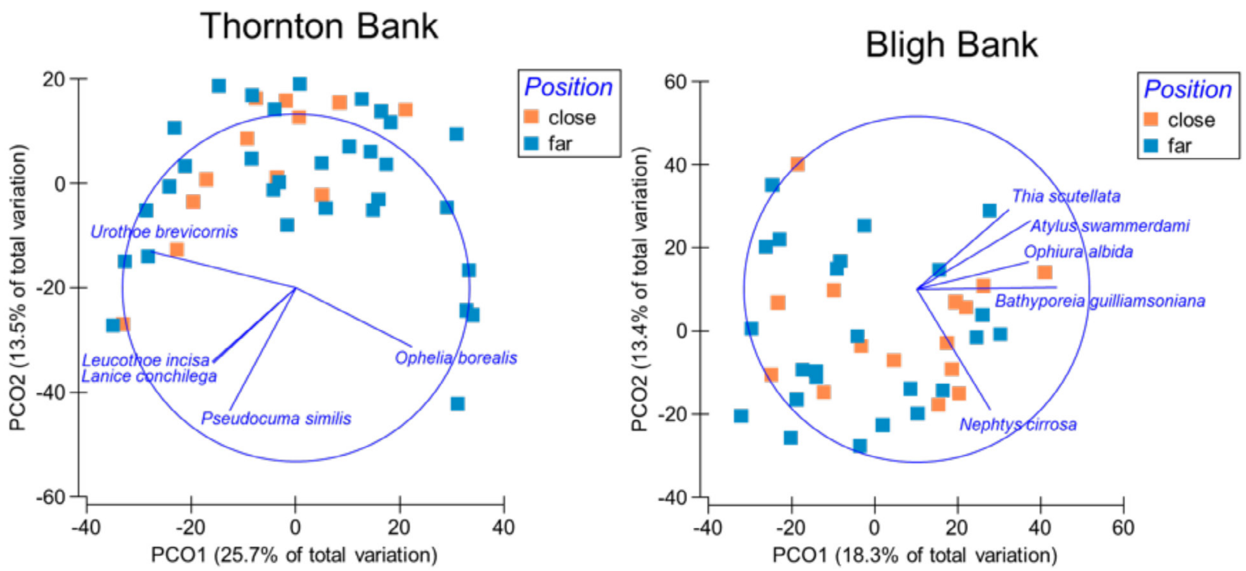

Figure 7. PCO (Principal Coordinates analysis) plots based on Bray-Curtis resemblance matrix of the fourth root transformed macrobenthic densities at the two sandbanks and at two distances from the wind turbines. Vector overlay is based on multiple correlations and only species with correlation > 0.6 are shown.

Table 4. Species that contributed to the difference in community composition between the close and far samples up to a cumulative value of ≥ 50%

	Group close	Group far		
Species	**Average abundance**	**Average abundance**	**Contribution %**	**Cumulative contribution %**
Urothoe brevicornis	13.15	8.73	13.91	13.91
Spiophanes bombyx	4.04	4.99	7.35	21.26
Bathyporeia elegans	2.54	3.95	5.71	26.97
Nemertea sp.	1.94	2.26	4.36	31.33
Nephtys juv.	3.59	5.02	4.32	35.65
Gastrosaccus spinifer	2.89	3.3	4.02	39.68
Nephtys cirrosa	7.29	8.23	3.96	43.64
Glycera sp.	0.79	1.70	3.59	47.23
Spio sp.	1.32	2.04	3.21	50.44

contributed more than 25% of this dissimilarity. *Urothoe brevicornis* was more abundant in the close samples, while *S. bombyx* and *B. elegans* were more abundant in the far samples. Many other species contributed to a lesser extent (table 4).

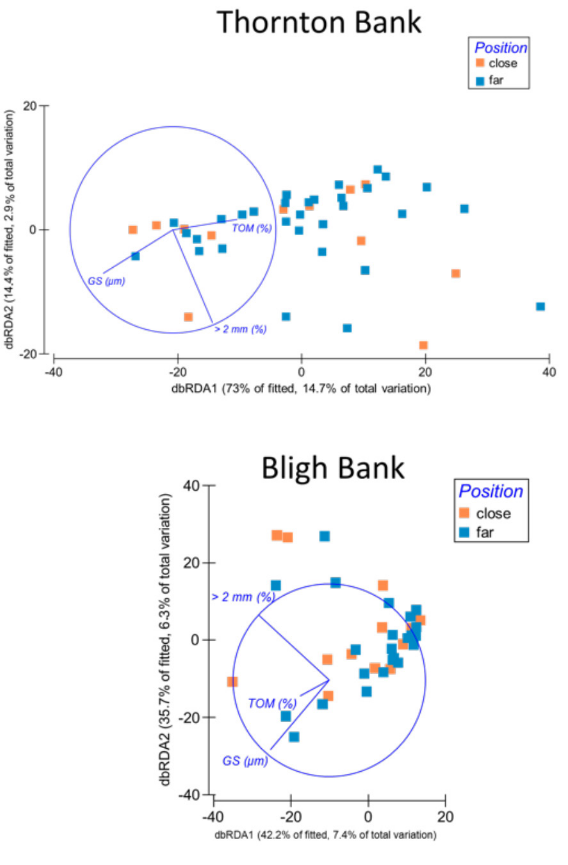

Figure 8. dbRDA plots based on Bray-Curtis resemblance matrix of the fourth root transformed macrobenthic densities at the two sandbanks and at two distances from the wind turbines.

A DistLM was carried out to investigate the relationship between the macrobenthic community and the environmental variables (fig. 8). The DistLM revealed that at the TB all three abiotic variables (grain size, total organic matter content and sediment fraction > 2 mm) have a significant relationship with the multivariate data, but together explained only 14.00% of the variation. At the BB, we also see a significant contribution of these three variables, but only 10.48% of the variation was explained.

3.2. Effect of foundation type

To reveal a possible foundation effect we studied the close samples of the Thornton Bank only, to exclude the "Bank" effect (the fact that the communities on both sandbanks are different). Within the Thornton Bank only three samples were taken at a gravity-based foundation and 13 at a jacket foundation. The PCO plot showed a large variation between the samples at the jacket foundations, which made it impossible to randomly select three samples for a balanced comparison (fig. 11). No significant differences were found between the two types, both for the abiotic and biotic variables (table 6). Additionally, no significant differences between the communities at jacket foundations and gravity-based foundations were observed (PERMANOVA, p = 0.810). These results suggest no foundation effect (gravity

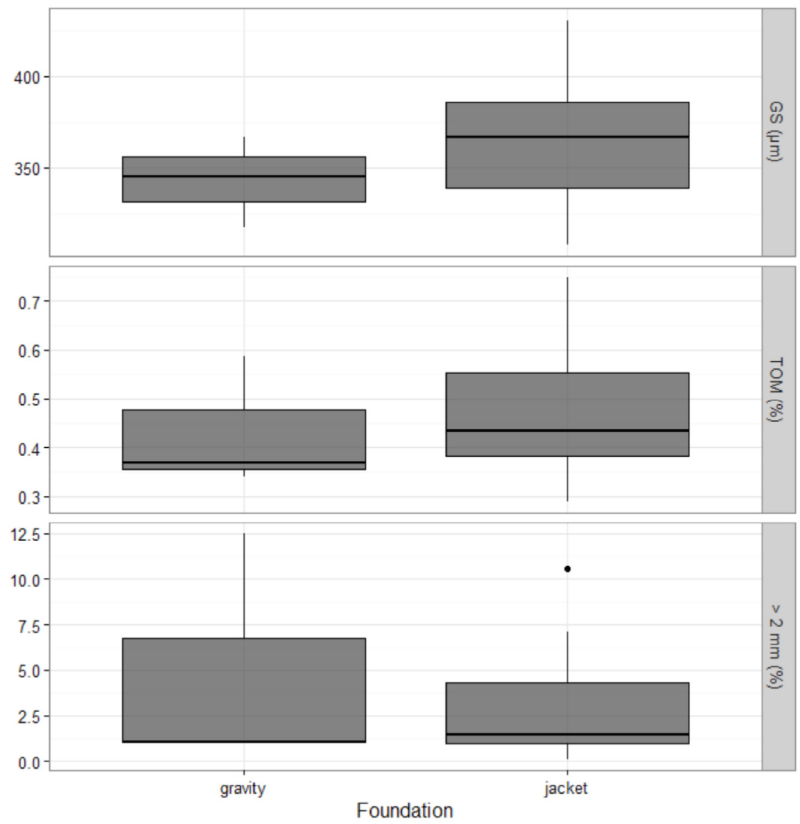

Figure 9. Box plots of the median grain size (GS [µm]), total organic matter (TOM [%]) and sediment fraction larger than 2 mm (> 2 mm %) at two types of foundation at the Thornton Bank. Black dots represent outliers.

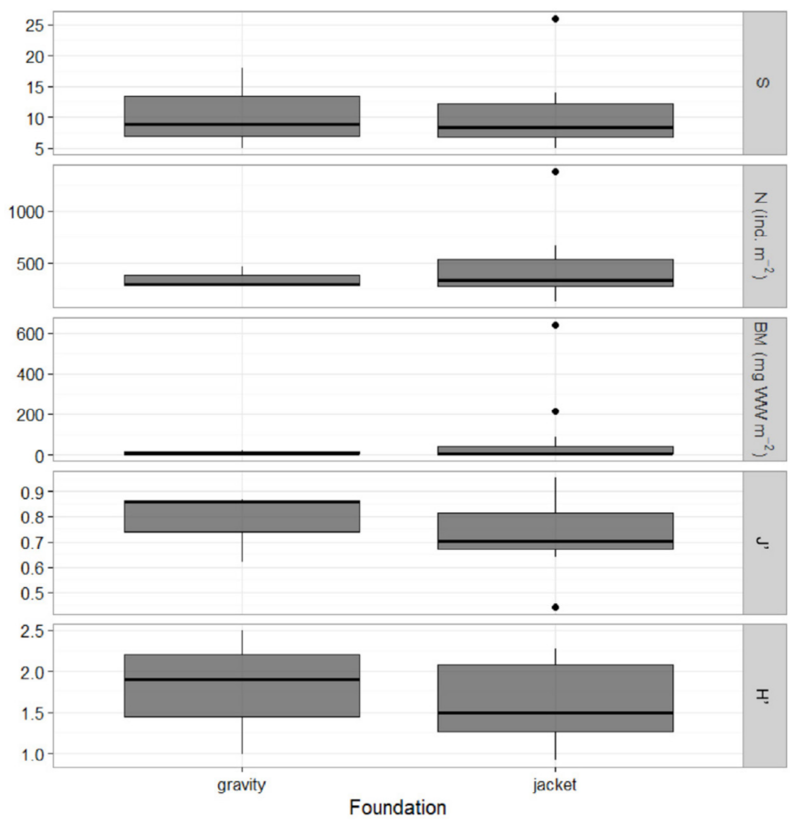

Figure 10. Box plots the number of species (S), abundance (N), biomass (BM), evenness (J’) and Shannon-Wiener diversity (H’) at two types of foundation at the Thornton Bank. Black dots represent the outliers.

Table 5. Overview of number of stations and calculated community descriptors (mean ± SE) at two types of foundation (gravity based and jacket) sampled at the Thornton Bank (TB - C-Power) in 2016

	TB gravity based	TB jacket
# Samples	3	12
Number of Species - S	10.67 ± 3.84	10.25 ± 1.66
Species abundance (ind. m^{-2}) - N	343.33 ± 63.60	447.50 ± 96.05
Biomass (mg WW m^{-2}) - BM	9.84 ± 5.72	83.42 ± 53.80
Evenness - J'	0.78 ± 0.08	0.72 ± 0.04
Shannon-Wiener - H'	1.80 ± 0.43	1.62 ± 0.14
Median grain size (µm) - GS	343.15 ± 14.18	366.73 ± 11.39
Total organic matter (%) - TOM	0.43 ± 0.08	0.48 ± 0.04
Sediment fraction > 2 mm (%) - > 2 mm	4.84 ± 3.81	2.89 ± 0.94

Table 6. Level of significance for all tests on the biotic and abiotic variables at the Thornton Bank, comparing the two types of foundation

	GS	TOM	> 2 mm	S	N	BM	H'	J'
TB gravityjacket	0.348	0.604*	0.492	0.964*	0.771*	0.543	0.600*	0.509*

* indicates that the analysis was performed with a one-way ANOVA, else PERMANOVA was used.

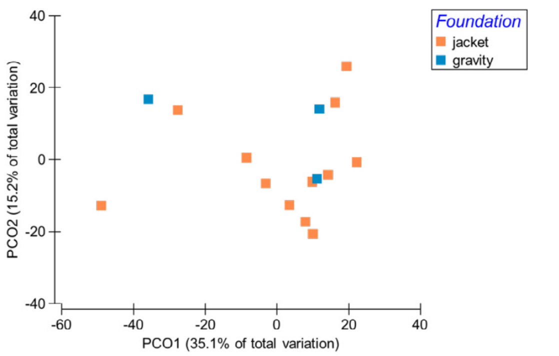

Figure 11. PCO (Principal Coordinates analysis) plots based on Bray-Curtis resemblance matrix of the fourth root transformed macrobenthic densities at the Thornton Bank for two foundation types.

vs. jacket) on the macrobenthic community on the Thornton Bank.

4. Discussion

In the BPNS, four subtidal macrobenthic communities have been distinguished, connected by transitional species assemblages (Degraer *et al.* 2003; 2008; Van Hoey *et al.* 2004). Situated in the eastern, offshore part of the BPNS, the macrofaunal communities in the OWF concession area are highly heterogeneous but primarily characterized by the *Nephtys cirrosa* and *Ophelia borealis-Glycera lapidum* communities (De Maersschalck *et al.* 2006). These communities are generally characterized by a low average species richness (5-7 species) and abundance (190-402 ind. m^{-2}), inhabiting medium sands with low organic matter content. The Thornton Bank was originally inhabited by these communities, but after windmill construction, a higher average species richness (10-30 species) and abundance (1390-18583 ind./m²) was observed, coinciding with a shift in dominant species (Coates *et al.* 2014a). As such, the community has evolved away from the *N. cirrosa* and *O. limacina-G. lapidum* communities. With an increased macrofauna abundance and a decreasing sediment grain size, it was suggested that the macrobenthic community is shifting towards a variation of the species-rich *Abra alba-Kurtiella bidentata* community (30 species and 6432 ind. m^{-2}), which is usually found in shallow and muddy sands (Van Hoey *et al.* 2004). It should be noted that these changes were mainly observed in close vicinity of the windmills (< 50 m). Van Veen grab sampling is currently the best available method to sample/characterize macrobenthic communities. However, the sampling efficiency in communities poor in abundance and richness is rather low. This low sampling efficiency should be taken into consideration when interpreting the results. Our results also show a significantly lower median grain size at the Thornton Bank (298-423 µm) than at the Bligh Bank (336-490 µm) and a significantly higher macrofauna abundance (TB: 100 to 1220 ind. m^{-2}; BB: 50 to 750 ind. m^{-2}). The maximum abundance at the TB is lower in comparison with Coates *et al.* (2014a) due to the fact that these high values were reached at 25 m and 15 m from the turbine, while in this study only samples at 50 m were taken, missing out this increase. Although the characteristics of the observed community at the Thornton Bank are not within the range of the characteristics of the *Abra alba-Kurtiella bidentata* community, we do see a significantly different community than at the Bligh Bank (fig. 4). For this reason, and for easier comparison with the results of Reubens *et al.* (2016), both sandbanks were analysed separately.

4.1. Effect of distance from turbines

The effect of distance from the turbine foundation was not unambiguous for both sandbanks.

The measured environmental conditions (GS, > 2 mm fraction and TOM content) on the Thornton Bank were similar close to (*i.e.*, ca 50 m) and far from (*i.e.*, 350-500 m) the turbines. Despite the similarity in habitat type, the communities close to the turbines differed significantly from those further away from the turbines. These differences were observed in community structure, with a higher evenness and Shannon-Wiener diversity far from the turbines. More specifically, the communities in the close samples were characterized by higher abundance of *Urothoe brevicornis*, whereas *Spiophanes bombyx* and *Bathyporeia elegans* were more dominant in the samples far from the turbines. To a certain extent, these results corroborate the study of Reubens *et al.* (2016), who also found differences in communities between areas near and far from the turbines. However, these differences were mainly present in species abundances and species richness, rather than in evenness and Shannon-Wiener diversity. On the other hand, the typifying species for the sampling sites close to and far from the turbines remained the same.

At the Bligh Bank, more TOM accumulated further away from the turbines than close to the turbines, but since this difference in TOM concentration was not observed in 2015 (Coomans 2017), this might also represent a temporary variation. Despite the potential difference in resource availability linked to different TOM concentrations, no significant differences were observed between the macrobenthic communities from the two distances. This agrees with the results of another study focusing on a wind farm with monopiles in Denmark, where no differences were found in benthic communities between sites at different distances (Leonhard & Pedersen 2005).

Sediment type and food supply are two of the main natural factors that structure macrobenthic communities. Grain size distribution can change in the immediate vicinity of an offshore wind turbine, inducing an important impact on the associated soft-sediment macrofauna, up to 50 m distance from the turbines (Leonhard & Pedersen 2005; Coates *et al.* 2014a). A significant refinement of the grain size close to (15-50 m) a gravity based turbine on the Thornton Bank (Coates *et al.* 2014a) and a tendency to finer sand close to monopiles in a Danish OWF (5-25 m) (Leonhard & Pedersen 2005) have been observed. In line with the study of Reubens *et al.* (2016), we did not observe such a refinement close to (50 m) the turbines. This suggests that such refinement effects remain highly local in the immediate proximity of turbines, and do not extend beyond a maximum of a few tens of meters, 50 m being the limit of detection for changes in sediment granulometry.

It is generally accepted that the hard-substrate epifauna growing on foundations contribute to the organic matter input on the seabed by sedimentation of faeces and detritus (Barros *et al.* 2001; Maar *et al.* 2009; Kerckhof *et al.* 2010, De Mesel *et al.* 2013). Therefore, total organic matter content can be higher close to the turbines (Coates *et al.* 2014a). However, the sediment TOM content in this study was similar in samples close to and far from turbines on the TB and even lower in the samples closer to the turbines on the BB. Epifaunal communities appear to differ in composition between the monopiles of the BB and the gravity and jacket based foundations of the TB (De Mesel *et al.* 2013; pers. comm. Jan Reubens). For example, a 1-m mussel zone (*Mytilus edulis*) has developed on the concrete gravity based foundations of the TB, while this zone is only 0.5 m on the steel surface of the monopiles of the BB (De Mesel *et al.* 2013), and the jacket foundations of the TB are fully covered with mussels (Krone *et al.* 2013; pers. comm. Jan Reubens). In addition, the epifouling communities on the turbines may be in a different phase of succession as the monopiles from the BB are operational since 2011 and the jackets of the TB since 2013 (Degraer *et al.* 2016). A stable epifaunal community is generally reached after 5-6 years (or longer in case of storms and hard winters) (Leonhard & Pedersen 2005). Consequently, the macrobenthic communities thriving at the base of the foundations might also receive different quality and quantities of organic matter. Nevertheless, no increase in quantity of organic matter was observed in this study at the Thornton Bank, nor in Reubens *et al.* (2016), whereas the higher organic matter content far from the Bligh Bank turbines in this study did not result in altered macrobenthic communities.

Although sediment characteristics are known to be an important factor structuring the macrobenthic community (Kröncke 2011; Kröncke *et al.* 2011), in this study, only a low proportion of the variation observed in the macrobenthic community structure was explained by the environmental variables (grain size, total organic matter and sediment fraction above 2 mm), and this for both sandbanks (TB: 14% and BB: 10%). This suggests that some other (abiotic and/or biotic) variables, which are key to explaining community differences, are missing in the current monitoring, of which a low sampling efficiency with Van Veen grab is one factor.

Other such factors potentially affecting macrobenthic communities are temperature and the influence of different water masses (Pearson & Rosenberg 1978; Wilhelmsson & Malm 2008; Kröncke 2011; Kröncke *et al.* 2011), as well as anthropogenic stressors such as fishing, dredging and eutrophication (Kröncke *et al.* 2011). The effect of temperature can be ruled out, since water masses at the BPNS are well mixed (MUMM 1996) and the studied areas experience similar water temperatures and eutrophication influence. Also, the effect of fisheries and dredging are trivial, since these activities are not permitted in the OWF. The studied banks are, however, influenced by different water masses: the Thornton Bank is situated on the edge between the clear water of the English Channel and the more turbid coastal water (Lacroix *et al.* 2004). The Bligh Bank, situated 40 km offshore, is influenced exclusively by English Channel water masses, which is reflected in a difference in organic matter content of the overlying waters. However, study of the water column was not included in this study. Therefore, we can only relate the observed differences in effects of distance to the turbine to natural spatial variability (Ysebaert & Herman 2003) or to the effect of foundation type.

The natural spatial variability in macrobenthic communities on the Thornton Bank and the Bligh Bank did not allow us to specifically test for the effect of foundation type across both sandbanks (jacket vs. monopile foundations), but the difference in effect of foundation presence on the sediment characteristics and on macrobenthic communities (BB: higher TOM levels far from foundation, but no community differences; TB: no TOM differences but different communities at the two distances) hints that there might be an effect of foundation type.

4.2. Effect of foundation type

Both the current study and the one of Reubens *et al.* (2016) contradict the observations of finer sediment and concomitantly of different communities closer to the turbines in Coates *et al.* (2014). The underlying reason is primarily the difference in scale (distance to the turbine: < 50 m in Coates *et al.* 2014 vs. < 250 m in this study and Reubens *et al.* 2016). However, another reason to consider might be the difference in turbine foundation type. We therefore investigated the sediment characteristics and macrobenthic community structure around two types of foundations at the Thornton Bank: gravity based and jacket foundation. We specifically focused on the Thornton Bank, to exclude the bank (location) effect (the fact that the original communities from the TB and BB are different). Twelve samples were taken at jacket foundations and only three samples at a gravity based turbine. The new sampling design (since 2015) was focused on a stratified random sampling in order to take samples close and far from the turbines, without taking into account the different turbine types, so only three of the six gravity based foundations were sampled. Because of this, no hard conclusions can be made, but our results do give an indication of the effect of foundation type. Gravity based foundations are concrete cylindrical/conical structures. They are support structures held in place by their own gravity (www.C-Power.be). The large concrete base profoundly affects local current flow (Leonhard & Pedersen 2005). Decreased current flow in the wake of the turbine prevents the resuspension of finer sands and enriched TOM close to the turbines (Reubens *et al.* 2016). On the other hand, jacket foundations are steel structures with four legs connected to each other with braces (www.C-Power.be). They are open structures allowing the main current flow to pass through the construction (Lancelot *et al.* 1987).

At locations with reduced currents (such as in the wake of gravity based turbines), the organic material can accumulate (Reubens *et al.* 2016). This is not seen in our results as the TOM values at the gravity based turbines (0.43%) were no different from those at the jacket foundations (0.48%). Clear results may not be apparent due to the fact that only three samples were taken at gravity based foundations; still, also at the monopiles of the Bligh Bank (which are similar to the gravity based foundation), the TOM values were even lower (0.37%) than at the jacket foundations of the TB.

However, we did not observe differences in sediment characteristics, nor in macrobenthic communities between gravity based and jacket foundations. Again, if any, the effect of turbine foundation type on benthic communities may be manifested in the immediate vicinity (< 50 m) of the turbine. This is confirmed by Coates *et al.* (2014a) where an increase in total abundance, species richness and biomass was observed in samples at 50 m and even more so, closer to a gravity based turbine (on the South West side). As such, the data from the samples taken at 50 m do not provide any conclusive result.

5. Conclusion and recommendations

It can be concluded that the installation of offshore wind turbines can induce changes in the macrobenthos. This is mainly seen at the Thornton Bank, where communities of the far sites differed significantly from the close sites, with a higher diversity at the far sites. These community changes occurred independently from the measured environmental variables (GS, TOM and 2 mm fraction), which remained unchanged with respect to turbine presence. However, on the Bligh Bank, a higher organic matter content was found further from the turbines, but this did not result in differences between the communities of the two distances to the turbine. No differences were observed for both the abiotic and the biotic variables between jacket and gravity based foundations. This may be due to a small sample size at the gravity based foundations. Alternatively, the effect of turbine presence and foundation type might manifest itself only within close vicinity of the turbines (< 50 m) and as such remain unconcealed by the current sampling design.

To enable long term studies, it is recommended to continue monitoring macrobenthic communities and their environment following the current sampling design (but with a higher number of samples at the gravity based foundations [6]). In addition, it would be highly interesting to perform a targeted monitoring study to investigate potential changes in sedimentology and organic enrichment in the close vicinity (7-100 m) of the three turbine types present in the BPNS, as different physical and biotic interactions can occur depending on turbine type, and since discrepancies between our results and those of other studies (Leonhard & Pedersen 2005; Coates *et al.* 2014) may well relate to differences in proximity of sample collection to turbines.

References

Anderson, M.J., Gorley, R.N. & Clarke, K.R. 2008. *PERMANOVA+ for PRIMER: Guide to software and statistical methods*. Plymouth: Primer-e, 214 p.

Barros, F., Underwood, A.J. & Lindegarth, M. 2001. The influence of rocky reefs on structure of benthic macrofauna in nearby soft-sediments. *Estuarine, Coastal and Shelf Science* 52 (2): 191-199.

Brabant, R., Degraer, S. & Rumes, B. 2013. Monitoring offshore wind farms in the Belgian part of the North Sea: Setting the scene. In S. Degraer, R. Brabant & B. Rumes (eds), *Offshore wind farms in the Belgian part of the North Sea. Learning from the past to optimize future monitoring programmes*. Royal Belgian Institute of Natural Sciences: Operational Directorate Natural Environment, Marine Ecology and Management Section: 15-23.

Clarke, K.R. & Gorley, R.N. 2006. PRIMER v6: user manual/tutorial PRIMER-E. Plymouth: Plymouth Marine Laboratory, 190 p.

Coates, D., Vanaverbeke, J., Rabaut, M. & Vincx, M. 2011. Soft-sediment macrobenthos around offshore wind turbines in the Belgian part of the North Sea reveals a clear shift in species composition. In S. Degraer, R. Brabant & B. Rumes (eds), *Offshore wind farms in the Belgian part of the North Sea: Selected findings from the baseline and the targeted monitoring*. Royal Belgian Institute of Natural Sciences: Management Unit of the North Sea Mathematical Models. Marine Ecosystem Management Unit, 157 p.

Coates, D., Deschutter, Y. Vincx, M. & Vanaverbeke, J. 2013. Macrobenthic enrichment around a gravity based foundation. In S. Degraer *et al.* (eds), *Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Learning from the past to optimise future monitoring programmes*, pp. 141-151.

Coates, D.A., Deschutter, Y., Vincx, M. & Vanaverbeke, J. 2014a. Enrichment and shifts in macrobenthic assemblages in an offshore wind farm area in the Belgian part of the North Sea. *Marine Environmental Research* 95: 1-12.

Coates, D.A., Van Hoey, G., Colson, L., Vincx, M. & Vanaverbeke, J. 2014b. Rapid microbenthic recovery after dredging activities in an offshore wind farm in the Belgian part of the North Sea. *Hydrobiologia* 756: 3-18.

Coates, D. 2014c. *The effects of offshore wind farms on macrobenthic communities in the North Sea*. Ghent: Ghent University, 182 p.

Coomans, N. 2017. Scale matters: The effects of offshore wind farms on macrobenthic communities in the North Sea? Thesis Master in Biology (to be submitted), University of Ghent.

Dannheim, J., Brey, T., Schröder, A., Mintenbeck, K., Knust, R. & Arntz, W.E. 2014. Trophic look at soft-bottom communities – short-term effects of trawling cessation on benthos. *Journal of Sea Research* 85: 18-28.

Degraer, S., Van Lancker, V., Moerkerke, G., Van Hoey, G., Vanstaen, K., Vincx, M. & Henriet, J.-P. 2003. Valuation of the ecological value of the foreshore habitat-model and macrobenthic side-scan sonar interpretation: Extension along the Belgian coastal zone. Ministry of the Flemish Community, Environment and Infrastructure Department. Waterways and Marine Affairs Administration, Costal Waterways, 63 p.

Degraer, S., Wittoeck, J., Appeltans, W., Cooreman, K., Deprez, T., Hillewaert, H., Hostens, K., Mees, J., Vanden Berghe, E. & Vincx, M. 2006. *The macrobenthos atlas of the Belgian part of the North Sea*. Brussels: Belgian Science Policy.

Degraer, S., Verfaillie, E., Willems, W., Adriaens, E., Vincx, M. & Van Lancker, V. 2008. Habitat suitability modelling as a mapping tool for macrobenthic communities: An example from the Belgian part of the North Sea. *Continental Shelf Research* 28: 369-379.

De Maersschalck, V., Hostens, K., Wittoeck, J., Cooreman, K., Vincx, M. & Degraer, S. 2006. Monitoring van de effecten van het Thornton windmolenpark op de benthische macro-invertebraten en de visfauna van het zachte substraat. Report, 136 p.

De Mesel, I., Kerckhof, F., Rumes, B., Norro, A., Houziaux, J.-S. & Degraer, S. 2013. Fouling community on the foundations of wind turbines and the surrounding scour protection. In S. Degraer *et al.* (eds), *Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Learning from the past to optimise future monitoring programmes*, pp. 123-137.

De Mesel, I., Kerckhof, F., Norro, A., Rumes, B. & Degraer, S. 2015. Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species. *Hydrobiologia* 756 (1): 37-50.

Degraer, S., Brabant, R., Rumes, B. & Vigin, L. (eds.) 2016. *Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Environmental impact monitoring reloaded.* Royal Belgian Institute of Natural Sciences: Operational Directorate Natural Environment, Marine Ecology and Management Section, 287 p.

Kerckhof, F., Rumes, B., Norro, A., Jacques, T.G. & Degraer, S. 2010. Seasonal variation and vertical zonation of the marine biofouling on a concrete offshore windmill foundation on the Thornton Bank (southern North Sea). In S. Degraer, R. Brabant & B. Rumes (eds), *Offshore* *wind farms in the Belgian part of the North Sea: Early environmental impact assessment and spatio-temporal variability*. Royal Belgian Institute of Natural Sciences: Management Unit of the North Sea Mathematical Models. Marine Ecosystem Management Unit, pp. 53-68.

Kröncke, I. 2011. Changes in Dogger Bank macrofauna communities in the 20th century caused by fishing and climate. *Estuarine, Coastal and Shelf Science* 94: 234-245.

Kröncke, I., Reiss, H., Eggleton, J.D., Aldridge, J., Bergman, M.J., Cochrane, S., Craeymeersch, J.A., Degraer, S., Desroy, N. & Dewarumez, J.-M. 2011. Changes in North Sea macrofauna communities and species distribution between 1986 and 2000. *Estuarine, Coastal and Shelf Science* 94: 1-15.

Krone, R., Gutow, L., Joschko, T.J. & Schröder, A. 2013a. Epifauna dynamics at an offshore foundation – implications for future wind power farming in the North Sea. *Marine Environmental Research* 85: 1-12.

Lacroix, G., Ruddick, K., Ozer, J. & Lancelot, C. 2004. Modelling the impact of the Scheldt and Rhine/Meuse plumes on the salinity distribution in Belgian waters (southern North Sea). *Journal of Sea Research* 52: 149-163. DOI: dx.doi.org/10.1016/j.seares.2004.01.003

Lancelot, C., Billen, G., Sournia, A., Weisse, T., Colijn, F., Veldhuis, M.J., Davies, A. & Wassmann, P. 1987. Phaeocystis blooms and nutrient enrichment in the continental coastal zones of the North Sea. *Ambio* 16: 38-46.

Leonhard, S.B. & Pedersen, J. 2005. Benthic communities at Horns Rev before, during and after construction of Horns Rev offshore wind farm. Final Report. Annual Report 2005, 154 p.

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

MUMM. 1996. Inventaris Stroom – en getijmetingen 1977 tot 1995. Technisch Rapport, BMM Meetdienst, Oostende. In K. Van Ginderdeuren, S. Vandendriessche, M. Vincx, Y. Prössler, H.D. Matola & K. Hostens (eds), Selective feeding by pelagic fish in the Belgian part of the North Sea. *ICES Journal of Marine Science* 71: 808-820.

Pearson, T.H. & Rosenberg, R. 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanography and Marine Biology: An Annual Review* 16: 229-311.

Petersen, J.K. & Malm, T. 2006. Offshore windmill farms: Threats to or possibilities for the marine environment. *AMBIO: A Journal of the Human Environment* 35: 75-80.

Reubens, J.T., Braeckman, U., Vanaverbeke, J., Van Colen, C., Degraer, S. & Vincx, M. 2013. Aggregation at windmill artificial reefs: CPUE of Atlantic cod (*Gadus morhua*) and pouting (*Trisopterus luscus*) at different habitats in the Belgian part of the North Sea. *Fisheries Research* 139: 28-34.

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

Reubens, J., Alsebai, M. & Moens, T. 2016. Expansion of small scale changes in macrobenthic community inside an offshore windfarm? In S. Degraer, R. Brabant, B. Rumes & L. Vigin (eds), *Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Environmental impact monitoring reloaded*. Royal Belgian Institute of Natural Sciences: Management Unit of the North Sea Mathematical Models. Marine Ecosystem Management Unit, 287 p.

Rumes, B., Coates, D., De Mesel, I., Derweduwen, J., Kerckhof, F., Reubens, J. & Vandendriessche, S. 2013. Does it really matter? Changes in species richness and biomass at different spatial scales. In S. Degraer, R. Brabant & B. Rumes (eds), *Environmental impacts of offshore windfarms in the Belgian Part of the North Sea: Learning from the past to optimise future monitoring programmes*. Royal Belgian Institute of Natural Sciences: Management Unit of the North Sea Mathematical Models. Marine Ecosystem Management Unit, pp. 183-189.

Vandendriessche, S., Derweduwen, J. & Hostens, K. 2015. Equivocal effects of offshore wind farms in Belgium on soft substrate epibenthos and fish assemblages. *Hydrobiologia* 756 (1): 19-35.

Vandendriessche, S., Reubens, J. Derweduwen, J., Degraer, S. & Vincx, M. 2013. Offshore windfarms as productive sites for fishes? In S. Degraer *et al.* (eds), *Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Learning from the past to optimise future monitoring programmes*, pp. 153-161.

Vandendriessche, S., Derweduwen, J. & Hostens, K. 2015. Equivocal effects of offshore wind farms in Belgium on soft substrate epibenthos and fish assemblages. *Hydrobiologia* 756: 19-35.

Van Hoey, G. 2004. Macrobenthic community structure of soft bottom sediments at the Belgian Continental Shelf. *Estuarine, Coastal and Shelf Science* 59: 599-613.

Wilhelmsson, D. & Malm, T. 2008. Fouling assemblages on offshore wind power plants and adjacent substrata. *Estuarine, Coastal and Shelf Science* 79 (3): 459-466.

Ysebaert, T. & Herman, P.M.J. 2003. Het beoordelen van de ecologische toestand van kust- en overgangswateren aan de hand van benthische macro-invertebraten (macrobenthos). Report, 39 p.

Ysebaert, T., Hart, M. & Herman, P.M.J. 2009. Impacts of bottom and suspended cultures of mussels *Mytilus spp.* on the surrounding sedimentary environment and macrobenthic biodiversity. *Helgoland Marine Research* 63: 59-74.