CHAPTER 7

MACROBENTHOS COMMUNITIES OF A NEARSHORE WINDFARM: DISTRIBUTION AND FIRST POST-CONSTRUCTION RESULTS

LEFAIBLE Nene*, VAN VOOREN Kobejoren, BRAECKMAN Ulrike & MOENS Tom

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

* Corresponding author: nene.lefaible@ugent.be

Abstract

The Norther wind farm represents a unique study site compared to other Offshore Wind Farms (OWFs) within the Belgian part of the North Sea (BPNS) such as Belwind and C-Power due to its dissimilarity in terms of physical conditions (nearshore, shallower water depths and more diverse sedimentary characteristics). Moreover, results from the baseline assessment (2016) and this first impact study indicate that the area is heterogenous both in terms of abiotic and biotic parameters. A classification of the abiotic parameters into categorical groups, revealed the presence of three broader habitat types and associated macrobenthic assemblages. One of these assemblages was linked to a habitat (Habitat Type 1, HT1) characterized by fine, organically enriched sediments with significant amounts of coarser material (fine gravel/granule fractions). These seabed conditions are in contrast with the well-sorted, medium-coarse sands with relatively low organic matter content that are typically found in more offshore situated wind farms in the BPNS. In addition, assemblages found within HT1 showed very high abundances, diversity and a distinctive faunal composition, making this habitat type ecologically valuable and therefore interesting for future research. Short-term impacts (construction phase) were reflected in lower average abundances and diversity compared to baseline conditions, while no significant differences were found between samples taken in close vicinity of the turbine compared to further away (operational phase) within each habitat type. While the absence of early post-construction effects is in line with previous studies within Belgian OWFs, different physical -and biological responses might be established within Norther. Therefore, future monitoring within this area, and especially within HT1 might reveal new insights on impacts related to the different phases of an operational wind farm.

1. Introduction

Since the last two offshore windfarms (OWFs) became operational in 2020, the entire eastern concession zone has been producing wind-generated electricity (2.26 GW), supplying approximately 10% of the total Belgian electricity demands (see Chapter 1). With a total surface area of 44 km^2, Norther provides a significant share (370 MW) of this renewable energy source (https://www.belgianoffshoreplatform.be).

The newly operational windfarm differs from other OWFs due to its position in relation to the coastline (nearshore), and the fact that it is not located on a natural sandbank and built at shallower water depths (https://www.norther.be).

As a part of the BACI design to evaluate turbine-induced impacts on the macrobenthos, the area was sampled during autumn 2016, one year before construction. Results from this pre-construction study were described by Lefaible *et al*. (2018), and provide insights on the 'natural' environment within the area. Abiotic parameters proved to be highly variable in terms of sedimentary characteristics. Moreover, reported coarser material (>2 mm fraction) and organic matter contents were rather high within the future impact site. This patchy distribution of seabed conditions was also reflected with regard to benthic assemblages, suggesting macrobenthic heterogeneity at different spatial scales. Samples were characterized by relatively high macrofaunal densities, diversity and different types of assemblages were described. One of these assemblages was associated with a specific habitat (organically enriched sediments with high coarse material and fine sand fractions), and showed very high abundances (>5000 ind. m^{-2}), diversity (>40 species per sample) and compositions which were dominated by tube-dwelling polychaeta, hard-substrate associated species and common occurrences of bivalves and ophiuroids.

These findings, in combination with its distinctive physical character, makes this a unique study area to investigate potential impacts related to OWFs. First of all, post-installation studies and follow-up monitoring programs within a neighboring OWF, C-Power (situated 1 km north of Norther) have shown consistent turbine-related impacts on the surrounding macrobenthic communities (Coates *et al*. 2014; Lefaible *et al*. 2018, 2019; Braeckman *et al*. 2020). The hypothesis to explain the locally increased macrobenthic biodiversity is that the introduction of hard structures induces hydrodynamic changes (bottom currents, sediment resuspension), resulting in finer and organically enriched sediments in the wake of the turbines (Dannheim *et al*. 2019). In addition, epifouling communities rapidly colonizing the structures can also influence these abiotic factors through biodeposition, while also increasing overall habitat complexity and biodiversity (Maar *et al*. 2009; Dannheim *et al*. 2019). Hypothesis-driven sampling at two distances (far vs very close samples) indicates a sediment fining around the jacket foundations at C-Power, while organic enrichment patterns (food availability for benthos) are variable. The higher macrobenthic densities and diversity in close vicinity of the jackets (Lefaible *et al*. 2018, 2019; Braeckman *et al*. 2020) do however show a high inter-turbine variability and effects appear to be site-specific, depending on local physical conditions and turbine type. Consequently, it is expected that similar mechanisms could also manifest within Norther, but might induce different abiotic changes and benthic responses.

Secondly, the relatively large size of the new OWF, together with its variability in terms of seabed conditions and associated benthic assemblages also offers the perfect study site to evaluate potential effects of fishery exclusion (Duineveld *et al*. 2007). Impacts related to fishery such as trawling are known to cause severe damage to benthic habitats, especially those that harbor communities with long-lived, fragile species or biogenic structures (Jennings *et al*. 2001; Coates *et al*. 2016). Through the exclusion of any fishing within operation OWFs, these areas are released from this frequent pressure, potentially allowing recovery and re-establishment of vulnerable species and naturally occurring benthic assemblages (Coates *et al*. 2016). Consequently, future monitoring within Norther (no fishing zone) and its reference area, where fisheries are still allowed, provide the opportunity to study and understand this so called 'fishery exclusion effect'.

Within this study, samples that were obtained during the first operational year of the windfarm Norther are explored. An important objective was to describe the current abiotic -and biotic conditions, which is achieved by dividing the area into different habitat types and their associated benthic assemblages. This classification is then further used to i) compare impact samples (T1, 2020) with pre-impact samples (T0, 2016) and ii) perform an initial distance-based (far vs very close samples) analysis in which the environmental and biological heterogeneity of the area is taken into account. Therefore, results obtained within this study will provide insights into early turbine-related impacts and offer a scientific basis for future monitoring and research.

2. Material and methods

2.1. Study area

Within the Belgian part of the North Sea (BPNS), sampling was conducted in the concession area of the recently developed Norther OWF. The OWF is situated 23 km from the Belgian coastline (port of Zeebrugge) and is positioned southeast of the Thornton Bank, therefore constituting the most nearshore OWF within the eastern concession zone. After applying for a concession in 2008, construction works in the Norther concession zone started in 2017 and ended at the beginning of 2019, with the installation of 44 'Vestas 164' monopiles (https://www.norther.be).

2.2. Data collection and treatment

Sediment samples were obtained during autumn (November) 2020 within the Norther concession area and in the reference area (September 2020). In order to allow future distance-based comparisons and comparisons with other OWFs which are already under study, a stratified sampling design was applied. Samples were collected at two distances on board of the vessels *RV* Simon Stevin and Aquatrot. 'Very close' samples were taken at 37.5 m in NE direction from the center of the turbines, while 'far' samples were collected in the middle between the four surrounding wind turbines (350-500 m from any turbine). Sampling positions were chosen based on the actual positions of the installed turbines, and located as such not to interfere with the in-field cables (Fig. 1). The reference samples are not processed yet and are therefore not included within this report.

The samples were collected 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 mm). After drying at 60°C, the grain size distribution was measured using laser diffraction on a Malvern Mastersizer 2000G, hydro version 5.40. Sediment fractions larger than 2 mm were quantified using a 2-mm sieve. The >2 mm fraction falls within the group of gravel based on the Wentworth classification scale, but no further distinction was made between different casts (boulders, cobbles, pebbles, granules and fine gravel). In order to avoid confusion with the naturally occurring gravel beds within the BPNS, this parameter will be reported as 'fine gravel/granule' throughout the following sections. In addition, results from the grain size distributions were also used to calculate the fine sand fraction (125-250 µm) within each sample and, whenever detectable measurements were found, the very fine sand fraction (63-125 µm) and the silt fraction (<63 µm). Total organic matter (TOM) content was calculated per sample from the difference between dry weight (48 h at 60°C) and ash-free dry weight (2 h at 500°C). The rest of the sample was sieved on board (1-mm mesh-sized sieve), and the macrofauna was preserved in a 4% formaldehyde-seawater solution and stained with Rose Bengal. In the laboratory, organisms were sorted, counted

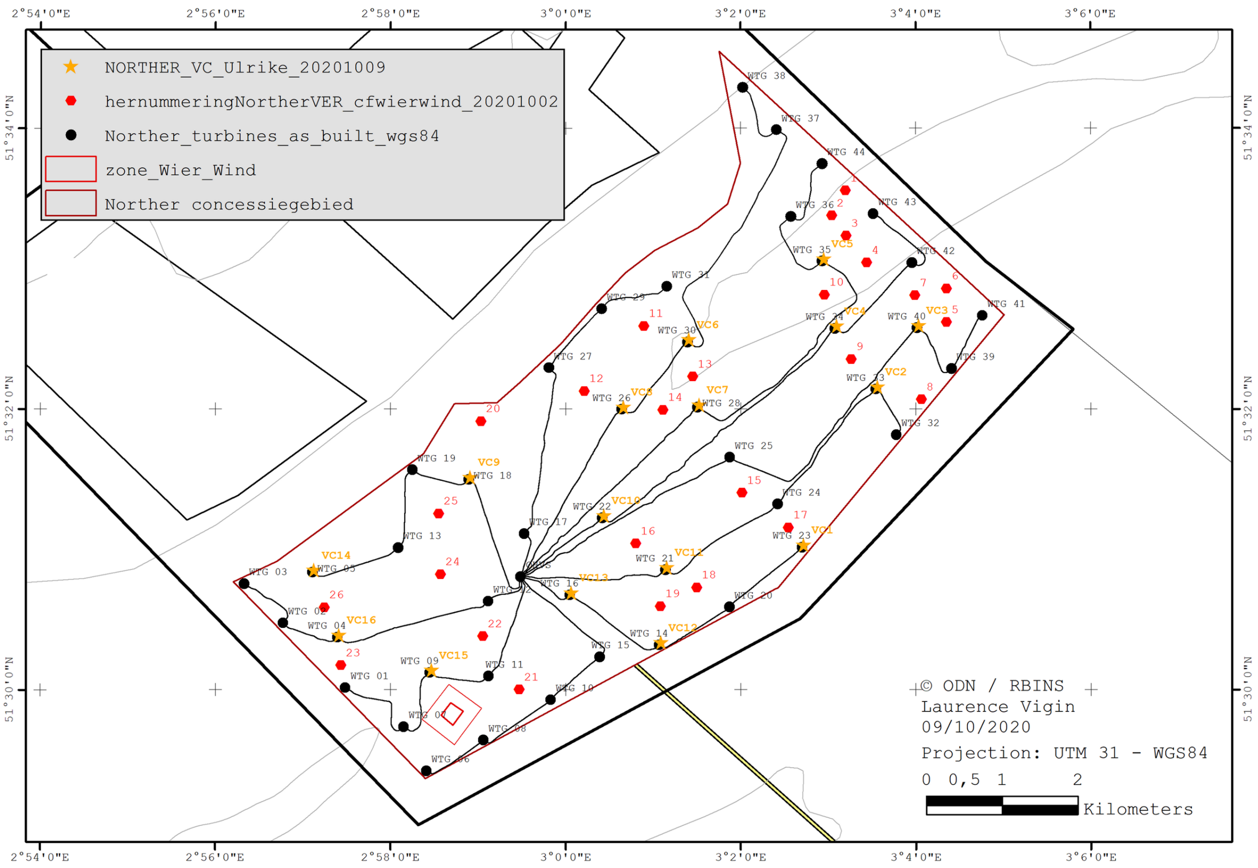

Figure 1. Overview of far positions (red dots) and very close positions (yellow stars) sampled in vicinity of the turbines (black dots) in 2020 at Norther.

and identified to the lowest possible taxonomic level. Biomass was also determined for each taxon level as blotted wet weight (mg).

2.3. Data analysis

Because of the Covid-19 measures, there was a limited time for sample processing at the lab. As a result, a priority list was developed, containing 15 'Far' samples (FAR) which were associated with 15 'Very Close' samples (VC) of the same turbine leading to a total of 30 samples. Prior to statistical analysis, the total abundance (ind. m^{-2}), number of species (S) and Shannon-Wiener diversity index (H') were also calculated from the dataset.

2.3.1. Habitat characterization

Due to the high variability in terms of abiotic and biotic variables within the baseline study, it was decided to categorize the Norther area into different habitat groups and corresponding benthic assemblages. First of all, a principal component analysis (PCA, based on normalized environmental data) was performed in order to visualize potential trends for the studied environmental parameters. Next, abiotic results for each sample were listed and divided into different categories based on predetermined threshold values. median grain size values were categorized as fine sands (0.125-0.250 mm), medium sands (0.250-0.500 mm) or coarse sands (0.500-1 mm) following the Wentworth scale. Other sedimentary variables included the fine sand and fine gravel / granule fractions (%) which were also classified into very high (>25%), high (>15%), medium (10-15%) and low (5-10 %) and very low (<5 %) values. In addition, a similar approach (high: >1%, medium: 1-0.65%, low: <0.65%) was used to categorize the total organic matter content within each sample. The obtained categorization was then used to describe the 'clusters' found within the PCA in more detail. Moreover, biotic properties such as density and diversity values were explored for each of the samples, together with nMDS and CLUSTER analysis (PRIMER version 6.1.11) to investigate a potential link with the abiotic habitat group and species / assemblages distributions. The final habitat groups were then used for all further statistical analyses.

2.3.2. Post-impact (T1) assessments

In order to assess short-term effects related to the construction phase, results from this study were compared with results from the baseline assessment performed in 2016. Due to a shift in sampling points between both sampling campaigns (turbines were constructed elsewhere than planned) and the natural variability of the area, it was only possible to investigate and report these temporal trends in a descriptive manner within the discussion section. Additionally, turbine-related impacts associated with the long-term presence of the structures were studied through a two-way ANOVA (distance, habitat groups) to assess differences between distances (far vs very close) from the turbines in terms of abiotic -and biotic parameters, while also taking into account the natural variability through the integration of the obtained habitat types within the analysis. Assumptions of normality and homogeneity of variances were tested by Shapiro-Wilk and Levene tests respectively, and log transformations were performed if these assumptions were not met. If after transformation the assumptions were still not fulfilled, a PERMANOVA (Permutational Anova, based on Euclidean distance matrix) was performed, allowing to perform univariate ANOVAs with p-values obtained by permutation (Anderson *et al.* 2008), thus avoiding the assumption of normality. Multivariate analysis was performed in PRIMER (version 6.1.11) with PERMANOVA add-on to investigate the potential effects of distance on macrobenthic community structure. These tests were based on a Bray-Curtis resemblance matrix (fourth-root transformed data) and were performed by using a fixed two-factor design (distance, habitat groups). Homogeneity of multivariate dispersions was tested using the PERMDISP routine (distances among centroids). 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).

3. Results

3.1. Current abiotic -and biotic conditions

Average seabed conditions within the whole concession zone were characterized by medium sands (379 ± 83 µm) and relatively high fine sand fractions (19.70 ± 18.06%), fine gravel / granule fractions (10.51 ± 10.75%) and total organic matter content (1.04 ± 0.68%). However, comparable to results from the pre-construction analysis, the area also showed considerable variability for all parameters. The majority of the samples was characterized by a median grain size of 250-500 µm, which corresponds with the widely distributed medium sands found within the BPNS. Hence, it was decided to omit this parameter from subsequent habitat classification due to its low value to indicate actual sedimentary differences between samples. The other parameters did show clear distinctions with regard to sedimentology (fine gravel / granule and fine sand fraction) and food availability (TOM), which is visualized on the PCA plot (Fig. 2).

On the right side of the PCA plot, a cluster of 6 samples (Fig. 2; Table 1) can be distinguished, which seem to correspond with sediments that have high fine gravel / granule and fine sand fractions. Samples within this group are indeed characterized by very high (>25%) fine gravel / granule and fine sand values together with high TOM contents (>1.5%). Moreover, these were the only samples in which considerable amounts of very fine sand (63-125 µm, min: 10% - max: 22%) and silt (<63 µm, min: 14% - max: 29%) were detected. Therefore, this group of samples will

Table 1. Classification of the three habitat types found within the Norther site, with a description, overview of samples (Very Close; VC and Far samples) and average values (± SD) for the abiotic parameters within each habitat type.

Proposed habitat classification	Fine gravel/ granule fraction (> 2 mm, %)	Fine sand fraction (125-250 µm, %)	Total organic matter (TOM, %)
Habitat Type 1 (HT1) (n = 6; VC01/14/16 and FAR23/25/26) _Description:_ fine, organically enriched sediments with a significant amount of coarser, fine gravel/granule material	28±4 %	51±6	1.95±0.50
Habitat Type 2 (HT 2) (n = 15; VC02/03/08/09/11/12/15 and FAR09/12/13/16/17/18/19/22) _Description:_ moderate (low-medium) and variable sediments with transitional samples between HT2-HT1	8±7 %	16±9	1.02±0.54
Habitat Type 3 (HT 3) (n = 9; VC04/05/06/07/10 and FAR03/04/10/11) _Description_: relatively coarse, organically impoverished sediments	2±3 %	5±4	0.47±0.08

Categorization based on following threshold values:

Fine gravel/granule and fine sand fraction: very low (< 5%), low (5-10%), medium (10-15%), high (>15%), very high (>25%).

Total organic matter (TOM) content: low (< 0.65%), medium (0.65-1%), high (> 1%).

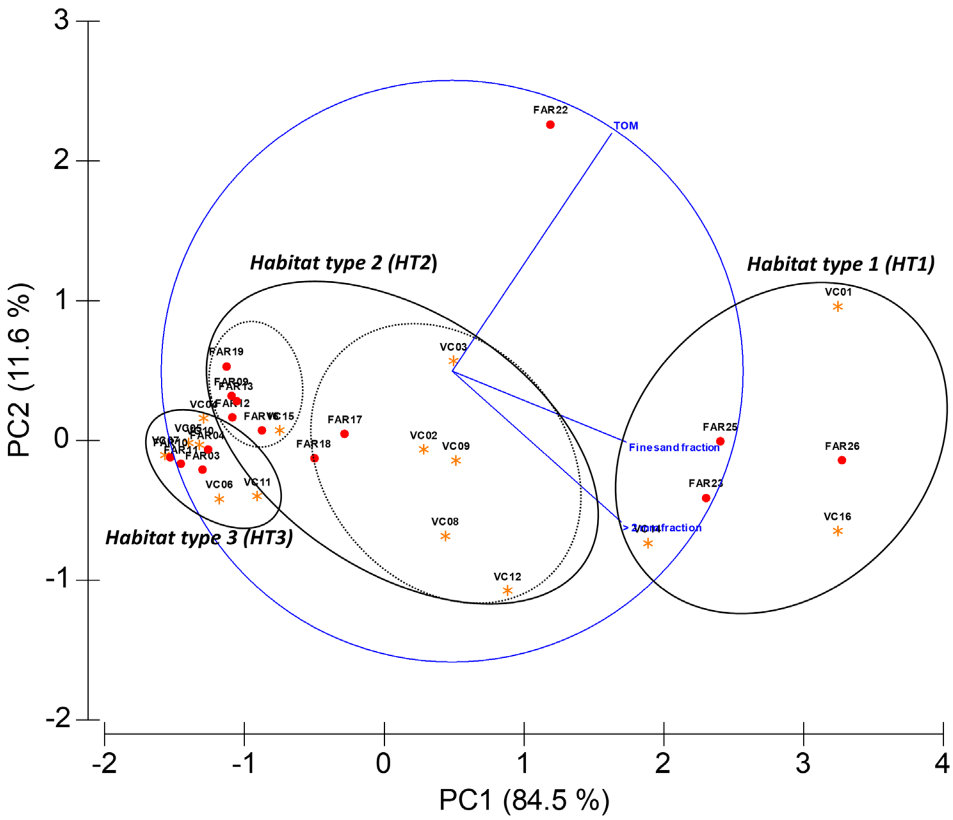

Figure 2. Ordination plot obtained for normalized environmental data after PCA analysis.

be further referred to as Habitat type 1 (HT1, Table 1), which constitutes fine, organically enriched sediments with significant amounts of coarser (fine gravel/granule) material. A larger, cluster was also found, containing the majority of the samples (see Table 1), which showed a rather scattered distribution of samples. Samples within this group were categorized as variable with values for the grain size associated parameters (fine gravel/granule and fine sand fraction) ranging from low (<5%) to medium (5-10%) and low (<0.65%) to medium (0.65-1%) TOM values. In addition, certain samples (VC02/03/08/09, FAR17/18/22) were positioned more towards HT1. These samples were therefore identified as 'transitional' samples between HT2-HT1, with very high-high values for certain environmental parameters. In contrast to the samples from HT1, a total of 9 samples are clustered at the bottom left side of the PCA plot, indicating rather low amounts for all the parameters under study. This was indeed confirmed by the categorization method, as all these samples showed very low-low fine gravel/granule (<5%, 5-10%) fractions together with low fine sand fractions (5-10%) and TOM contents (<0.65%). As a result, a third habitat type (HT3) was proposed, being composed of relatively coarse, organically impoverished sediments (Table 1).

In accordance with the abiotic results, there appears to be a high variability between samples in terms of average macrobenthos abundances, species richness and Shannon-Wiener diversity. However, it can be stated that the area is characterized by relatively high abundances (1408±1899 ind. m^{-2}) and diversity (S: 17±12, H': 2.04±0.55). Regarding community composition, results from the nMDS plot and CLUSTER analysis did show some interesting patterns (Fig. 3), on which a distinction can be seen of the samples into three larger groups: VC02/09/14/16 + FAR23/25/26, a rest group containing the majority of the samples and VC05/07 + FAR11.

Figure 3. Visualization of multivariate density data (fourth root transformed, Bray-Curtis similarity matrix) through an nMDS plot for both distances. Additional circles were added to highlight the different groups.

Benthic assemblages of the first group (7 samples: VC02/09/14/16 + FAR23/25/26) show very high average abundances (3791 ind. m^{-2}) and diversity (S = 33, H = 2.6). Next, SIMPER results showed that besides the relatively abundant presence of the commonly found Nemertea sp., these assemblages were also characterized by the occurrence of several other species. *Ablomelita obtusata* and *Monocorophium* sp. were the most abundant amphipod species, and cumaceans of the family of Bodotriidae (*Bodotria scorpioides*) were also well represented within these samples. Polychaete densities were dominated by *Notomastus latericeus*, larger *Nereis* sp. individuals, *Pholoe minuta,* Cirratulidae sp. and tube-dwelling species such as *Poecilochaetus serpens*, *Owenia fusiformis* and *Lagis koreni* were often encountered. Furthermore, moderate to high densities of epibenthic species such as sea anemones, *Spirobranchus* sp. (calcareous-tube dwelling polychaetes attached to rocks and shells) and Phoronida sp. (horseshoe worms) were also found together with motile species such as *Ophiura* juv., *Echinocyamus pusillus* and juvenile decapods. The second group contains the majority of the samples (17 samples in total) and is also the most heterogenous group. Most of the samples can be considered as moderate in terms of average densities (483 ind. m^{-2}) and diversity (S = 12, H = 1.8), while some poorer samples (VC06, VC11, FAR13/16/19) and richer samples (VC01, VC08, FAR17, FAR18) can also be distinguished. Nevertheless, no clear differences were found in terms of composition between samples of this group, which were mainly made up by amphipods (*Urothoe brevicornis*, *Bathyporeia elegans*) and polychaetes (*Nephtys cirrosa*, *Glycera* sp.). At the other end of the spectrum, benthic assemblages of the last group (3 samples: VC05/07, FAR11) are characterized by rather low average abundances (162 ind. m^{-2}) and diversity (S = 7, H = 1.6) and are dominated by *Nephtys cirrosa* and *Urothoe brevicornis*. When these groups of assemblages are linked with the previously obtained habitat types, it can be concluded that HT 1 harbors abundant and diverse assemblages of group 1, but these can also be encountered within transitional samples from HT 2. Assemblages found within HT 2 and HT 3 are less distinct from each other and contain the less abundant and diverse assemblages of groups 1 and 2, with variable species composition.

3.2. Post-impact assessment on turbine-related impacts

In order to test for potential early distance-based differences within the OWF, a two-way Anova was run to examine the effect of distance (levels; Far, VC) and habitat type (levels; type 1, type 2, type 3) on the abiotic -and biotic parameters. Average values (± SD) are listed in Table 2 and visualized on the overview Figs 4 and 5. There was a significant interaction between the effects of ‘habitat type’ and ‘distance’ on the average MGS ($p = 0.036$), but pairwise post-hoc tests only revealed significant differences between the habitat types. Furthermore, there were statistically significant differences in average fine sand fractions, fine gravel/granule fractions and TOM contents for the main effect ‘habitat type’ ($p = 0.00001$, $p = 0.001$, $p = 0.00003$), while there were no differences between distances ($p > 0.05$). Similar to the abiotic results, significant differences for the average biotic parameters, were found between habitat types (densities: $p = 0.0009$, S: $p = 0.004$ and H’: $p = 0.007$), while average values were comparable between distances ($p > 0.05$). In addition, macrobenthic structure did not differ significantly between both distances (Permanova, $p = 0.22$) within each habitat type, but general differences in terms of species composition were found between habitat types (Permanova, $p = 0.001$). In general, it can be stated that no evidence was found for early distance-based differences, but other results within this analysis did confirm the proposed distinction between the proposed habitat types described in the previous section.

Table 2. Overview of calculated abiotic sediment and community descriptors (mean ± SD) for the spatial comparison between both distances from turbines within Norther (2020) for every habitat type. Average values are also added from the far samples during the baseline assessment (2016).

Univariate results	Habitat Type 1		Habitat Type 2		Habitat Type 3		Norther (2016)
	VC	*FAR*	*VC*	*FAR*	*VC*	*FAR*	FAR
Median grain size (MGS, µm)	244 ± 36	249 ± 27	380 ± 52	424 ± 53	455 ± 31	395 ± 31	355 ± 89
Fine sand fraction (125-250 µm, %)	52 ± 8	50 ± 6	21 ± 8	11 ± 1	4 ± 2	7 ± 5	21 ± 1
Total organic matter (TOM, %)	1.99 ± 0.75	1.92 ± 0.25	0.96 ± 0.34	1.06 ± 0.69	0.51 ± 0.10	0.43 ± 0.05	1.09 ± 0.49
Fine gravel/granule fraction (> 2 mm, %)	28 ± 4	27 ± 5	13 ± 08	4 ± 3	3 ± 2	2 ± 1	11 ± 10
Total abundance (N, ind. m^{-2})	4083 ± 2815	4097 ± 1244	1644 ± 1953	435 ± 196	326 ± 255	268 ± 140	8855 ± 2612
Number of species (S)	36 ± 10	34 ± 8	20 ± 12	11 ± 5	9 ± 4	11 ± 6	30 ± 14
Shannon-Wiener (H')	2.83 ± 0.12	2.68 ± 0.01	2.09 ± 0.52	1.70 ± 0.44	1.68 ± 0.28	2.03 ± 0.52	2.40 ± 0.48

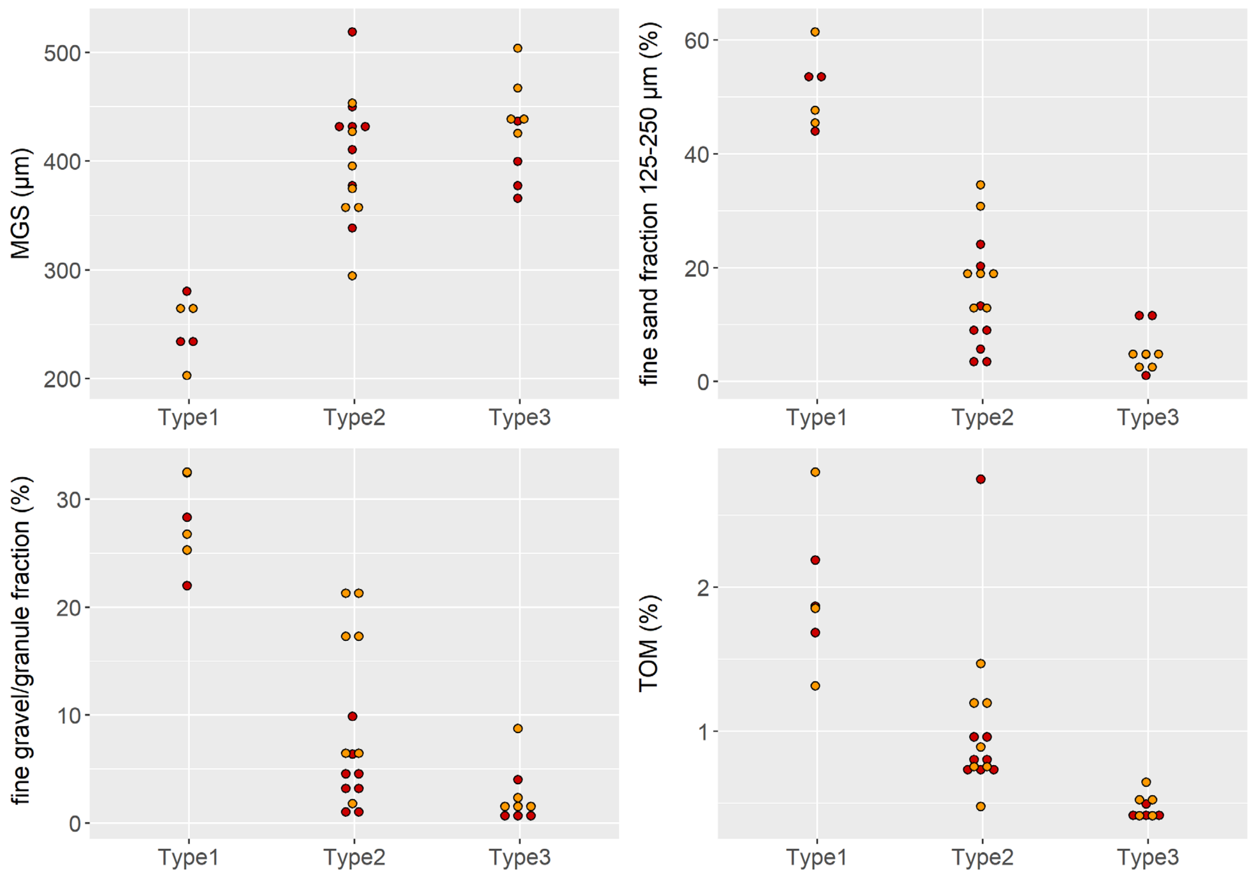

Figure 4. Overview dotplots of the abiotic variables: median grain size (MGS), fine sand fraction, fine gravel/granule fraction and total organic matter (TOM) for far (red dots) and very close samples (orange dots) within all three habitat types.

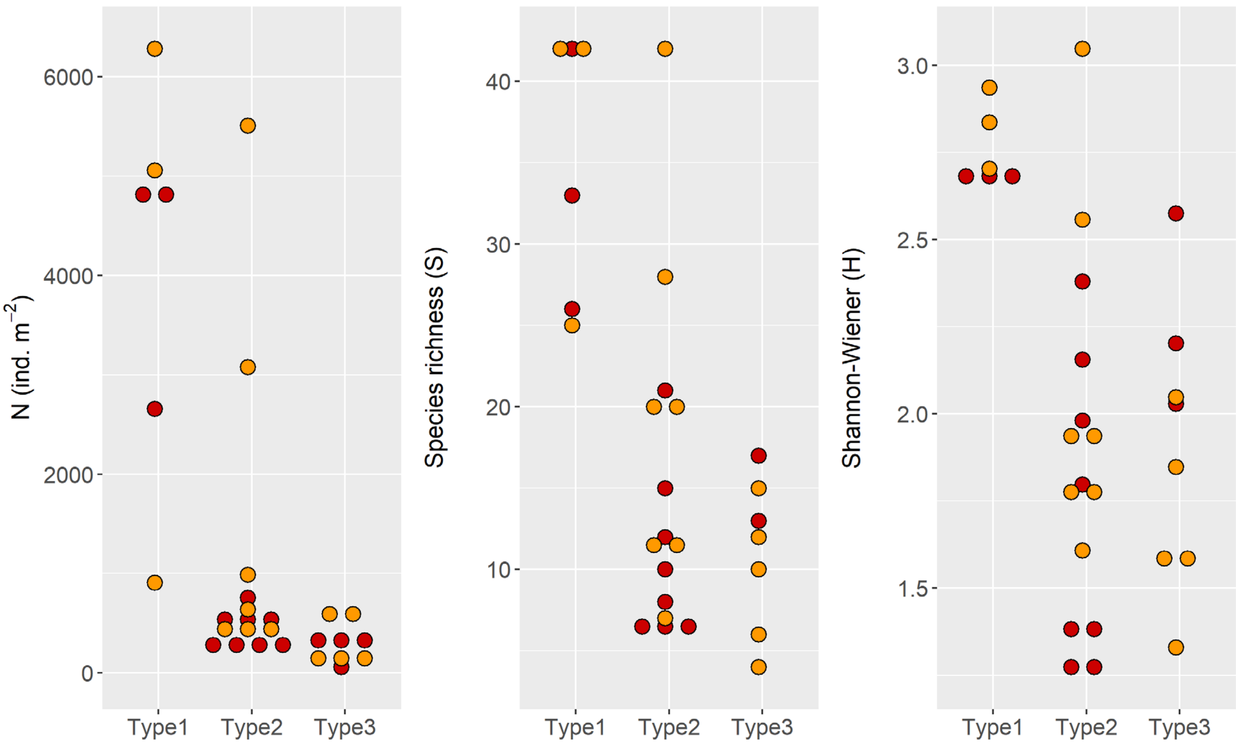

Figure 5. Overview dotplots of the biotic variables: total abundance N (ind. m-2), Species richness (S) and Shannon-Wiener diversity (H') for far (red dots) and very close samples (orange dots) within all three habitat types.

4. Discussion

One of the most recent wind farms, Norther, is rather unique compared to other OWFs in the BPNS due to its dissimilarity in terms of physical conditions. First of all, the concession zone is not completely located on a sandbank and is positioned more nearshore (<27 km, Rumes *et al*. 2017). Secondly, Norther has been constructed in relatively shallow water depths and results from the baseline study conducted in 2016, revealed the occurrence of rather heterogenous sediments with high fine sand and fine gravel/granule fractions together with high organic matter contents. These findings are in contrast with the generally coarse and organically impoverished sediments that are found within more offshore located wind farms such as Belwind. Moreover, results from the baseline assessment also indicate that the area is very heterogenous both in terms of macrobenthic communities (Lefaible *et al*. 2018). Both the short-term (construction phase; transient physical disturbances) and long-term (operational phase; artificial reef effect, fishery exclusion effect) impacts are highly dependent on local physical conditions. Therefore, exploring these aspects within an area such as Norther could provide new insights on the effects on the marine environment related to this fast-growing industry.

4.1. Current seabed conditions and associated benthic assemblages

Comparable to results from the baseline study, all environmental parameters within this study showed high variability, suggesting the presence of different microhabitats within Norther. Therefore, an attempt was made to classify the samples into different habitat types. This resulted in the distinction of three final habitat types which were explained within section 3.1 and are visualized in Fig. 6. The first habitat type (HT1) is characterized by fine, organically enriched sediments with significant amounts of coarser material (fine

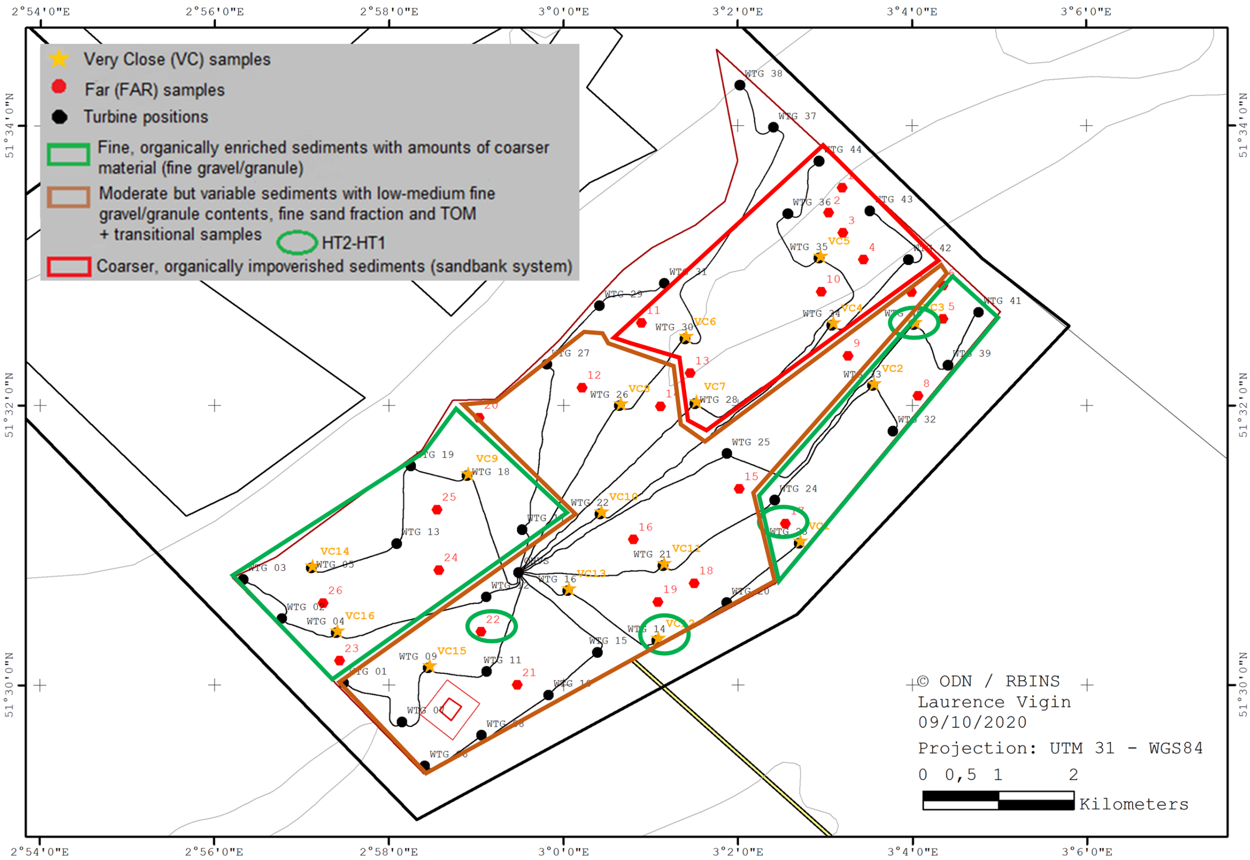

Figure 6. Overview of the proposed habitat types within the Norther study site.

gravel/granule). This habitat type can be found in the NW and SE part of the OWF. The second habitat type (HT2) occupies the largest area within Norther and consists of low-medium fine gravel/granule contents, fine sand fractions and TOM contents. However, considerable variability was found within this habitat type with transitional samples between HT2-HT1. A third habitat type (HT3) was found in the eastern part of the OWF, located on an area of the Thornton Bank, which seems to correspond with described conditions in other OWFs such as C-Power and Belwind with relatively coarse, organically impoverished sediments typically associated with sandbank systems (Van Hoey *et al*. 2004; Breine *et al*. 2018).

Interestingly, these habitat types could be linked with the described macrobenthic distribution and diversity patterns. Results from the in-depth community analysis and PCA-analysis revealed that assemblages found within HT1, showed very high abundances and diversity. It appears that next to the typical soft-sediment species, the high fine gravel/granule contents form a patchy substrate composition which offers a rich and varied habitat for other hemi sessile, tube-dwelling and motile species. If we were to link this habitat type and benthic assemblages to already known distributions within the BPNS, abiotic conditions, benthic structural indices and community compositions correspond rather well with the coastal/onshore '*Abra alba-Mysella bidentata*' (SA1) community (Van Hoey *et al*. 2004; Breine *et al*. 2018). The second habitat type has less clear environmental conditions and this is also reflected in the rather heterogenous assemblages found within this habitat type. The majority of the samples within HT2 can be considered as moderate in terms of average abundance and biodiversity with the occurrence of some 'poorer' and 'richer' transitional samples. However, this variability is not reflected within the compositions which are mainly dominated by common species such as *Nephtys cirrosa, Urothoe brevicornis* and *Bathyporeia elegans*. As a result, this habitat type and its assemblages resemble the widely distributed '*Nephtys cirrosa*' (SA4) community, found in well-sorted, medium sands (Van Hoey *et al*. 2004; Breine *et al*. 2018). Benthic assemblages found within the last habitat type (HT3) are comparable to the rather 'poor' communities (SA5 and SA6) described by Van Hoey *et al*. (2004), which are dominated by *Nephtys cirrosa* and *Urothoe brevicornis* and typically found on natural sandbanks. In general, it can be stated that the patchiness found at Norther in terms of sediments and organic matter distribution creates different habitats, supporting several species assemblages which is in accordance with the high benthic variability at nearshore/onshore zones described by Van Hoey (2004) and Breine (2018).

4.2. Post-impact (T1) assessment within Norther (short-term effects)

During the development of a new OWF, several activities precede the operational phase, depending on the type of turbine that is being used. Within Norther, these pre-installation activities and the deployment of 44 monopile foundations were carried out throughout 2018-2019. Typical construction works for a monopile foundation comprise driving the large, hollow steel pile into the seabed. Next, a transition piece is attached and the center of the pile is filled with concrete. During the last step, an additional layer of larger stones and pebbles is applied (erosion protection layer, EPL) to the surface of the seabed to ensure long-term erosion protection. In addition, in-field cables are also positioned within the OWF (Desmond *et al.* 2016). Impacts associated with this phase are considered to be 'temporary' and include underwater noise emissions and local seabed disturbances such as dredging, sediment disposal and cable laying (Dannheim *et al*. 2020). Despite the ephemeral nature of these disturbances, they can result in strong physical changes on the seabed and affect macrobenthic communities through the direct removal and dispersal of sediments (Coates *et al*. 2014). Post-impact studies within several European OWFs and the Belgian OWFs C-Power and Belwind, revealed an initial reduction in macrobenthic abundances, diversity and composition, followed by a relatively fast recovery 2-4 years after installation (Jak & Glorius 2017; Coates *et al*. 2014). This fast recovery is believed to result from the fact that benthic communities appear to be less sensitive in areas that are characterized by high natural physical disturbance such as those found on these offshore natural sandbanks (Coates *et al*. 2014). Therefore, it was concluded that no substantial short-term impacts were expected during the first years as a result of the high resilience of the benthic communities in more offshore situated OWFs such as Belwind.

The physical conditions (nearshore, shallower water depth and sedimentary characteristics) described within the first discussion section, are all indications of a 'lower energy' environment at Norther with lower rates of natural physical disturbance compared to the OWFs on the sandbanks (Thornton, Belwind). In addition, both the baseline and T1 studies within Norther have revealed the presence of some locations characterized by high fine gravel/granule (>2 mm fraction) contents that contain unique assemblages with high densities, diversity and the presence of long-lived, fragile species. Impact studies within English gravel extraction sites have shown that faunal communities in areas with lower physical disturbance and high gravel contents appear to be more sensitive (recovery potential negatively correlated with the proportion of gravel %) and that differences between reference and impacts sites were still found 6 years after the cessation of the dredging activities (Boyd *et al*. 2005; Cooper *et al*. 2011). Whereas these studies refer to gravel habitats that are not comparable to the one described in this assessment, potential differences in physical and biological recovery rates within Norther might establish compared to other, more offshore situated windfarms.

Results of this first post-impact study within Norther did indeed show a trend of decreased average abundances and diversity compared to pre-installation conditions (2016). It must be stated however that average densities in 2016 were also strongly influenced by a few samples with extremely high abundances (>10.000 ind. m^{-2}), which were mainly attributed to the high occurrences of *Monocorophium* sp. and *Apseudopsis latreilli*. Moreover, these samples were also situated in the upper NW part of the future windfarm site, within the area that has been characterized as habitat type 1 in this study. While *Monocorophium* sp. was still encountered in 2020, abundances were much lower compared to 2016 and *Apseudopsis latreilli* was even absent within the post-impact samples. In addition, abundances of other important species within this habitat type such as *Ablomelita obtusata*, *Notomastus latericus* and *Owenia fusiformis* were visibly lower in 2020 compared to 2016. Due to the fact that the sampling positions from 2016 and 2020 do not correspond exactly and the finding of large small-scale variability in terms of abiotic and biotic conditions within both studies, it is difficult to draw any robust conclusions. Therefore, close follow-up monitoring is strongly advised within the next years, especially within habitat type 1.

4.3. Initial research on turbine-related impacts

Results from the two-way Anova analysis revealed significant differences in terms of abiotic -and biotic variables between habitat types, which confirms the proposed habitat classification within this assessment. However, no differences were found between the two sampled distances within each habitat type. While the physical impacts associated with the presence of introduced hard structures such as changes in local hydrodynamics, sediment characteristics and the colonization by epifauna will start once the turbines are in place, actual shifts in macrobenthic assemblages are believed to occur over longer time periods, which could partially explain the lack of distance-based differences within this study. Another reason may also be the unequal and low number of replicates/samples within each subgroup under study, and a low statistical power. Therefore, these initial results should be interpreted with caution and should be taken into account for future sampling design strategies. As already described in previous reports, the intensity and spatial extent of the turbine-related impacts seem to be very site-specific (Lefaible *et al*. 2017, 2018). Therefore, aspects such as water depth, local hydrodynamic regimes and epifaunal/infaunal composition will have a strong influence on the measurability of effects (Keeley *et al.* 2013; Van Berkel *et al*. 2020). These findings might be especially relevant within this new OWF, when we consider the spatial heterogeneity described within this study. It is proposed that deeper sites with more exposed sediments such as Belwind, will have widely dispersed depositional ‘footprints’ with less intense organic enrichment compared to shallower, poorly-flushed sites (Keeley *et al*. 2013). In addition, the monopiles constructed at Norther, represent one of the largest types (8 MW) currently found in the BPNS, which could result in stronger turbine-related impacts such as hydrodynamic changes and epifauna colonization). These combined factors could result in more pronounced physical disturbances and localized bio depositions, leading to stronger or adverse effects throughout the following years.

4.4. Future research

In order to get a complete overview of the post-impact (T1) situation at the Norther site, the remaining far samples and reference samples will also be processed. These in-situ results, in combination with other habitat mapping techniques such as multibeam analysis, can then be used to provide the final habitat distributions within the area. Once the spatial variability is established, following monitoring campaigns will allow further exploration of the temporal research questions linked to the different phases of a windfarm. In addition, hyperbenthos sampling will be included within future campaigns, as it is expected that impacts will also affect this ecosystem component. It will be crucial to determine the sampling strategy in such a way that a sufficient number of samples are taken within the different habitat types to allow robust statistical analyses. Furthermore, it is also possible to perform a more in-depth and increased sampling effort within habitat type 1, due to its distinctive character compared to other OWFs within the existing eastern concession zone.

5. Conclusion

Norther represents a unique study site compared to other OWFs within the BPNS such as Belwind and C-Power owing to its nearshore position, shallower water depths and more heterogeneous sedimentary characteristics. The combined results from the baseline assessment (2016) and this first impact study indicate that the area is very heterogenous both in terms of sedimentological and macrobenthic community parameters, which is in accordance with the high benthic variability at nearshore / onshore zones described in previous studies within the BPNS.

A classification of the abiotic parameters into categorical groups, revealed the presence of three habitat types and associated benthic assemblages. One of these habitats (habitat type 1) was very distinct from the other and was characterized by finer, organically enriched sediments with significant amounts of coarser material (fine gravel/granule fractions). Macrobenthic assemblages found within these sediments showed high abundances, diversity and was composed of typical soft-sediment species in combination with hemi sessile and tube-dwelling species. Short-term impacts related to construction activities (2018-2019) were reflected in the lower average abundances and diversity compared to baseline conditions, which is in accordance with older impact studies in other Belgian OWFs. In terms of turbine-related effects, no significant differences were found for the initial spatial comparison ('very close' vs 'far' samples) within each habitat type.

While it is expected that long-term impacts related to the operational phase will not be manifested during the first years, it is also known that impact intensity and spatial extent are very site-specific. Therefore, the distinctive abiotic -and biotic conditions found at Norther and especially those within habitat type 1, might lead to differences in physical -and biological recovery rates within the area. In addition, these aspects in combination with the technical differences (larger, broader turbines) could result in stronger long-term effects compared to other OWFs. Consequently, extensive follow-up monitoring during the coming years is advised in which the established environmental and biological heterogeneity is taken into account.

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.

Boyd, S.E., Limpenny, D.S., Rees, H.L. & Cooper, K.M. 2005. The effects of marine sand and gravel extraction on the macrobenthos at a commercial dredging site (results 6 years post-dredging). *ICES Journal of Marine Science* 62: 145-162. https://doi.org/10.1016/j.icesjms.2004.11.014

Braeckman, U., Lefaible, N., Bruns, E. & Moens, T. 2020. Turbine-related impacts on macrobenthic communities: an analysis of spatial and temporal variability. *In*: Degraer, S., Brabant, R., Rumes, B. & Vigin, L. (eds) *Environmental Impacts of Offshore Wind Farms in the Belgian*

Part of the North Sea: Empirical Evidence Inspiring Priority Monitoring, Research and Management. *Memoirs on the Marine Environment*: 61-78. Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management Section, Brussels.

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

Clarke, K.R. & Gorley, R.N. 2006. *PRIMER v6: User Manual/Tutorial PRIMER-E*. Plymouth: Plymouth Marine Laboratory, 190 p.

Coates, D.A., Deschutter, Y., Vincx, M. & Vanaverbeke, J. 2014. Enrichment and shifts in macrobenthic assemblages in an offshore wind farm area in the Belgian part of the North Sea. *Marine Environmental Research* 95: 1-12. https://doi.org/10.1016/j.marenvres.2013.12.008

Coates, D., Kapasakali, A., Vincx, M. & Vanaverbeke, J. 2016. Short-term effects of fishery exclusion in offshore wind farms on macrofaunal communities in the Belgian part of the North Sea. *Fisheries Research* 179: 131-138. https://doi.org/10.1016/j.fishres.2016.02.019

Cooper, K.M., Curtis, M., Wan Hussin, W.M.R., Barrio Froján, C.R.S., Defew, E.C, Nye, V. & Paterson, D.M. 2011. Implications of dredging induced changes in sediment particle size composition for the structure and function of marine benthic macrofaunal communities. *Marine Pollution Bulletin* 62: 2087-2094. https://doi.org/10.1016/j.marpolbul.2011.07.021

Dannheim, J., Bergström, L., Birchenough, S.N.R., Brzana, R., Boon, A.R., Coolen, J.W.P., Dauvin, J.-C., De Mesel, I., Derweduwen, J., Gill, A.B., Hutchison, Z.L., Jackson, A.C., Janas, U., Martin, G., Raoux, A., Reubens, J., Rostin, L., Vanaverbeke, J., Wilding, T.A., Wilhelmsson, D. & Degraer, S. 2020. Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research. *ICES Journal of Marine Science* 77: 1092-1108. https://doi.org/10.1093/icesjms/fsz018

Desmond, C., Murphy, J., Blonk, L. & Haans, W. 2016. Description of an 8 MW reference wind turbine. *Journal of Physics: Conference Series (JPCS)*. IOP Publishing Ltd, Bristol, UK, 753 pp. https://doi.org/10.1088/1742-6596/753/9/092013

Duineveld, G.C.A., Bergman, M. & Lavaleye, M. 2007. Effects of an area closed to fisheries on the composition of the benthic fauna in the southern North Sea. *ICES Journal of Marine Science* 64: 899-908. https://doi.org/10.1093/icesjms/fsm029

Jak, R. & Glorius, S.T. 2017. Marcobenthos in offshore wind farms: a review of research, results, and relevance for future developments. Wageningen Marine Research (University & Research centre), *Wageningen Marine Research report C043/17*, 477 pp. https://doi.org/10.18174/415357

Jennings, S., Pinnegar, J., Polunin, N. & Warr, K. 2001. Impacts of trawling disturbance on the trophic structure of benthic invertebrate communities. *Marine Ecology Progress Series* 213: 127-142. https://doi.org/10.3354/meps213127

Keeley, N. 2013. *Literature Review of Ecological Effects of Aquaculture: Benthic Effects*. Ministry for Primary industries Cawthron Institute, Nelson, 33 pp.

Lefaible, N., Braeckman, U. & Moens, T. 2018. Effects of wind turbine foundations on surrounding macrobenthic communities. *In*: Degraer, S., Brabant, R., Rumes B. & Vigin, L. (eds) *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Assessing and Managing Effect Spheres of Influence*: 57-77. Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management Section, Brussels.

Lefaible, N., Colson, L., Braeckman, U. & Moens, T. 2019. Evaluation of turbine related impacts on macrobenthic communities within two offshore wind farms during the operational phase. *In*: Degraer, S., Brabant, R., Rumes, B. & Vigin, L. (eds) *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea*: 57-64. Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management Section, Brussels.

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. https://doi.org/10.1016/j.seares.2009.01.008

Rumes, B & Brabant, R. 2017. Offshore renewable energy development in the Belgian part of the North Sea. *In*: Degraer, S., Brabant, R., Rumes, B. & Vigin, L. (eds) *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: A Continued Move towards Integration and Quantification. Royal Belgian Institute of Natural Sciences*: 13-15. Management Unit of the North Sea Mathematical Models. Marine Ecosystem Management Unit, Brussels.

Van Berkel, J., Burchard, H., Christensen, A., Mortensen, L. O., Petersen, O. S., & Thomsen, F. 2020. The effects of offshore wind farms on hydrodynamics and implications for fishes. *Oceanography* 33(4): 108-117. https://doi.org/10.5670/oceanog.2020.410

Van Hoey, G., Degraer, S. & Vincx, M. (2004). Macrobenthic community structure of soft bottom sediments at the Belgian Continental Shelf. *Estuarine Coastal and Shelf Science* 59: 599-613. https://doi.org/10.1016/j.ecss.2003.11.005