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# MEMOIRS

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## ENVIRONMENTAL IMPACTS OF OFFSHORE WIND FARMS IN THE BELGIAN PART OF THE NORTH SEA

**ATTRACTION, AVOIDANCE  
AND HABITAT USE AT  
VARIOUS SPATIAL SCALES**

Edited by  
Steven Degraer  
Robin Brabant  
Bob Rumes  
Laurence Vigin



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# CONTEXT

The European Directive 2009/28/EC on the promotion of electricity produced from renewable energy sources in the internal electricity market, imposes a target figure for the contribution of the production of electricity from renewable energy sources upon each Member State. On 31 December 2019, Belgium submitted a National Energy and Climate Plan to the European Commission which envisions a target figure of 17.5% for the contribution of the production of electricity from renewable energy sources by 2030. Offshore wind farms in the Belgian part of the North Sea are expected to make an important contribution to achieve that goal.

Within the Belgian part of the North Sea, a zone of 238 km<sup>2</sup> is reserved for the production of electricity from water, currents or wind. In that zone, eight wind farms are operational with a combined installed capacity of 2.26 MW. A second area for renewable energy of 285 km<sup>2</sup> is foreseen by the new Belgian marine spatial plan (2020-2026) with the government aiming for an installed capacity of 3.1 tot 3.5 GW in this zone.

Prior to installing a wind farm, a developer must obtain a domain concession and an environmental permit. The environmental permit includes a number of terms and conditions intended to minimise and/or mitigate the impact of the project on the marine ecosystem. Furthermore, as required by law, the permit imposes a monitoring programme to assess the effects of the project onto the marine environment.

Within the monitoring programme, the Royal Belgian Institute of Natural Sciences and its partners assess the extent of the anticipated impacts onto the marine ecosystem and aim at revealing the processes behind these impacts. The first objective is tackled through basic monitoring, focusing on the *a posteriori*, resultant impact quantification, while the second monitoring objective is covered by the targeted or process monitoring, focusing on the cause-effect relationships of *a priori* selected impacts.

This report, targeting marine scientists, marine managers and policy makers, and offshore wind farm developers, presents an overview of the scientific findings of the Belgian offshore wind farm environmental monitoring programme (WinMon.BE), based on data collected up to and including 2020.

DEGRAER Steven, BRABANT Robin, RUMES Bob and VIGIN Laurence



# EXECUTIVE SUMMARY

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## ATTRACTION, AVOIDANCE AND HABITAT USE AT VARIOUS SPATIAL SCALES

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In this report, we zoom in on patterns of attraction, avoidance and habitat use at various spatial scales (i.e., wind farm-scale, turbine-scale and microhabitat-scale) and across different ecosystem components (i.e., marine mammals, (sea)birds, fish and benthic invertebrates), and demonstrate the benefits of such knowledge to design appropriate measures to mitigate undesired impacts. Attraction to and avoidance of offshore wind farms (OWFs) reshuffle species distribution patterns, altering the local expression of ecological functions, and probably are the most commonly known effects of OWFs. Seabirds like red-throated divers *Gavia stellata* avoid OWFs up to more than ten kilometers, while marine mammals such as harbor porpoises *Phocoena phocoena* avoid areas with excessive sound levels like pile driving locations (see former editions of this publication series). Attraction to OWFs on the other hand, has been demonstrated for cormorants *Phalacrocorax carbo* roosting on the structures but also for harbor seals *Phoca vitulina* hunting for fish close to the turbines. Fish like pouting *Trisopterus luscus* and cod *Gadus morhua* are also attracted to the artificial reefs formed by OWFs because these offer excellent feeding opportunities. Insights into the extent of attraction, avoidance, and the associated ecological consequences are, however, hampered by a main focus on higher

trophic levels, while these effects also play at lower trophic levels. Working our way down the food web, attraction and avoidance become more subtle as they are often linked to small-scale effects and ecological processes such as (micro)habitat use and habitat provision, often driven by species interactions like inhibition and facilitation.

The degree of attraction and avoidance is expected to be positively correlated to the size of the OWF and the size of the constituting structures. With the completion of the Northwester 2 and Seamade projects in 2020, the Belgian OWF projects now cover a contiguous area of no less than 238 km<sup>2</sup>. This area accommodates 399 offshore wind turbines with a total capacity of 2.26 GW and an expected annual production of 8 TWh (Chapter 1). Furthermore, the installed capacity per turbine has gradually increased with extra-large monopiles (i.e., with a diameter larger than 7 m) becoming the dominant foundation type in the Belgian part of the North Sea. An additional zone for 3.5 GW of OWFs has been identified in the marine spatial plan 2020-2026. With (1) 523 km<sup>2</sup> realized and planned for OWFs in Belgium, 344 km<sup>2</sup> in the adjacent Dutch Borssele zone, and 122 km<sup>2</sup> in the French Dunkerque zone and (2) the ambition to co-locate other human activities in Belgian



OWFs (e.g., aquaculture), cumulative impacts on species distribution patterns as a result of attraction and avoidance continue to be a major point of attention.

Starting with changes in the spatial distribution of species at the highest trophic levels, marine mammals have been shown to avoid OWF construction areas, and concerns over the possible impact of high-intensity impulsive sound generated during the construction of OWFs on harbor porpoise have been a driving force in determining national impulsive noise regulations in North Sea countries. In Belgium, concern over the high levels of underwater noise generated during pile driving operations for the building of the first OWFs and the observed large-scale avoidance of the construction zone by porpoises led to the formulation of a threshold for impulsive underwater sound in the Belgian part of the North Sea at 185 dB re 1  $\mu$ Pa (sound pressure level, zero to peak) at 750 m from the source. Since 2017, OWF developers have applied several noise mitigation systems with incremental progress in reducing noise levels during pile driving. Using passive acoustic monitoring datasets from 2016 (no sound mitigation) and 2019 (Double Big Bubble Curtain sound mitigation in place), we investigated whether sound mitigation measures applied during the construction of OWFs influenced the likelihood of detecting harbor porpoises during pile driving in the Belgian part of the North Sea (Chapter 2). Despite the inherent variability in the dataset, exploratory analyses indicate reductions to the spatial and temporal extent of avoidance of the construction area by porpoises when sound mitigation is applied. Detections of harbor porpoises in the 0-5 and 5-10 km range were greatly reduced in 2016 (no sound mitigation) but not in 2019 (Double Big Bubble Curtain sound mitigation in place). Results should be interpreted with caution, as porpoise detections in the area decrease even before the start of deterrence and pile driving, likely due to other construction-related noise (increased vessel noise, sonar, anchoring, ...).

Avoidance of operational wind farms by seabirds was illustrated by investigating the distribution patterns of 156 GPS-tagged lesser black-backed gulls *Larus fuscus* from nearby breeding colonies during the pre-construction, construction and operational phases (Chapter 3). Interestingly, these results contradict earlier findings of attraction of lesser black-backed gulls to OWFs in Belgian waters, which can possibly be explained by differences in attraction and avoidance cues between adult breeding birds (this study) and, e.g., birds on migration or immature birds. Attraction to and avoidance of wind farms by seabirds is the result of multiple causes including visual disturbance induced by the turbines, the presence of offshore rest and foraging opportunities, and may in part also be explained by the absence of fisheries in Belgian wind farms. Further investigations into behavior are needed to obtain those insights in the habitat use that will elucidate the cause-effect relationships behind attraction and avoidance. Preliminary findings from the first monitoring survey of the full Belgian wind farm concession zone showed good numbers of northern gannet *Morus bassanus* (84 ind. km<sup>-2</sup>) and, higher densities of common guillemot *Uria aalge* and razorbill *Alca torda* inside the OWFs; the number of razorbills was even twice as high inside the OWFs compared to densities outside (4.59 versus 2.36 ind. km<sup>-2</sup>). These results are unexpected since these particular species are generally perceived to actively avoid OWFs across European waters. Future surveys will confirm whether this indicates a trend of habituation of seabirds to the presence of OWFs. Habituation may be positive for auks (razorbill, guillemot) but negative for gannets because their increased presence between wind turbines might lead to a higher collision-induced mortality.

Migrating songbirds are also at risk of collision with offshore wind turbines (Chapter 4). The intensity of songbird migration is especially high at night. This was confirmed by our continuous bird radar surveys in a Belgian OWF. When flying at

rotor height, these migrating birds are at risk of collision with turbine blades. This risk can increase when weather conditions deteriorate. Such deteriorating conditions can result in large numbers of possibly disoriented, weakened birds that fly at rotor height and thereby possibly to large numbers of bird collisions. An effective measure to reduce the number of collisions with wind turbines during intense migration events, is to temporarily idle turbines. OWFs in the Dutch Borssele area, adjacent to the Belgian wind farms, will have to idle turbines from 2023 onwards when the flux of birds exceeds 500 birds km<sup>-1</sup> hour<sup>-1</sup> at rotor height. Such events occurred 14 times during autumn 2019 (maximum of 995 bird tracks km<sup>-1</sup> hour<sup>-1</sup>) and did not occur in spring 2021 (maximum of 261 bird tracks km<sup>-1</sup> hour<sup>-1</sup>) at the study site in a Belgian OWF. Applying a collision risk model on the detected bird flux, a total estimated number of 682 songbird collisions would have been avoided if the turbines of all Belgian OWFs would have been idled during the 14 hours in autumn 2019 when the bird flux exceeded 500 bird tracks km<sup>-1</sup> hour<sup>-1</sup> at rotor height. The uncertainty of the collision risk model results and the fact that we do not exactly know which species were registered by the radar does not allow to assess the significance of the number of songbird collisions with wind turbines in the Belgian part of the North Sea. It is however unlikely that this has a significant effect at the population level. Whether this will still be the case for the cumulative effects of all planned wind farms in the (southern) North Sea so far remains unknown. This example shows that insights into patterns in habitat use in space and time will aid defining efficient and effective mitigation measures.

While wind farm-scale surveys for marine mammals and (sea)birds allow for demonstrating attraction and avoidance, this is much less the case for bottom-dwelling organisms. Based on data from a wind farm-scale survey of soft sediment epibenthos and fish (i.e., beam trawl tracks in between the turbines at ca 200 m distance), the first

relatively consistent, yet subtle signs of changes in the distribution of soft sediment epibenthos and fish species in Belgian OWFs could be identified only seven years after construction. Currently (i.e., > 10 years of construction), typical hard substrate-species such as blue mussel *Mytilus edulis*, Anthozoa, common starfish *Asterias rubens*, sea-urchin *Psammechinus miliaris*, hairy crab *Pilumnus hirtellus* and European seabass *Dicentrarchus labrax* are observed in higher densities inside OWFs, probably as a result of the expansion of the artificial reef effect into the soft sediments (Chapter 5). This led to significantly higher overall densities and biomass for epibenthos inside the farms, while for fish overall density was significantly lower. However, the species undergoing changes in density differed between OWFs. The wind farm-specificity of the aforementioned effects suggests that the environmental responses of soft sediment epibenthos and fish is likely to be site-specific, while the subtlety of the changes suggests that more targeted, small-scale surveys may be needed to determine the cause-effect relationships that drive the changes in distribution patterns.

Attraction of fish to the OWFs mainly takes place at the turbine-scale, as shown before for e.g., pouting and cod inhabiting the hard substrate habitat of the scour protection layers (SPLs). When investigated at appropriate spatial scales (< 50 m away from the turbine, including the SPL and the nearby sandy sediments) even soft sediment-dwelling flatfish proved to show attraction to the turbines (Chapter 6). Five different flatfish species and a total of 41 individuals were detected during 20 visual transect dives, with plaice *Pleuronectes platessa* having by far the most sightings (n = 31). Significantly more plaice were found in the SPL habitat compared to the surrounding sand (2.15 vs 0.52 ind. 100 m<sup>-2</sup>). The fact that this finding contradicts the absence of small-scale attraction to or even avoidance of hard substrates described in other studies, may be explained by the presence of sand patches in the less dense scour protection layer of the

investigated wind farm. All flatfish observed by the divers in the SPL were found on these sandy patches, which benefit the burrowing behavior of flatfish species.

Attractivity of the natural benthic habitat may also be enhanced in those OWFs where fisheries are excluded. This fisheries exclusion effect offers opportunities for benthic communities to recover from fisheries disturbance, likely enhancing densities, biomass and species richness. Short-term (i.e., 1 year after construction) artificial reef and fisheries exclusion effects on soft sediment macrobenthic assemblages were investigated in recently commissioned OWF, heterogenous both in terms of abiotic and biotic conditions (Chapter 7). A classification of the abiotic parameters into categorical groups, revealed the presence of three broader habitat types and associated macrobenthic assemblages. 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 within each habitat type during the operational phase. One assemblage was linked to a habitat characterized by fine, organically enriched sediments with substantial amounts of coarser material (fine gravel/granule fractions), which does not occur in the Belgian wind farms investigated before. Its very high abundances, diversity and a distinctive faunal composition composed of typical soft-sediment species in combination with hemi-sessile and tube-dwelling species, makes this habitat type ecologically valuable. Future monitoring within this assemblage might reveal new insights into OWF effects, and specifically – for the first time – into the fisheries exclusion effect on benthos recovery.

Attraction and avoidance may finally be detected at the microhabitat-scale, where particularly species interactions start playing an important role. Mussel belts, for example, a very prominent feature on the offshore wind turbine foundations worldwide, do provide secondary hard substrate habitat attractive to colonizing organisms. To investigate the habitat provision effect on attraction, we compared the species composition of the early (mussels not prevalent) and mature (mussels prevalent) subtidal colonizing communities at offshore wind turbine foundations (Chapter 8). A distinction was made between fauna living directly on the (artificial) primary hard substrate and that of the secondary hard substrate offered by the shells of the blue mussels. 47 species belonging to nine different phyla were identified. The main phyla present in the samples were molluscs, arthropods, annelids and bryozoans. 21 species were unique to the mussels and these were all sessile species. All bryozoan species were exclusively observed on the secondary substratum provided by the shells of the mussels. Our findings confirm the hypothesis that, by providing a secondary substratum for colonization by attached (i.e., sessile and hemi-sessile) epifauna, mussels counteract the impoverishment of species richness caused by the abundant presence of the plumose anemone *Metridium senile*, considered a space invader in mature artificial hard substratum communities in OWFs. The species assemblage found on these mussels is different from the one previously encountered on the piles and is in fact more similar to that on the scour protection. This may be due to the fact that the secondary substratum provided by the mussels differs in physical properties (e.g., microhabitat complexity) from the primary (vertical) substratum of the pile.

# CHAPTER 1

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## OFFSHORE RENEWABLE ENERGY DEVELOPMENT IN THE BELGIAN PART OF THE NORTH SEA – 2021

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### Abstract

With the completion of the Northwester 2 and Seamade projects in 2020, an installed capacity of 2.26 Gigawatt (GW), consisting of 399 offshore wind turbines, is operational in the Belgian part of the North Sea (BPNS). They are expected to produce an average of 8 TWh annually, which is around 10% of the total national electricity demand. An additional zone for 3.15 to 3.5 GW of offshore wind energy has been identified in the marine spatial plan 2020-2026. As “Blue Growth” matures to a sustainable blue economy, it has been tasked with ensuring the environmental sustainability of the natural capital of the oceans and seas (EU, 2021).

With 523 km<sup>2</sup> reserved and planned for offshore wind farms in Belgium, 344 km<sup>2</sup> in the adjacent Dutch Borssele zone, and 122 km<sup>2</sup> in the French Dunkerque zone, cumulative ecological impacts continue to be a major concern. These anticipated impacts, both positive and negative, triggered an environmental monitoring program focusing on various aspects of the marine ecosystem components, but also on the human appreciation of offshore wind farms. This introductory chapter provides an overview of the status of offshore renewable energy development in the BPNS.

### 1. Offshore wind energy development in Belgium

With the Royal Decree of 17 May 2004, a 264 km<sup>2</sup> area within the BPNS was reserved for the production of electricity from water, currents or wind. It is located between two major shipping routes: the north and south traffic separation schemes. In 2011, the zone was adjusted on its Northern and Southern side in order to ensure safe shipping traffic in the vicinity of the wind farms. After this adjustment the total surface of the area amounted to 238 km<sup>2</sup> (Fig. 1). A second area of 285 km<sup>2</sup> is reserved in the marine spatial plan that came in force on March 20<sup>th</sup>, 2020.

The European Directive 2001/77/EC on the promotion of electricity produced from renewable energy sources in the internal electricity market, imposes a target figure for the contribution of the production of electricity from renewable energy sources upon each Member State. For Belgium, this target figure is 13% of the total energy consumption, which must be achieved by the end of 2020. Offshore wind farms in the BPNS will make an important contribution to that goal.

On 31 December 2019, Belgium submitted a National Energy and Climate Plan to the European Commission which envisions



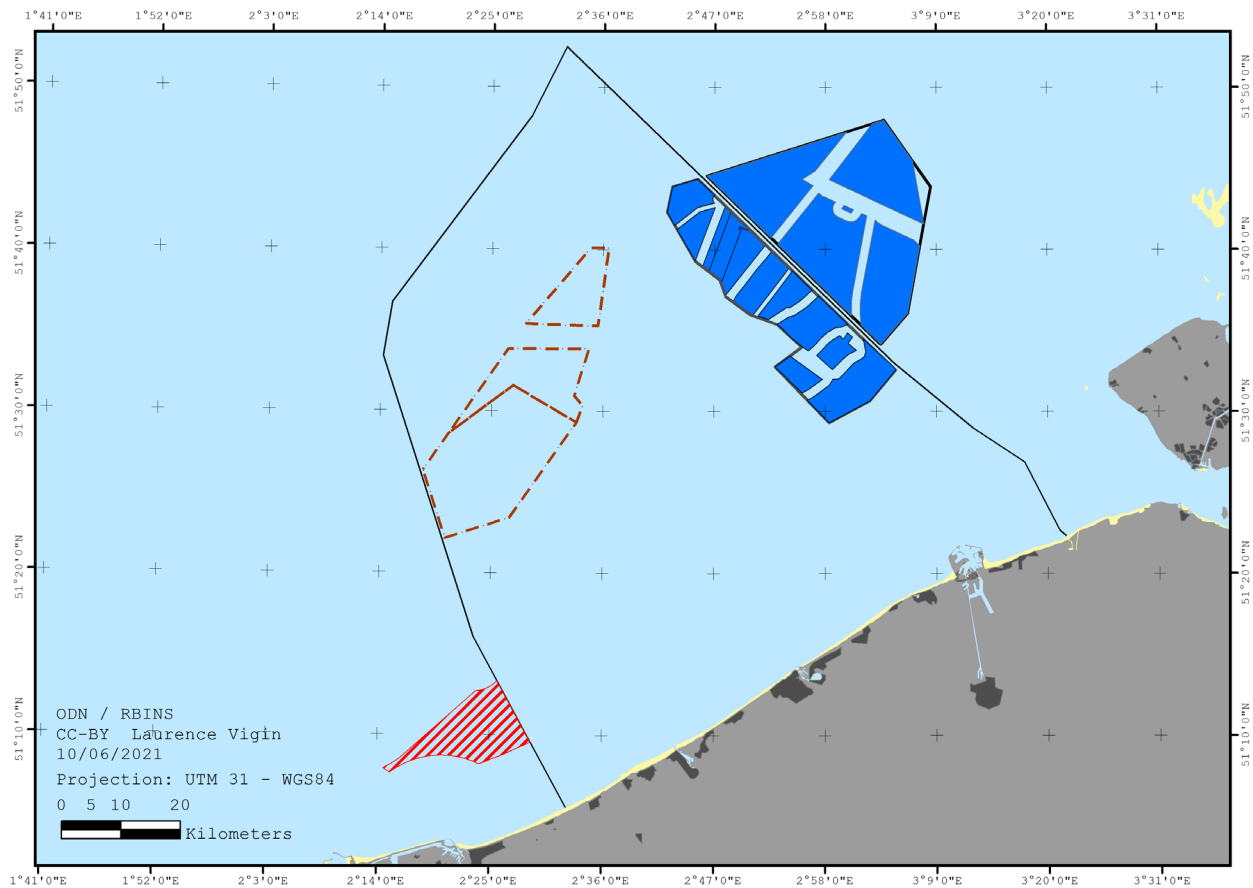
a target figure of 17.5% for the contribution of the production of electricity from renewable energy sources by 2030. This plan includes 4 GW of operational offshore wind.

Prior to installing a renewable energy project, a developer must obtain (1) a domain concession and (2) an environmental permit. Without an environmental permit, a project developer is not allowed to build and exploit a wind farm, even if a domain concession was granted.

When a project developer applies for an environmental permit an administrative procedure, mandatory by law, starts. This procedure has several steps, including a public consultation during which the public and other stakeholders can express any comments or objections based on the environmental impact study (EIS) that is set up by the project developer. Later on, during the permit

procedure, the Management Unit of the North Sea Mathematical Models (MUMM), a Scientific Service of the Operational Directorate Natural Environment (OD Nature) of the Royal Belgian Institute of Natural Sciences, gives advice on the acceptability of expected environmental impacts of the future project to the Minister responsible for the marine environment. MUMM’s advice includes an environmental impact assessment, based on the EIS. The Minister then grants or denies the environmental permit in a duly motivated decree.

At present, nine projects were granted a domain concession and an environmental permit (from South to North: Norther, C-Power, Rentel, Northwind, Seastar, Nobelwind, Belwind, Northwester II & Mermaid (Table 1; Fig. 1). On July 20<sup>th</sup> 2018, the Seastar and Mermaid projects were



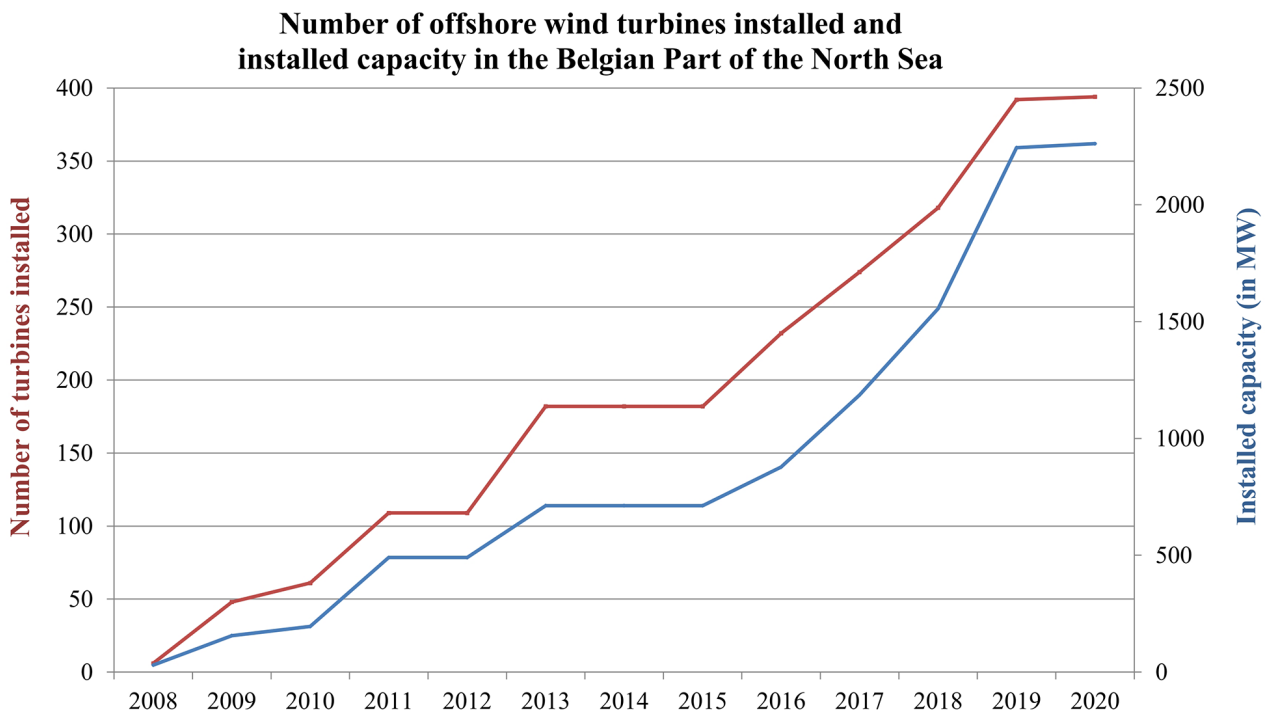
**Figure 1.** Current and planned zones for renewable energy in and around the Belgian Part of the North Sea with indications of wind farms that are operational (blue), the proposed Dunkerque offshore wind farm (shaded red area) and the new renewable energy zone as delimited in the marine spatial plan 2020-2026 (dashed lines).



merged and the resulting project was named Seamade NV. A little less than 400 wind turbines are operational in the Belgian part of the North Sea (Fig. 2). The entire first area has a capacity of 2.26 MW and can cover up to 10 % of the total electricity needs of Belgium or nearly 50 % of the electricity needs of all Belgian households. The capacity density of the first wind energy zone, defined as the ratio of the wind energy zone rated capacity to its ground area, is at 9.5 MW/km<sup>2</sup> among the highest in Europe which results in a higher levelized cost of electricity than other North Sea countries. The Belgian Offshore Platform, the association of investors and owners of wind farms in the BPNS, has recommended a density of 5 to 6 MW of installed capacity/km<sup>2</sup> for future developments in order to be able to realize maximum energy yields, and thereby reduce production costs. Over the last decade, installed capacity per turbine has gradually increased with extra-large monopiles (i.e., with a diameter larger than 7 m) becoming the dominant foundation type in our (shallow) waters (Fig. 3).

The environmental permit includes a number of terms and conditions intended to mitigate and/or minimize the impact of the project on the marine ecosystem. Furthermore, as required by law, the permit imposes an environmental monitoring programme to assess the effects of the project on the marine environment. Based on the results of the monitoring programme, and recent scientific insights or technical developments, permit conditions can be adjusted.

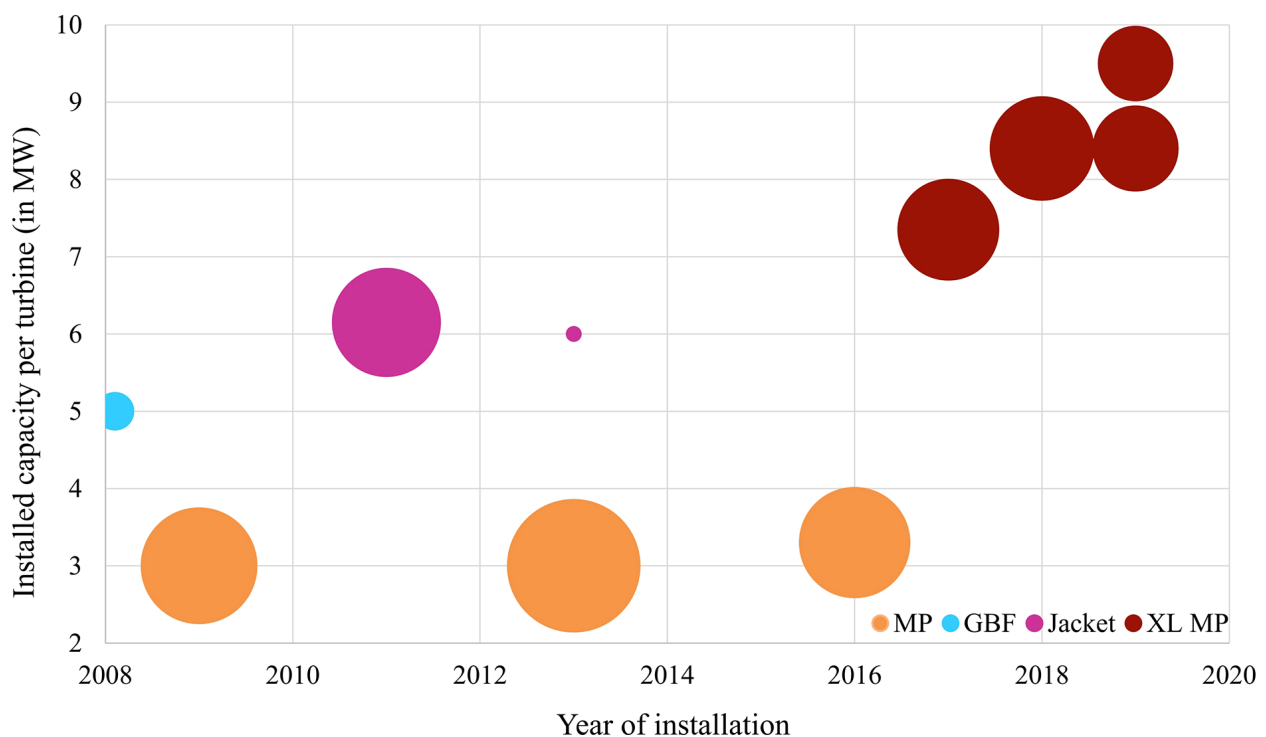
On 20 March 2020, the second marine spatial plan for the BPNS (Royal Decree of May 22<sup>nd</sup>, 2019 establishing the marine spatial planning for the period 2020 to 2026 in the Belgian sea-areas) came into force. This plan lays out principles, goals, objectives, a long-term vision and spatial policy choices for the management of the Belgian territorial sea and the Exclusive Economic Zone (EEZ) for the period 2020-2026. Management actions, indicators and targets addressing marine protected areas and the management of human uses including commercial fishing, offshore aquaculture, offshore renewable energy, shipping, dredging, sand



**Figure 2.** Number of offshore wind turbines installed and installed capacity in the Belgian Part of the North Sea since 2008.

**Table 1.** Overview of wind farms in the Belgian part of the North Sea.

Project	Number of turbines	Capacity (MW)	Total capacity (MW)	Operational since
Norther	44	8.4	370	2019
C-Power	phase 1	6	5	Phase 1: 2009
	phases 2 and 3	48	6.15	Phases 2 and 3: 2013
Rentel	42	7.35	309	2019
Northwind	72	3	216	2014
SeaMade	58	8.4	487	2020
Belwind	phase 1	55	3	Phase 1: 2011
	Alstom Demo project	1	6	Demo turbine: 2013
Nobelwind	50	3.3	165	2017
Northwester 2	23	9.5	219	2020



**Figure 3.** Overview of the timing, individual capacity and foundation type of offshore wind turbines installed in the Belgian Part of the North Sea since 2008. The size of the bubbles is proportional to the number of turbines installed per project of phase (see Table 1). Abbreviations: MP = monopile foundation; GBF = Gravity based foundation; Jacket = Jacket foundation; XL MP = monopile foundations exceeding approximately 7 m in diameter.

and gravel extraction, pipelines and cables, military activities, tourism and recreation, and scientific research are included. In this revision of the marine spatial plan, the Belgian federal government has delineated a second zone for renewable energy of 285 km<sup>2</sup> located at 35-40 km offshore (Fig. 1). This second zone would be suitable for an additional 3.15-3.5 GW of installed capacity. Storage of energy and grid reinforcement (see below) continue to be major hindrances to the further integration of renewables into the electricity grid and locations are foreseen for reinforcing the offshore electricity grid.

This second Belgian zone for marine renewable energy is partly located inside a designated Natura 2000 area. A targeted research programme was designed in order to determine whether and how renewable energy development is compatible with the conservation objectives for this Natura 2000 area. This programme commenced in 2019 and is expected to last four years.

## 2. WinMon.BE outreach event

18<sup>th</sup> of May 2021, the WinMon.BE programme organized an outreach event to share and discuss results from the monitoring programme. This symposium was hosted as a side event of the 52<sup>nd</sup> Liège Colloquium on Ocean Dynamics (Towards an understanding and assessment of human impact on coastal marine environments, 17<sup>th</sup>–21<sup>st</sup> of May 2021). This session was targeted at scientists, industry, managers and policy makers. Because of the pandemic safety measures, the event was hosted online. 223 participants joined from 18 nationalities, representing research, industry, consulting, policy and environmental NGOs.

Lessons learned from the WinMon.BE programme were presented and followed by a panel discussion. The presentations addressed key features of the WinMon.BE philosophy, being the importance of long-term data collection, adaptive management and elucidating cause-effect relationships. During the discussion, which was titled

‘WinMon.BE: ready for accommodating the future of OWFs?’, special attention was paid to the science-management-policy nexus as how to best achieve an environment-friendly implementation and an ecosystem-based management of offshore renewables. The main topics of the questions to the panel and the presenters were the presence of plumes of suspended particulate matter (SPM) in the wake of turbines; the difference in the faunal community found on artificial hard substrates compared to natural gravel beds and how nature inclusive designs can contribute to the restoration of natural gravel beds (e.g., scour protection layers of future wind farms could be designed in such way that they resemble natural gravel bed habitat); organic enrichment of the soft sediment surrounding the turbines; the effects of piling and possible alternative techniques to install turbine foundations with less excessive underwater noise; multi-use of OWF areas (e.g., Belgian multi-use case study on offshore wind farms, nature conservation and (passive) aquaculture); the effects on seabird densities and possible habituation of seabirds to wind farms and the use of individual-based models to assess seabird effects.

## 3. Multi-use in Belgian offshore wind farms

Rapid development of offshore wind in the Southern North Sea has led to conflict with other maritime users (shipping, fisheries...) as historically these activities have been excluded from wind farms in order to minimize the risk to wind farm operation and infrastructure. This exclusion does however offer opportunities for other marine users who had previously avoided Belgian waters due to the high intensity of shipping. The first Belgian offshore energy zone was thus reserved for the production of electricity not only from wind but also from water and currents, and wind farm operators were obliged to facilitate the development of aquaculture in their concessions. In order to stimulate the development of marine energy in Belgium, the Mermaid project obtained its

domain concession license only on condition that a certain amount of energy would be generated from waves as well as from wind. However, wave energy developments have not reached the anticipated level of commercial deployment and although the environmental permit of the Mermaid (now Seamade) project allows for an installed capacity of 20 MW of wave energy converters (WEC) no actual WEC deployment is foreseen in the immediate future.

In 2022, the Blue Accelerator at Ostend will deploy a floating solar power production installation as part of the European SCalable Offshore Renewable Energy Sources (EU-SCORES) project. This project envisions a full-scale demonstration of a 3MW offshore solar photovoltaic system by Oceans of

Energy off the Belgian coast co-located with a bottom fixed windfarm.

Other forms of multi-use being tested in Belgian wind farms include the cultivation of seaweed and European flat oyster (*Ostrea edulis*) combined with the restoration of flat oyster reefs at the Belwind wind farm as part of the EU Horizon 2020 project UNITED (Fig. 4).

It is anticipated that in the second Belgian zone for marine renewable energy both aquaculture and fisheries with passive gears will be allowed. It is also partly co-located with a nature conservation zone (see above). Finally, individual projects are expected to make use of a shared platform for the transmission of electricity to the shore (Elia-MoG-II).



**Figure 4.** Installation of ‘oyster tables’ to facilitate restoration of European flat oyster (*Ostrea edulis*) reefs in the Belwind wind farm as part of the EU Horizon 2020 project UNITED (© Annelies M. Declercq).



## References

EU. 2021. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on a New Approach for a Sustainable Blue Economy in the EU Transforming the EU's Blue Economy for a Sustainable Future*. COM/2021/240 final.

World Energy Council Netherlands. 2017. *Bringing North Sea Energy Ashore Efficiently*, 59 p.





# CHAPTER 2

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## EFFECTS OF THE USE OF NOISE-MITIGATION DURING OFFSHORE PILE DRIVING ON HARBOUR PORPOISE (*PHOCOENA PHOCOENA*)

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### Abstract

In recent years, noise-mitigation technology became more efficient and noise levels during pile driving were reduced significantly. Using passive acoustic monitoring (PAM) datasets from 2016 (Nobelwind construction – no noise mitigation) and 2019 (Northwester 2 and SeaMade construction – Double Big Bubble Curtain) we analyse whether noise mitigation measures applied during the construction of offshore wind farms influenced the likelihood of detecting harbour porpoise (*Phocoena phocoena*) during pile driving in the Belgian part of the North Sea (BPNS). Exploratory analyses indicate reductions to the spatial and temporal extent of avoidance of the construction area by porpoise when noise mitigation is applied. Without noise mitigation, mean detection rates of porpoises reduced up to 15-20 km from the pile driving location. With noise mitigation however, mean detection rates of porpoises reduced to a lesser extent and this reduction mainly took place at 0-10 km from the pile driving.

### 1. Introduction

The harbour porpoise (*Phocoena phocoena*) is by far the most common marine mammal in the BPNS, after several years of virtual absence (Haelters *et al.* 2011). The estimation of the harbour porpoise density ranges from 0.05 to 1.03 individuals per km<sup>2</sup>, leading to an abundance of 186 to 3697 animals (Haelters *et al.* 2011). The animals show a distinct spatial and temporal distribution in Belgian waters with relatively high densities from January to April and lower numbers from May to August, plus they tend to stay in more northerly and offshore waters (Haelters *et al.* 2011, 2016). In the Greater North Sea, the harbour porpoise is considered vulnerable because of high bycatch levels (Kaschner 2003) and its exposure to increasing levels of noise pollution ranging from continuous shipping noise (Wisniewska *et al.* 2018) to impulsive noise from, e.g., pile driving (Brandt *et al.* 2018), and seismic surveys (Van Beest *et al.* 2018). Nonetheless, the species is protected by both national (Belgian Government 2001) and EU law (EU 1992), and consequently deliberate actions of killing, disturbing, injuring, and habitat deterioration are prohibited throughout its

range. In the absence of mitigating measures, the high levels of impulsive underwater sound generated during pile driving can potentially kill, injure or disturb marine mammals depending on their distances from the source (see, e.g., Carstensen *et al.* 2006; Bailey *et al.* 2010). Some studies have even indicated potential negative cumulative impacts on the harbour porpoise population of wind farm development over the next decade in the North Sea (de Jong *et al.* 2019). Concerns over the possible impact of high intensity impulsive sound generated during the construction of offshore wind farms on harbour porpoise have been a driving force in determining national impulsive noise regulations in North Sea countries with Germany, the Netherlands and Belgium all formulating different, but similar, underwater sound thresholds (see Rumes *et al.* 2016 for a comparison). In Belgium, concern

over the high levels of underwater noise being generated during pile driving operations for the building of the first offshore wind farms (Norro *et al.* 2010, 2013) and the observed large-scale avoidance of the construction zone by porpoises (Haelters *et al.* 2011) led to the formulation of a threshold for impulsive underwater sound in the BNS at 185 dB re 1  $\mu$ Pa (Sound Pressure Level, zero to peak) at 750 m from the source (Anonymous 2012). Offshore wind farm developers in the BPNS have applied several noise mitigation systems with incremental progress in complying with this threshold (Rumes & Degraer 2020). In this chapter, we aim to determine whether the reduced levels of impulsive underwater sound during construction are likely to have influenced the observed spatial and temporal extent of harbour porpoise avoidance.



**Figure 1.** Timing and location of pile driving events in the Belgian part of the North Sea (period 2009-2020, data RBINS). From 2013 onwards, a seasonal pile driving ban from January 1<sup>st</sup> to April 30<sup>th</sup> was enforced. From 2017 onwards developers were obliged to use noise mitigation measures that limit the transmission of noise pollution to the marine environment.

## 2. Material and methods

### 2.1. Study area

The Southern bight of the North Sea includes the Belgian continental shelf or BPNS with a surface of approximately 3457 km<sup>2</sup>. The BPNS only covers 0.5% of the entire area of the North Sea. The Belgian continental shelf is characterized by shallow waters with a maximum depth of 45 m and a complex system of sandbanks. In the western part of the BPNS, a 238 km<sup>2</sup> zone has been designated for renewable energy. Between 2009 and 2020, nine projects have constructed wind farms in this part of the BPNS (Fig. 1).

Over time, the terms and conditions in the environmental permits that were intended to minimize and/or mitigate the impact of offshore wind farm construction on marine mammals changed gradually as monitoring information became available (see Rumes & Degraer 2020 for an overview). Initial permit conditions were aimed at preventing near-field injury to individual animals and included the use of an acoustic deterrent device (ADD) as well as a prohibition on starting pile driving if a marine mammal was observed in the vicinity of the construction zone. Progressive insight in the potential population consequences of far-field behavioural disturbance resulting from exposure to excessive levels of impulsive underwater sound led to the formulation of further permit conditions. These included a seasonal pile driving ban from January 1<sup>st</sup> to April 30<sup>th</sup>, a period with high local porpoise densities, and an obligation to use noise mitigation measures that limit the transmission of noise pollution to the marine environment.

For this study we focused on three wind farms: Nobelwind, Northwester 2 and SeaMade. At Nobelwind, pile driving without the use of noise mitigation measures took place in 2016. Both Northwester 2 and SeaMade used a similar noise mitigation set up in 2019, namely a double big bubble curtain (DBBC) albeit with differing levels of success. A DBBC consists of two rings of perforated pipes positioned on the sea

floor around the foundation to be piled. Compressors located on the construction vessel or on a separate platform feed air into the pipes. The air passes into the water column by regularly arranged holes. Freely rising bubbles form a large curtain around the entire structure, even during running tides, thus shielding the environment from the noise source (Koschinski & Lüdemann 2013). Northwester 2 was the only project to successfully use noise mitigation measures that limit the transmission of noise pollution to the marine environment to the extent that the in-situ measured sound level (SPL<sub>z-p</sub>) remained below the national threshold (Norro 2020).

Nobelwind NV obtained an environmental permit on 7 October 2015 to build and operate its offshore wind farm. The windfarm was built at a distance of 47 km from the coastline at the Lodewijk bank. The total capacity of this wind farm of 165 MW is provided by 50 turbines, each with a capacity of 3.3 MW. Pile driving for the Nobelwind wind farm comprised 51 piling events (50 turbines and one offshore high voltage station) from May 16<sup>th</sup> up to September 22<sup>nd</sup> 2016. Pile diameter ranged from 4.5 to 6.8 m, penetration depth lay between 29 to 39 m and total piling time varied between 1 h 27 min and 4 h 31 min. All piles were installed using an S-1400 Hydraulic Hammer (maximum energy per pile 1254 ± 114 kJ). The contractor was legally obliged to turn on an acoustic deterrent device one hour before the start of piling. Construction logs show that on average the acoustic deterrent device was switch on much earlier in casu 150 minutes (Rumes & Degraer 2020).

The second wind farm, NV Northwester 2, is located at 51 km off the coast of Zeebrugge to the northwest of Nobelwind, was granted an environmental permit on 18 December 2015. The total capacity of this wind farm of 219 MW is provided by 23 turbines, each with a capacity of 9.5 MW. Pile driving for the Northwester 2 wind farm comprised 24 piling events (23 turbines and one offshore high

voltage station) from July 29<sup>th</sup> up to November 13<sup>th</sup> 2019. Pile diameter ranged from 7.4 to 8.0 m, penetration depth lay between 29 to 39 m and total piling time varied between 1 h 36 min and 3 h 40 min. All piles were installed using an S-3000 Hydraulic Hammer (maximum energy per pile  $1942 \pm 406$  kJ). The contractor was legally obliged to turn on an acoustic deterrent device 30 minutes before the start of piling. Construction logs show that on average the acoustic deterrent device was started 60 minutes before the start of piling (Rumes & Degraer 2020).

The third wind farm, SeaMade, is comprised of two separate sections located at 40 and 54 km off the coast of Zeebrugge, and was granted an environmental permit on 13 April 2015. The total capacity of this wind farm of 487 MW is provided by 58 turbines, each with a capacity of 8.4 MW. Pile driving for the Seamade wind farm comprised 60 piling events (58 turbines and two offshore high voltage stations) from September 8<sup>th</sup> up to January 2<sup>nd</sup> 2020. Pile diameter ranged from 7.5 to 8.0 m, penetration depth lay between 27 to 41 m and total piling time varied between 1 h 5 min and 3 h 26 min. All piles were installed using an S-4000 Hydraulic Hammer (maximum energy per pile  $1930 \pm 423$  kJ). The contractor was legally obliged to turn on an acoustic deterrent device 30 minutes before the start of piling. Construction logs show that on average the acoustic deterrent device was started 40 minutes before the start of piling (Rumes & Degraer 2020).

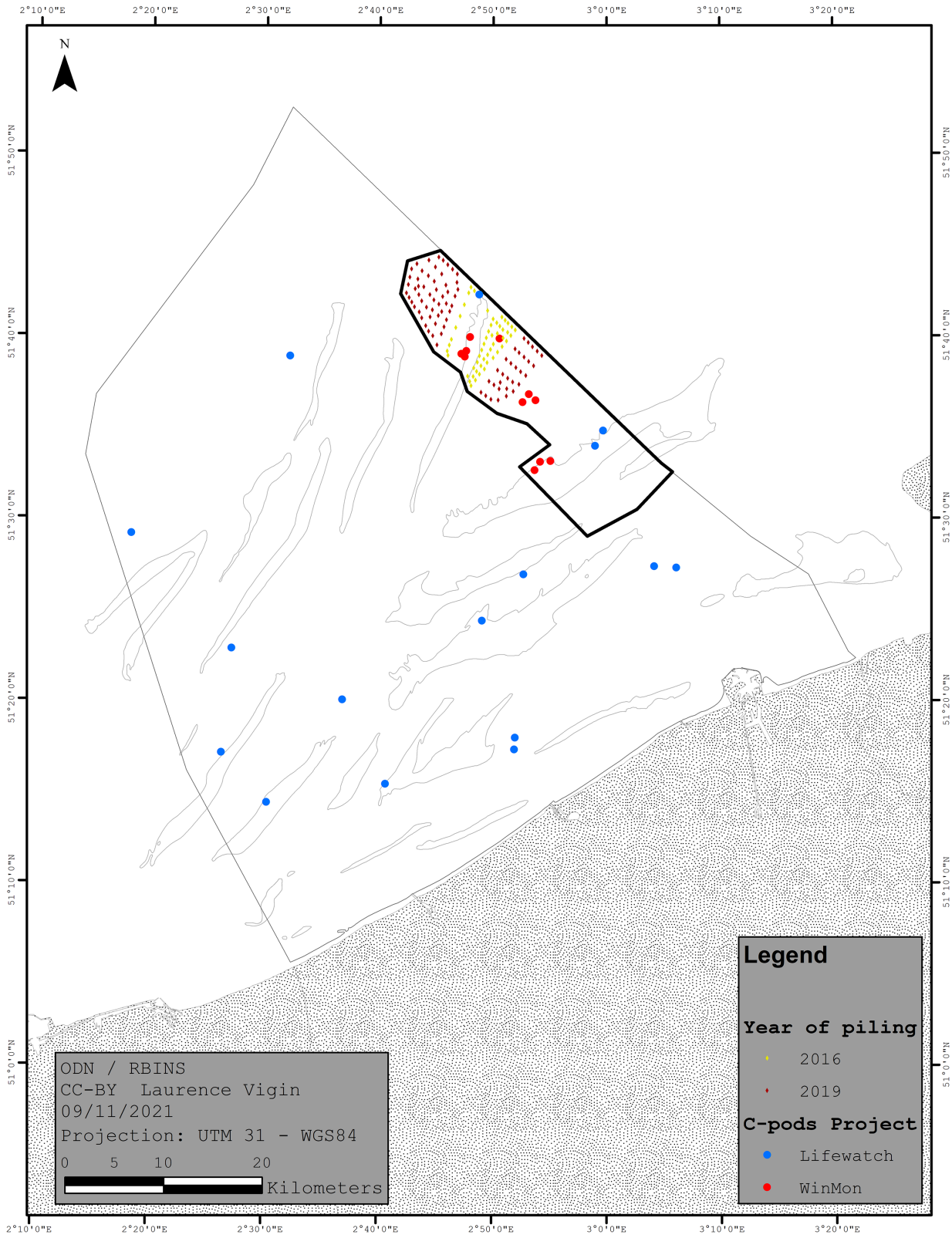
## 2.2. Study set up

Echolocation is likely the most important sensory perception for harbour porpoises and they have been shown to use their echolocation system almost continuously (Akamatsu *et al.* 2007; Wisniewska *et al.* 2016). This allows correlation between detection rates of porpoise clicks by passive acoustic monitoring devices and porpoise density in a marine area. Passive acoustic monitoring of porpoises was conducted using the Continuous Porpoise Detector (C-PoD, further indicated as PoD).

PoDs consist of a hydrophone, a processor, batteries and a digital timing and logging system. They continuously monitor sounds between 20 kHz and 160 kHz, and can detect all odontocetes except sperm whales (*Physeter macrocephalus*). A PoD does not record sound itself, but compresses data, generating a raw file with for each click characteristics such as time of occurrence, duration, dominant frequency, bandwidth and sound pressure level. Using dedicated software (CPOD.exe; Tregenza 2014), the raw file can be objectively analysed to find click trains and to classify these into trains produced by odontocetes and trains that originate from other sources such as boat SONAR. Distinction can be made between harbour porpoises, a species producing narrow-band, high frequency clicks, and dolphins, producing more broadband clicks with a lower frequency. The maximum detection range for porpoises is approximately 400 metres. PoDs have autonomy of up to 200 days ([www.chelonia.co.uk](http://www.chelonia.co.uk)). As porpoise click sounds are emitted in frontal direction with a beam angle of 16.5° maximum (Au *et al.* 1999), PoDs are only able to detect porpoises if they are facing towards the hydrophone.

For this study, we used data from PoDs deployed at 27 locations in the BPNS (Fig. 2): 11 of which were specifically deployed for this study and the other 16 forming part of the VLIZ EU Lifewatch observatory (Flanders Marine Institute 2015). PoD locations need to be visited every 3-4 months to replace the batteries and memory card. This wasn't always possible due to logistical issues (incl. COVID-19) leading to gaps in the dataset (see below). In addition, between 2016 and 2019, certain mooring locations were changed in function of ongoing construction activities. To increase the robustness of our dataset, mooring locations were divided into range classes: 0-5 km, 5-10 km, 10-15 km, 15-20 km and > 20 km from the individual piling events using the R package geosphere version 1.5.10 (Hijmans 2019).





**Figure 2.** Location of selected porpoise detectors and pile driving events.

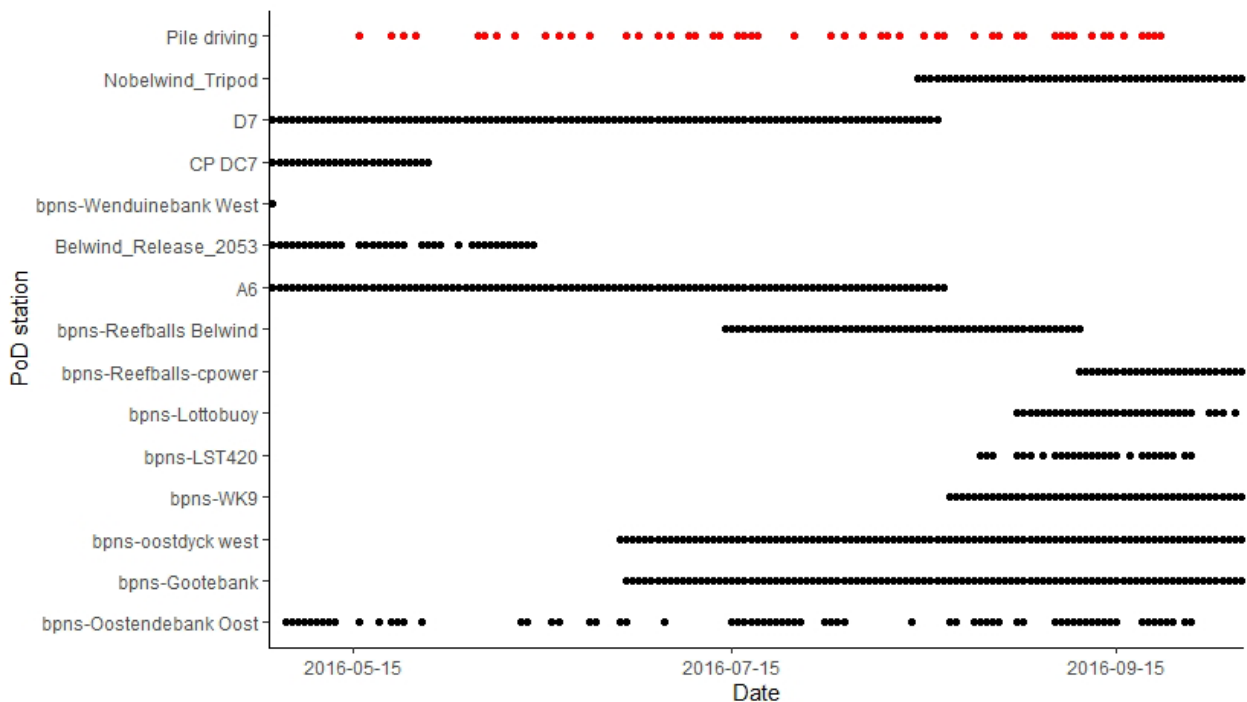
### 2.3. Data selection and dataset preparation

For the 2016 and 2019 pile driving period, PoD data (merged high and moderate quality click train detections) were downloaded from the Lifewatch observatory (Flanders Marine Institute 2021). The selected PoD data ranged from May 2<sup>nd</sup> 2016 to October 6<sup>th</sup> 2016 (Nobelwind) and the 14<sup>th</sup> of July 2019 to the 16<sup>th</sup> of January 2020 (Northwester 2 and SeaMade), and included a 14-day window pre- and post-pile driving was included. As between September 8<sup>th</sup> and November 13<sup>th</sup> 2019, pile driving activities for Northwester 2 and SeaMade overlapped, and as both projects used similar noise mitigation technology, data from both projects was combined. Detections were aggregated per hour to Detection Positive Hours (i.e., 0/1; DPH). We only used data where the PoD recorded a full hour (60 minutes). When minutes exceed the maximum number of clicks per minute (4096), minutes are lost. As in Brandt *et al* (2016), a maximum of two lost minutes were allowed per hour.

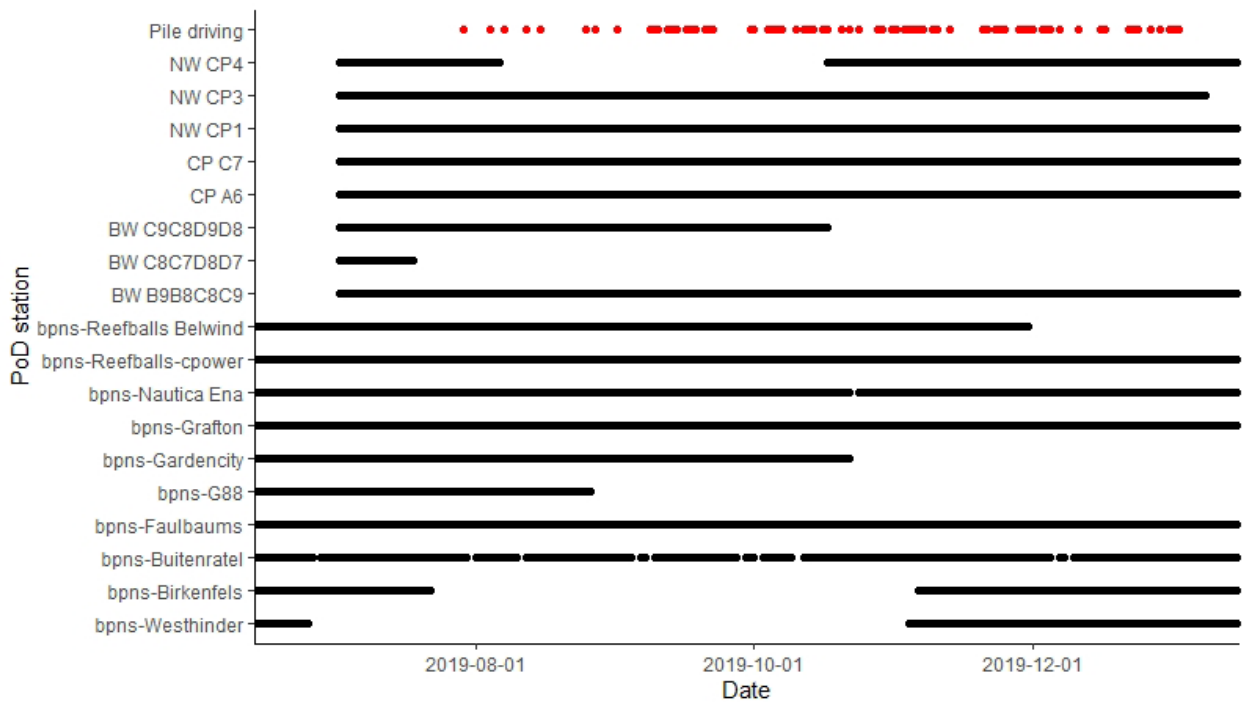
At least 30 minutes before pile driving an ADD is to be activated in order to deter porpoises from the immediate vicinity of the

construction site and to protect them from the acute effects of construction noise. However, due to operational uncertainties, the actual interval between ADD activation and the start of pile driving is quite variable (Rumes & Degraer 2020) and for these analyses, the start of pile driving was provided by the developers in daily reports on piling activities. Here, the start the activation of the ADD was considered the onset of acoustic disturbance, with the end of pile driving being considered as the end of acoustic disturbance. To align the (per hour) DPH information on detections with the (per minute) information on acoustic disturbance, the latter was rounded to the nearest hour, and for each hour the following information was generated: time since acoustic disturbance in hours and location of the most recent disturbance. We calculated the minimum time since acoustic disturbance (in hours) per PoD station and per hour and combined it with the information on the distance to the individual piling events.

The PoD network was expanded between 2016 and 2019 resulting in an increase of available stations from 13 to 18, Figs 3-4).



**Figure 3.** Location of selected porpoise detectors and timing of pile driving events in 2016.



**Figure 4.** Location of selected porpoise detectors and timing of pile driving events in 2019.

#### 2.4. Exploratory statistical analysis

Plots were used to visualise porpoise detections by phase and distance. Mean detection-positive hours/hour ( $\bar{x}$  dph/h) with standard deviation (SD) and standard error (se) were calculated for three phases of a piling event (Impact (during acoustic deterrence or pile driving: hours since disturbance 0, Aftermath (shortly after pile driving: hours since disturbance 1-6), Recovery (at least two days after pile driving: hours since disturbance 48-96) and by distance to the construction site for both projects (0-5 km, 5-10 km, 10-15 km, 15-20 km and > 20 km). The use of a Baseline phase (hours before disturbance 48-24) was considered but had to be abandoned given the limited time between pile driving events.

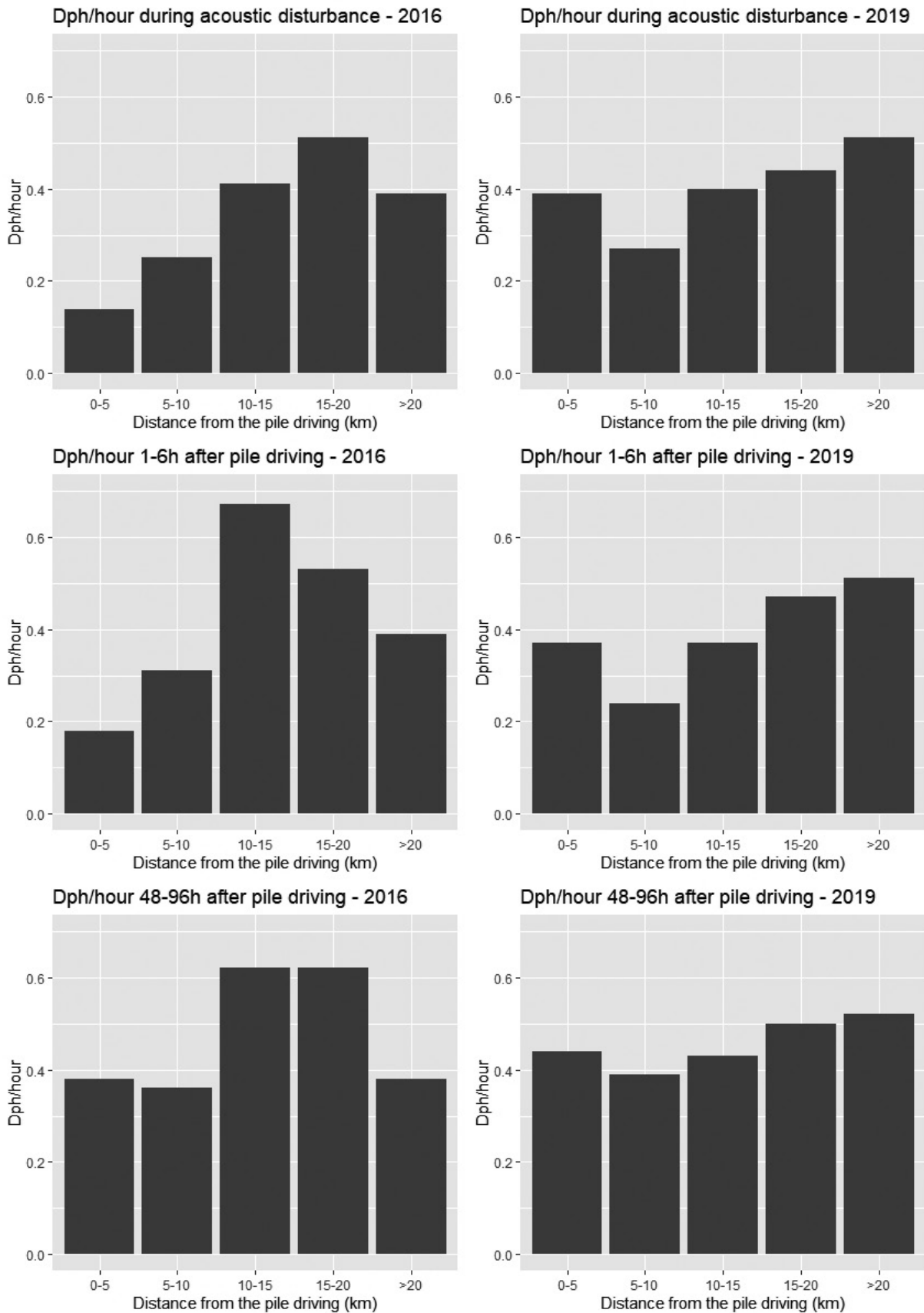
The hourly POD data will later be used to develop a generalized linear model including both piling- and noise-related variables (to account for noise exposure and applied mitigation), time-related variables (to account for temporal autocorrelation and inherent temporal patterns such as seasonality).

All data analyses were performed in R version 3.6.1 (R Core Team 2019).

### 3. Results

In 2016, at relatively short distances to the pile driving (0-5 km), mean detection rates were 63% and 53% lower during acoustic disturbance (Impact) and immediately after (Aftermath) respectively, compared to a baseline of 48-96 hours after pile driving (Recovery). With increasingly higher distances from pile driving these differences became smaller (e.g., ~30% reduction during the Impact and Aftermath phases at 5-10 km) (Table 1; Fig. 5).

In contrast, in 2019, at relatively short distances to the pile driving (0-5 km and 5-10 km), mean detection rates during pile driving decreased less during the acoustic disturbance (11% and 31% respectively) compared to the Recovery phase. At larger distances from the pile driving (from 10-15 km onwards) differences in mean detection rates were



**Figure 5.** Mean detection-positive hours/hour ( $\bar{\sigma}$  dph/h) for three phases of a pile driving event (Impact – top, Aftermath - middle, and Recovery - bottom) by distance to the construction site (0-5 km, 5-10 km, 10-15 km, 15-20 km and > 20 km) for pile driving without (2016) and with effective noise mitigation systems (2019).

**Table 1.** 2016 and 2019: Relative differences (%) in Mean detection-positive hours/hour for five distance classes over between Impact (during acoustic deterrence or pile driving: hours since disturbance 0), aftermath (shortly after pile driving: hours since disturbance 1-6), and recovery (at least two days after pile driving: hours since disturbance 48-96). Differences exceeding 30% are indicated in bold.

Year	Phase	0-5 km	5-10 km	10-15 km	15-20 km	> 20 km
2016	Impact – Aftermath	22.2	19.4	<b>38.8</b>	3.8	0.0
	Impact - Recovery	63.2	30.6	33.9	17.7	-2.6
	Aftermath – Recovery	<b>52.6</b>	13.9	-8.1	14.5	-2.6
2019	Impact – Aftermath	-5.4	-12.5	-8.1	6.4	0.0
	Impact - Recovery	11.4	<b>30.8</b>	7.0	12.0	1.9
	Aftermath – Recovery	15.9	<b>38.5</b>	14.0	6.0	0.0

relatively small (less than 15%) over the entire period.

In both years, the furthest distance class (>20 km) showed no changes in mean detection rates between the different time periods. If we compare between years, detections in the furthest distance class (> 20 km) were ~25% lower in 2016 than in 2019. In the vicinity of the pile driving (0-5 km) this difference becomes even more pronounced with 64% (during acoustic disturbance) and 51% (in the first six hours after pile driving) less detections when no noise mitigation was used.

## 4. Discussion

### 4.1. Spatial and temporal extent of porpoise displacement during pile driving

To meet the EU objective of reaching net-zero greenhouse gas emissions by 2050, offshore wind capacity in the North Sea should increase to a total installed capacity of at least 150 GW in the next thirty years (North Seas Energy Cooperation 2020). In Belgian waters, the installed capacity of offshore wind farms is expected to triple in the next ten years which will require the installation of hundreds of turbines with a construction period likely lasting multiple years. Mitigation measures are formulated to reduce the impact of offshore wind farms construction on marine mammals (and other

marine life), but these are considered onerous by developers as they increase project cost both directly (i.e., the cost of the mitigation measures) and indirectly (by increasing construction time) (Koschinski & Lüdemann 2013). In this chapter, we explored how the use of these noise mitigation systems, which results in reduced levels of impulsive underwater sound during construction, influenced the spatial and temporal extent of harbour porpoise avoidance of the construction sites.

Our results show a relative reduction in avoidance of porpoise at short to middle distances to the pile driving, both during the acoustic disturbance (use of acoustic deterrent devices and pile driving) and in the immediate aftermath thereof. Without noise mitigation, mean detection rates of porpoises reduced in all intervals up to 15-20 km from the pile driving, confirming what was previously observed using aerial survey data, where decreased porpoise densities were observed up to 20 km from the piling event (Haelters *et al.* 2013). With noise mitigation however, mean detection rates of porpoises reduced to a lesser extent and this reduction mainly took place at 0-10 km from the pile driving. This is in line with a study in German waters which found the effects of unmitigated pile driving on porpoise to reach much farther (26 km [s.e.: 22-30 km]) than those of mitigated pile driving (11 km [s.e.: 10-12 km]) (Rose *et al.* 2019). However,



the same study also indicated a lower limit to the effectiveness of noise mitigation stating that, all other aspects remaining equal, further improvements in noise mitigation did not result in a further decrease in the displacement range and duration for porpoises due to piling noise. This may be due to (a combination of) a stereotypical escape distance, the displacement effect of the acoustic deterrent devices, other construction-related noise, cumulative effects due to increasingly tight piling sequences, and local habitat characteristics at different offshore wind farm areas influencing porpoises' tolerance of disturbance (Rose *et al.* 2019). Nonetheless, current noise mitigation efforts have reduced the number of harbour porpoises responding to pile driving noise by ~75% (Rose *et al.* 2019; this study), demonstrating the role that noise mitigation can have in decreasing the likelihood of offshore wind farm development in the North Sea causing negative cumulative impacts at the porpoise population scale (de Jong *et al.* 2019).

#### 4.2. Effects of exposure to elevated levels of underwater sound

Elevated levels of underwater sound can affect harbour porpoises in several ways ranging from injury and death to discomfort and the masking of communication. Harbour porpoises are considered particularly sensitive to underwater noise (Tougaard *et al.* 2015) and will temporarily vacate too noisy areas even if these are otherwise suitable (Culik *et al.* 2000). The fact that no porpoises

were observed during the obligatory marine mammal surveys prior to pile driving may lead one to suspect that they completely avoid the construction zone during the construction work (Rumes & Degraer 2020). However, as noted previously (Rumes *et al.* 2017), even during pile driving, harbour porpoises are not completely absent from sites in the vicinity of pile driving. Lacking information on the movement on individual porpoises, the amount of underwater sound these animals are exposed to remains unclear. Detections in the vicinity of the construction zone can be due to both the continued presence of animals which tolerate higher levels of underwater sound and animals which are moving away from the sound source. A future comparison of the proportion of feeding buzzes to total porpoise click trains (*sensu* Nuuttila 2013; Zein *et al.* 2019) during and after acoustic disturbance can provide more information on their behavior during acoustic disturbance.

#### Acknowledgements

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#### References

- Anonymous, 2012. *Omschrijving van Goede Milieutoestand en vaststelling van Milieudoelen voor de Belgische mariene wateren. Kaderrichtlijn Mariene Strategie – Art 9 & 10*. BMM, Federale Overheidsdienst Volksgezondheid, Veiligheid van de Voedselketen en Leefmilieu, Brussel, België. 34 pp.
- Au, W.W.L., Kastelein, R.A., Rippe, T. & Schooneman, N.M. 1999. Transmission beam pattern and echolocation signals of a harbor porpoise (*Phocoena phocoena*). *The Journal of the Acoustical Society of America* 106 (6): 3699-3705.
- Akamatsu, T., Teilmann, J., Miller, L.A., Tougaard, J., Dietz, R., Wang, D., Wang, K., Siebert, U. & Naito, Y. 2007. Comparison of echolocation behaviour between coastal and riverine porpoises. *Deep Sea Research Part II: Topical studies in Oceanography* 54 (3): 290-297. <https://doi.org/10.1109/UT.2007.370755>

- Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G. & Thompson, P.M. 2010. Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. *Marine Pollution Bulletin* 60: 888-897. <https://doi.org/10.1016/j.marpolbul.2010.01.003>
- Brandt, M., Dragon, A., Diederichs, A., Schubert, A., Kosarev, V., Nehls, G., Wahl, V., Michalik, A., Braasch, A., Hinz, C., Ketzner, C., Todeskino, D., Gauger, M., Laczny, M. & Piper, W. 2016. *Effects of Offshore Pile Driving on Harbour Porpoise Abundance in the German Bight: Assessment of Noise Effects*. Report by BioConsult SH, IBL Umweltplanung GmbH, and Institute of Applied Ecology (IfAO). pp. 262.
- Brandt, M.J., Dragon, A.C., Diederichs, A., Bellmann, M.A., Wahl, V., Piper, W., Nabe-Nielsen, J. & Nehls, G. 2018. Disturbance of harbour porpoises during construction of the first seven offshore wind farms in Germany. *Marine Ecology Progress Series* 596 213-232. <https://doi.org/10.3354/meps12560>
- Belgian Government. 2001. Koninklijk besluit van 21 december 2001 betreffende de soortenbescherming in de zeegebieden onder de rechtsbevoegdheid van België. *Belgisch Staatsblad*. 14.02.2002, Ed. 3: 5568-5577.
- Carstensen, J., Henriksen, O.D. & Teilmann, J. 2006. Impacts on harbour porpoises from offshore wind farm construction: acoustic monitoring of echolocation activity using porpoise detectors (T-PODs). *Marine Ecology Progress Series* 321 295-308. <https://doi.org/10.3354/MEPS321295>
- Culik, B.M., Koschinski, S., Tregenza, N. & Ellis, G. 2000. Reactions of harbour porpoises (*Phocoena phocoena*) and herring (*Clupea harengus*) to acoustic alarms. *Marine Ecology Progress Series* 211: 255-260. <https://doi.org/10.3354/meps211255>
- de Jong, C.A.F., Heinis, F., von Benda-Beckmann, A.M. & Binnerts, B. 2019. *Testing CEAF in SEANSE case studies - Impact of piling for wind farms on North Sea harbour porpoise population*. TNO, Den Haag. 36 pp.
- European Union. 1992. Council Directive 92/43/EEC of 21 May 1992. Official Journal of the European Communities 35: 7-51
- Flanders Marine Institute (VLIZ) 2021. *LifeWatch observatory data: permanent Cetacean passive acoustic sensor network in the Belgian part of the North Sea*. Marine Data Archive. <https://doi.org/10.14284/447>
- Haelters, J., Kerckhof, F., Vigin, L. & Degraer, S. 2011. Offshore wind farm impact assessment: monitoring of marine mammals during 2010. *Offshore Wind Farms in the Belgian Part of the North Sea: Selected Findings from the Baseline and Targeted Monitoring*: 131-146.
- Haelters, J., Debusschere, E., Botteldooren, D., Dulière, V., Hostens, K., Norro, A., Vandendriessche, S., Vigin, L., Vincx, M. & Degraer, S. 2013. The effects of pile driving on marine mammals and fish in belgian waters. In: Degraer, S., Brabant, R. & Rumes B. (eds) *Environmental Impacts of Offshore Wind Farms in the Belgian Part of The North Sea*: 71-77. Royal Belgian Institute of Natural Sciences, Brussels.
- Haelters, J., Rumes, B., Vanaverbeke, J. & Degraer, S. 2016. Seasonal and interannual patterns in the presence of harbour porpoises (*Phocoena phocoena*) in Belgian waters from 2010 to 2015 as derived from passive acoustic monitoring. In: Degraer, S. et al. (ed.) *Environmental Impacts of Offshore Wind Farms in the Belgian Part of The North Sea: Environmental impact monitoring reloaded*: 249-267.



- Hijmans, R.J. 2019. Geosphere: Spherical Trigonometry. R package version 1.5-10. <https://CRAN.R-project.org/package=geosphere>
- Kaschner, K. 2003. Review of small cetacean bycatch in the ASCOBANS area and adjacent waters – current status and suggested future actions. *North* 122.
- Koschinski, S. & Lüdemann K. 2013. *Development of noise mitigation measures in offshore wind farm construction*. Federal Agency for Nature Conservation.
- Norro, A. 2020. An evaluation of the noise mitigation achieved by using double big bubble curtains in offshore pile driving in the southern North Sea. In: Degraer, S. *et al.* (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*: 19-27.
- Norro, A., Haelters, J., Rumes, B. & Degraer, S. 2010. Underwater noise produced by the piling activities during the construction of the Belwind Offshore Wind Farm (Bligh Bank, Belgian Marine Waters). In: *Offshore Wind Farms in the Belgian Part of the North Sea: Heading for an Understanding of Environmental Impacts*: 37-51. Royal Belgian Institute of Natural Sciences, Brussels.
- Norro, A., Rumes, B. & Degraer, S. 2013. Differentiating between underwater construction sound of monopile and jacket foundations for offshore Wind turbines: A case study from the Belgian part of the North Sea. *The Scientific Journal* 2013: 897624. <https://doi.org/10.1155/2013/897624>
- North Seas Energy Cooperation. 2020. Joint Statement of North Seas Countries and the European Commission – 6 July 2020. Accessed from [https://ec.europa.eu/info/news/progress-north-seas-energy-cooperation-2020-jul-06\\_en](https://ec.europa.eu/info/news/progress-north-seas-energy-cooperation-2020-jul-06_en)
- Nuuttila, H. 2013. Identifying foraging behaviour of wild bottlenose dolphins (*Tursiops truncatus*) and harbour porpoises (*Phocoena phocoena*) with static acoustic dataloggers. *Aquatic Mammals* 39 (2): 147-161. <https://doi.org/10.1578/am.39.2.2013.147>
- R Core Team. 2019. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna. Available from <https://www.R-project.org/>.
- Rose, A., Brandt, M., Vilela, R., Diederichs, A., Schubert, A., Kosarev, V., Nehls, G., Volkenandt, M., Wahl, V., Michalik, A., Wendeln, H., Freund, A., Ketzer, C., Limmer, B., Laczny, M. & Piper, W. 2019. *Effects of Noise-Mitigated Offshore Pile Driving on Harbour Porpoise Abundance in the German Bight 2014-2016 (Gescha 2)*. IBL Umweltplanung GmbH.
- Rumes, B. & Degraer, S. 2020. Fit for porpoise? Assessing the effectiveness of underwater sound mitigation measures. In: Degraer, S. *et al.* (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*: 29-41.
- Rumes, B., Erkman, A. & Haelters, J. 2016. Evaluating underwater noise regulations for piling noise in Belgium and the Netherlands. In: Degraer, S., Brabant, R., Rumes, B. & Vigin L. (eds) *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea. Environmental Impact Monitoring Reloaded*: 37-50. Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management Section, Brussels.
- Rumes, B., Debusschere, E., Reubens, J., Norro, A., Haelters, J., Deneudt, K. & Degraer, S. 2017. Determining the spatial and temporal extent of the influence of pile driving sound on harbour

- porpoises, In: Degraer, S. *et al.* (eds) *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: A Continued Move towards Integration and Quantification*: 129-141.
- Tougaard, J., Wright, A.J. & Madsen, P.T. 2015. Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoises. *Marine Pollution Bulletin* 90: 196-208. <https://doi.org/10.1016/j.marpolbul.2014.10.051>
- Tregenza, N. 2014. CPOD.exe: a guide for users. Available from [https://www.chelonia.co.uk/cpod\\_downloads.htm](https://www.chelonia.co.uk/cpod_downloads.htm)
- van Beest, F.M., Teilmann, J., Hermanssen, L., Galatius, A., Mikkelsen, L., Sveegaard, S., *et al.* 2018. Fine-scale movement responses of free-ranging harbour porpoises to capture, tagging and short-term noise pulses from a single airgun. *Royal Society Open Science* 5: 170110. <https://doi.org/10.1098/rsos.170110>
- Wisniewska, D.M., Johnson, M., Teilmann, J., Rojano-Doñate, L., Shearer, J. Sveegazard, S., Miller, L.A., Siebert, U. & Madsen, P.T. 2016. Ultra-high foraging rates of harbor porpoises make them vulnerable to anthropogenic disturbance. *Current Biology* 26 (11): 1441-1446. <https://doi.org/10.1016/j.cub.2016.03.069>
- Wisniewska, D.M., Johnson, M., Teilmann, J., Siebert, U., Galatius, A., Dietz, R. & Madsen, P.T. 2018. High rates of vessel noise disrupt foraging in wild harbour porpoises (*Phocoena phocoena*). *Proceedings of the Royal Society B, Biological Sciences* 285: 20172314. <https://doi.org/10.1098/rspb.2017.2314>
- Zein, B., Woelfing, B., Dahne, M., Schaffeld, T., Ludwig, S., Rye, J.H., Baltzer, J., Ruser, A. & Siebert, U. 2019. Time and tide: seasonal, diel and tidal rhythms in Wadden Sea Harbour porpoises (*Phocoena phocoena*). *PLoS ONE* 14 (3): e0213348. <https://doi.org/10.1371/journal.pone.0213348>



# CHAPTER 3

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## BELGIAN SEABIRD DISPLACEMENT MONITORING PROGRAM

### MACRO-AVOIDANCE OF GPS-TAGGED LESSER BLACK-BACKED GULLS & POTENTIAL HABITUATION OF AUKS AND GANNETS

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#### Abstract

This study illustrates macro-avoidance by GPS-tagged lesser black-backed gulls at the Norther wind farm, by comparing the presence of tagged birds before and after construction and comparing the observed trend with the trend in two nearby control areas. The results mirror those obtained at the Thornton Bank wind farm just north of the study site (Vanermen *et al.* 2019a). Collision risk models should thus always take into account post-construction avoidance to reliably estimate the number of expected collision fatalities in lesser black-backed gull, a species highlighted to potentially suffer population impact following current wind farm development plans in the North Sea. The second part of this chapter reports the results of the first two-day monitoring survey of the full Belgian wind farm concession zone, performed in February 2021. Though much too soon to draw any conclusions, the findings are quite remarkable as we encountered good numbers of northern gannet *Morus bassanus*,

common guillemot *Uria aalge* and razorbill *Alca torda* inside the concession zone, all species generally perceived to actively avoid offshore wind farms across European waters (Vanermen & Stienen 2019). Coming surveys should tell whether these first results were anecdotic, or alternatively fit into a trend of actual habituation of seabirds to the presence of offshore wind farms.

#### 1. Introduction

In this chapter we will elaborate on the progress of two (sub)studies following the feasibility study (Vanermen *et al.* 2020) on targeted monitoring of seabirds at offshore wind farms (OWFs) in the Belgian Part of the North Sea (BPNS). One of the proposals was to take advantage of the momentum of the construction of the Norther wind farm in 2018–2019, coinciding with the availability of GPS data of lesser black-backed gulls *Larus fuscus*, tagged in the nearby colonies of Ostend, Zeebrugge and Vlissingen in the period 2013–2020 (Stienen *et al.* 2016). As

such we have data on the habitat use of the wind farm area from before the wind farm construction up to one year after installation, allowing to perform a BACI analysis (§2).

Secondly, Vanermen *et al.* (2020) proposed a new strategy for the monitoring of OWF-induced seabird displacement. This strategy includes a full coverage of the entire concession zone alongside a wide reference area, thus stepping away from the earlier adopted farm-by-farm approach. The intense coverage of the study area will allow state of the art spatial analyses once enough data are collected. As such we aim to gain insight in the effect of turbine density on seabird displacement rates and the use of corridors between individual farms for local or migration movements. In February 2021 we sailed the proposed two-day monitoring route for the first time and in §3 we discuss the

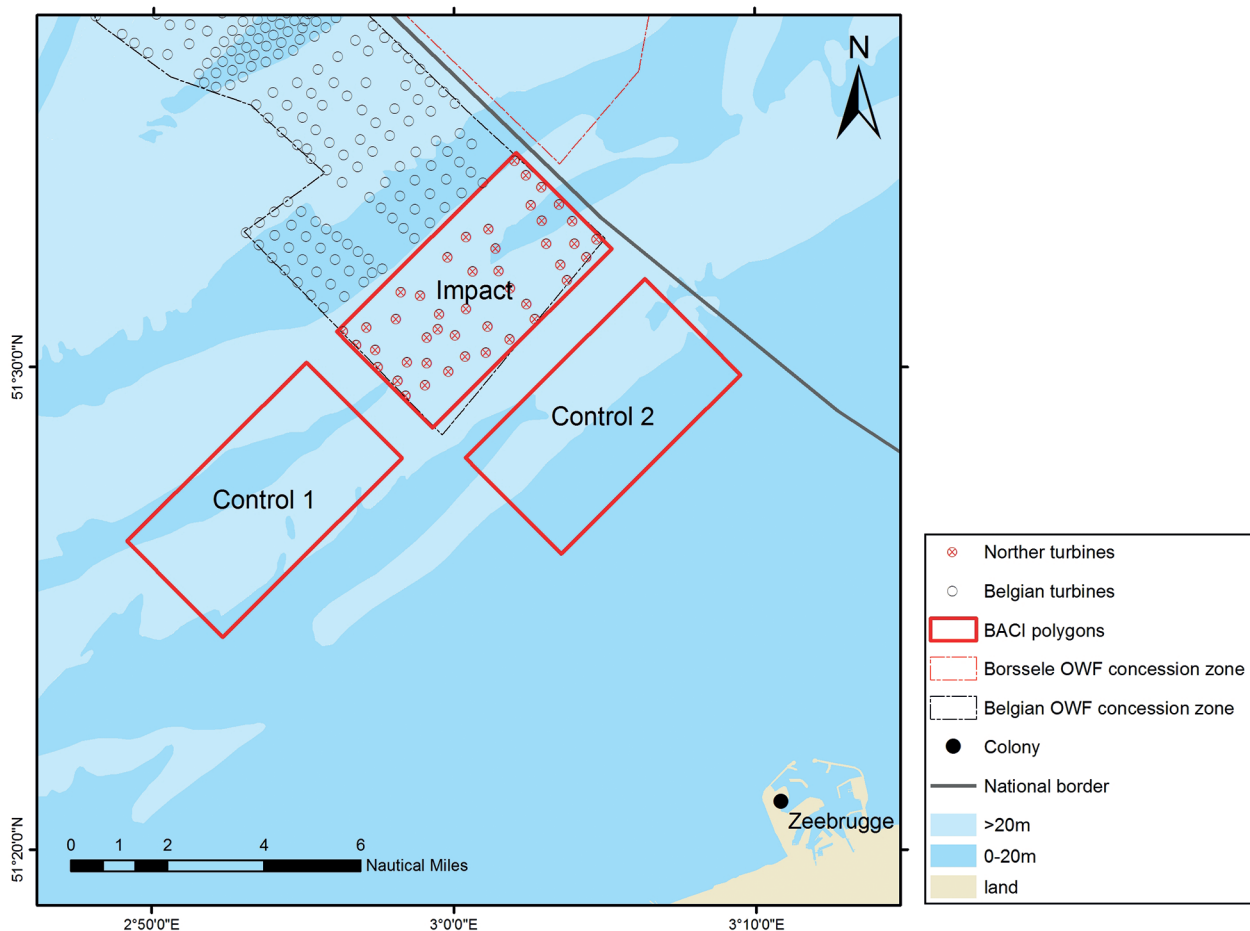
numbers and distribution of six key seabird species encountered during this trip.

## 2. Lesser black-backed gull presence in the Norther wind farm: a BACI analysis of GPS data

### 2.1. Methods

#### 2.1.1. BACI set-up

The recent installation of the Norther wind farm in the most south-east part of the Belgian wind farm concession zone offered the opportunity to compare the distribution of tracked lesser black-backed gulls in and around this particular OWF site before, during and after construction of the turbines by applying a classic BACI set-up. To this end, one impact and two equally-sized control areas were delineated as illustrated in Fig. 1.



**Figure 1.** BACI setup to study the impact of the construction of the Norther OWF on the habitat use of lesser black-backed gulls.

Based on the project timeline (<https://www.norther.be/#timings>), we defined the different periods for application in the BACI analysis as follows:

- Pre-construction period: 01/01/2017–30/06/2018
- Construction period: 01/07/2018–31/08/2019
- Impact period: 01/09/2019 – present

### 2.1.2. GPS data

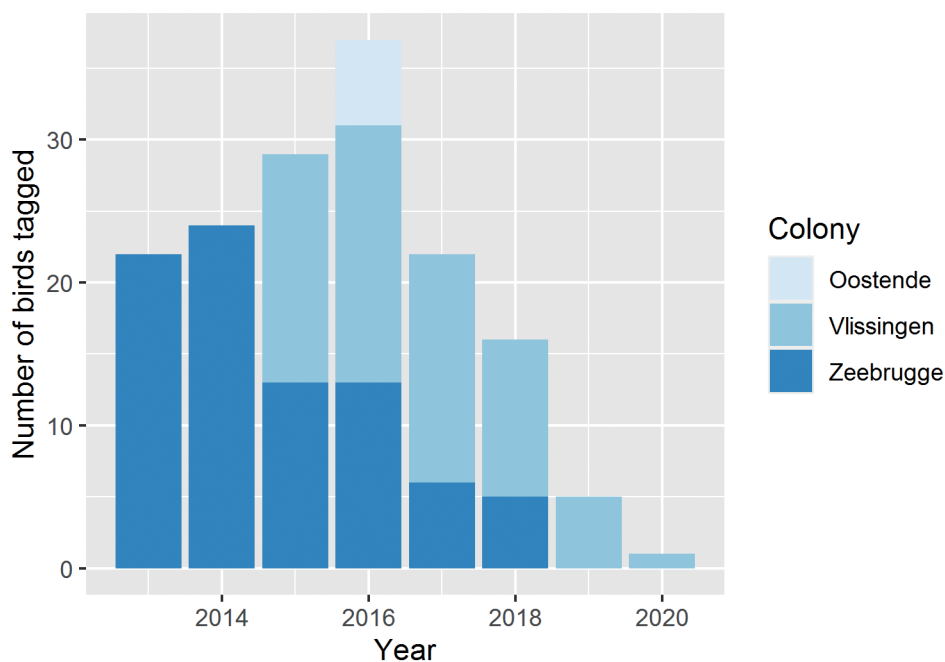
Between 2013 and 2020, 156 lesser black-backed gulls breeding in Zeebrugge (n=83), Ostend (n=6) and Vlissingen (n=67) were equipped with a UvA-BiTS tracker generating three-dimensional GPS fixes (Bouten *et al.* 2013, Stienen *et al.* 2016). The deployment of the trackers was authorized by the ethical committee for animal experiments (license number CDE2013–73) and conducted in accordance with Flemish and Belgian legislation. To fit the GPS trackers, all individuals were caught on their nests during incubation using walk-in traps or clap nets. Trackers were attached using a wing harness of Teflon ribbon threaded with a nylon string (Stienen *et al.* 2016). The collected data were remotely transmitted to a base station located inside each colony. Tagging effort strongly decreased after 2018, with only 6 more birds

tagged in 2019 and 2020 (Fig. 2). Since the trackers generate data for an average period of about one year and a half (due to loss of the tracker, tracker malfunctioning or birds moving to other colonies), this implies an overall decrease in the number of records in the study area over time.

In the raw database, the sampling rate of GPS fixes varied strongly from 10 to 3600 seconds resulting from the different needs and priorities of the data end-users. In order to obtain an unbiased dataset and meanwhile avoid temporal correlation between records (Ross-Smith *et al.* 2016; Shamoun-Baranes *et al.* 2017), data were subsampled to a minimum frequency of 1100 seconds, after which tracks with a frequency of more than 1500 seconds were omitted as well. This way the sampling frequency of the resulting dataset is in line with the principal frequency of 20 minutes (Fig. 3).

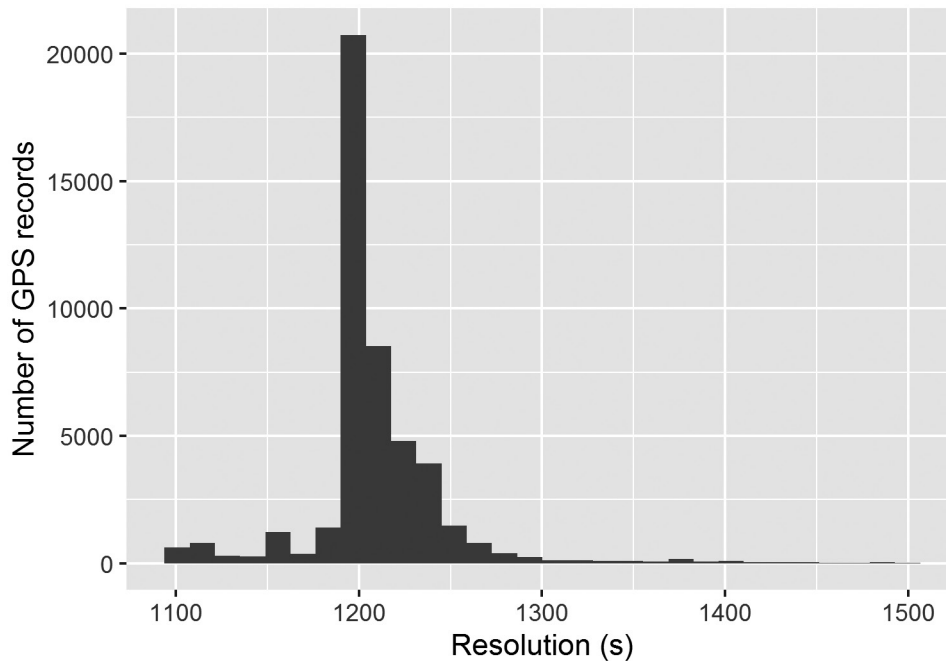
### 2.1.3. Model

We estimated the effect of the installation of the Norther OWF on the area use of lesser black-backed gull by modelling the number of GPS records in the study area (Fig. 1). The response variable in our model was the number



**Figure 2.** Tagging effort of lesser black-backed gulls per year and per colony.





**Figure 3.** Sampling frequency of the GPS records after subsampling.

of records per day per area, and as covariates we chose month, area (impact area and two reference areas) and period (pre-construction, construction and post-construction), allowing interaction between the two latter. We only considered days between the 1<sup>st</sup> of March and the 31<sup>st</sup> of August, as the species is largely absent outside this period. With 306, 246 and 184 days of sampling, respectively in the pre-construction, construction and impact period, and three areas considered, the database holds 2208 unique day-area combinations. The estimated coefficients of the interaction between the impact area factor level on the one hand and the construction/impact period levels on the other hand are thus a measure of the (indirect) effect of the OWF construction / presence. We tested 4 distributions, *i.e.* Poisson, negative binomial, zero-inflated Poisson and zero-inflated negative binomial, and chose the best fitting distribution based on the resulting AIC value (Akaike 1974).

## 2.2. Results

### 2.2.1. Maps

Though difficult to interpret visually due to an overall decreasing number of records

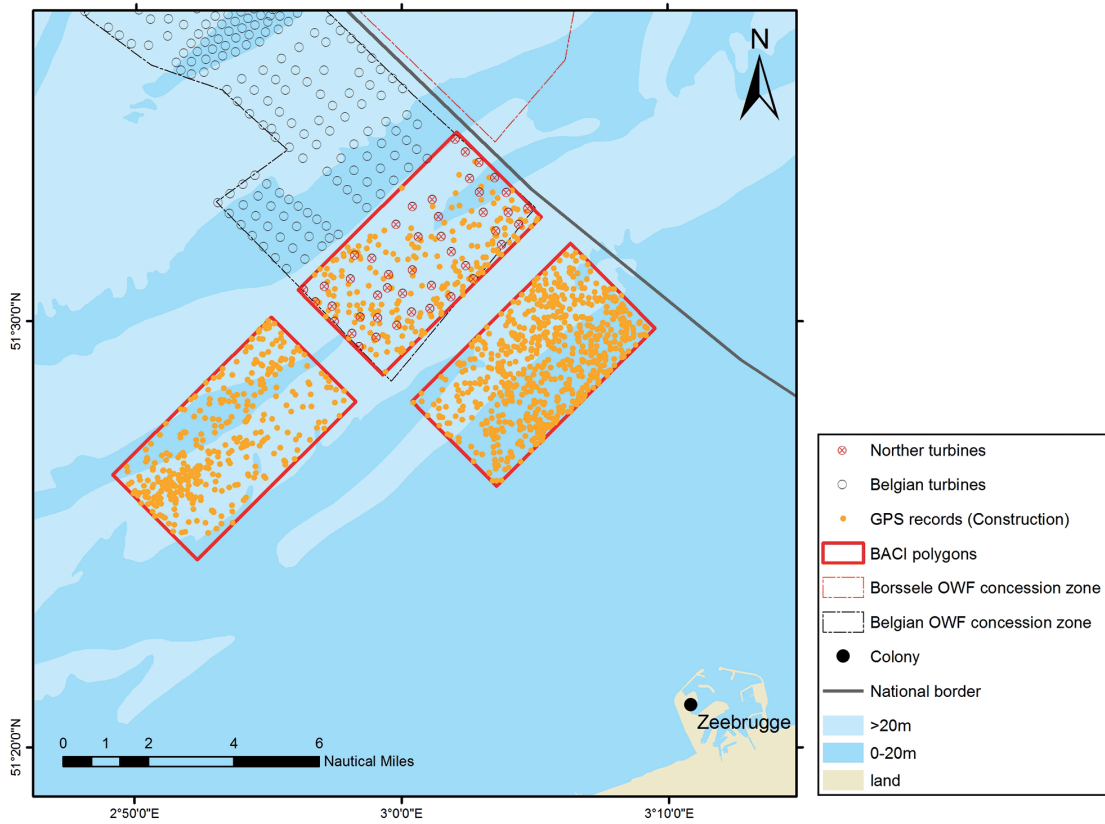
over time, related to the decreased tagging effort after 2016 (Fig. 2), Figs 4 to 6 illustrate a clear change in the spatial distribution of lesser black-backed gull presence following the construction of the Northern OWF. The northern part of the wind farm in particular seems to be largely avoided by the gulls during the operational impact period (Fig. 6).

### 2.2.2. Model results

The best model fit was obtained through a negative binomial distribution based on the corresponding AIC, and the model summary is shown in Table 1. The factors ‘periodConstruction’ and ‘periodAfter’ were significantly (and progressively) negative, which reflects the overall decrease in the number of tagged birds since 2016 (see Fig. 2). The factor ‘areaControl2’ was significantly positive, implying a consistently higher number of records inside Control area 2 compared to Control area 1. Importantly, the interactions ‘periodAfter:areaControl2’ and ‘periodConstruction:areaControl2’ were not significant, in line with the assumption that the trend in the number of records in Control area 2 should not be any different from that in Control area 1.



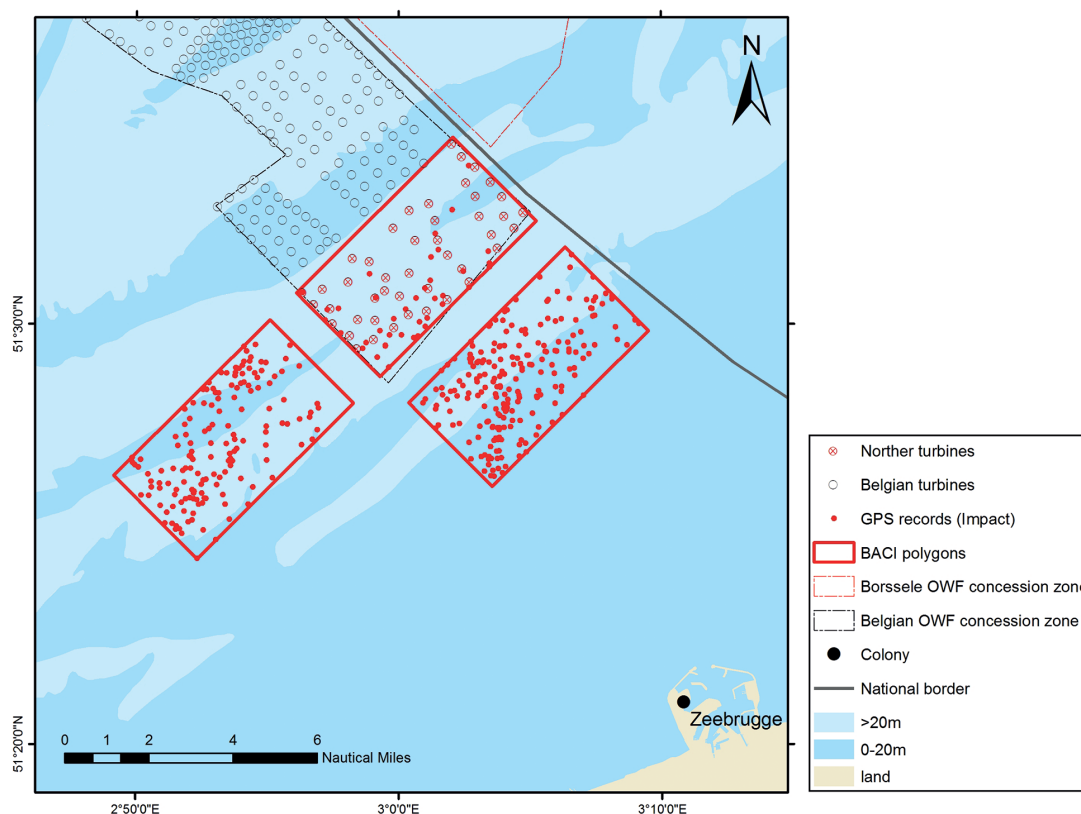
**Figure 4.** GPS records inside the BACI polygons during the pre-construction period (01/01/2017 – 30/06/2018; N=2174).



**Figure 5.** GPS records inside the BACI polygons during the construction period (01/07/2018 – 31/08/2019; N = 1274).

**Table 1.** BACI model summary results ( $P < 0.1$ .,  $P < 0.05^*$ ,  $P < 0.01^{**}$ ,  $P < 0.001^{***}$ ; the coefficient of the estimated wind farm impact is indicated in red).

	Estimate	Std. Error	Z-value	P-value
(Intercept)	-0.156	0.180	-0.866	0.387
as.factor(month)4	1.078	0.183	5.886	0.000***
as.factor(month)5	1.059	0.182	5.824	0.000***
as.factor(month)6	0.812	0.184	4.402	0.000***
as.factor(month)7	1.278	0.184	6.930	0.000***
as.factor(month)8	0.398	0.190	2.097	0.036*
periodConstruction	-0.375	0.207	-1.814	0.070.
periodAfter	-0.943	0.231	-4.086	0.000***
areaControl2	0.524	0.188	2.784	0.005**
areaImpact	0.010	0.190	0.053	0.958
periodConstruction:areaControl2	0.109	0.284	0.383	0.701
periodAfter:areaControl2	-0.178	0.321	-0.554	0.579
periodConstruction:areaImpact	-0.363	0.291	-1.250	0.211
<b>periodAfter:areaImpact</b>	<b>-1.252</b>	<b>0.352</b>	<b>-3.553</b>	<b>0.000***</b>



**Figure 6.** GPS records inside the BACI polygons during the impact period (01/09/2019 – present; N=412).

Lastly, though negative, the interaction between ‘periodConstruction’ and ‘areaImpact’ was not significant, implying that the construction activities did not affect the distribution of tagged lesser black-backed gulls to a statistically discernible extent. The interaction between ‘periodAfter’ and ‘areaImpact’ on the other hand was significant, confirming our earlier visual interpretation of Figs 4 to 6 and the effect of the presence of the Norther turbines on the distribution of lesser black-backed gulls in the study area. The coefficient of -1.252 stands for a decrease in lesser black-backed gull occurrence by 71% compared to the pre-construction period and taking account of the trend in the control areas.

### 2.3. Discussion BACI analysis GPS data

For the Thornton Bank wind farm, Vanermen *et al.* (2019a) already showed how lesser black-backed gulls avoided the wind farm interior, but were attracted to the outer edge turbines for roosting. This study again illustrates the general avoidance of OWFs by tagged lesser black-backed gulls, at yet another location just south-east of the earlier mentioned Thornton Bank. Interestingly, the results obtained through GPS studies counter earlier reported results from designated ship-based surveys, pointing towards attraction of lesser black-backed gulls to the Bligh Bank OWF (Vanermen *et al.* 2019b). Part of the explanation could be that the Bligh Bank is located outside the foraging range of the (adult) birds breeding in the study colonies, and that the perceived attraction effect thus involves birds on migration, immature birds and/or birds with another provenance.

As tagging effort in the colonies of Zeebrugge, Ostend and Vlissingen has decreased over the last few years, a general decrease in the number of GPS records has occurred in the study area. Though easily accounted for by the model, it would be interesting to be able to include more post-construction records to build an even stronger case. In this respect, about ten more birds will

be tagged in Zeebrugge in the breeding season of 2021. We may further opt to include GPS data from individuals tagged in the Dutch colony of Neeltje Jans, the foraging range of which is expected to overlap with the study area.

Another step forward would be the analysis of the accelerometer data, that allows to classify GPS records in behavioural categories, most interesting of which is the category ‘pecking’, indicating foraging behaviour. Analysing the (change in) behaviour in the impact area may give further insight in the habitat use of OWFs by lesser black-backed gulls.

As argued before, the prohibition for trawlers to fish between the turbines is likely to be at least a co-driving force behind the observed decrease in records of lesser black-backed gulls in the impact area. The offshore density of GPS records is indeed closely related to fishery activities. Within Control area 1 for example, the density of GPS records is highest both north and south of the Gootebank (Figs 4 to 6), which relates to less intense fishery activity on sandbank ridges across the BPNS (data download from <https://globalfishingwatch.org/>). Whether wind farm avoidance is due to a disturbance effect induced by the turbines, the absence of fisheries or a combination of both, however, is hard to assess. To stay close to the set-up of this study, one would actually need to include an additional control area from which all fishery activity can be excluded, in order to ‘isolate’ its particular effect. Regardless of what actually induces the wind farm avoidance, we should note that the main concern regarding lesser black-backed gulls and OWFs is still the potential population level impact due to increased (collision) mortality, rather than the impact of habitat loss. Importantly, collision risk studies often use pre-construction bird densities to feed the collision models, yet this strategy is expected to result in an overestimation of the number of expected victims by not taking account of post-construction avoidance.

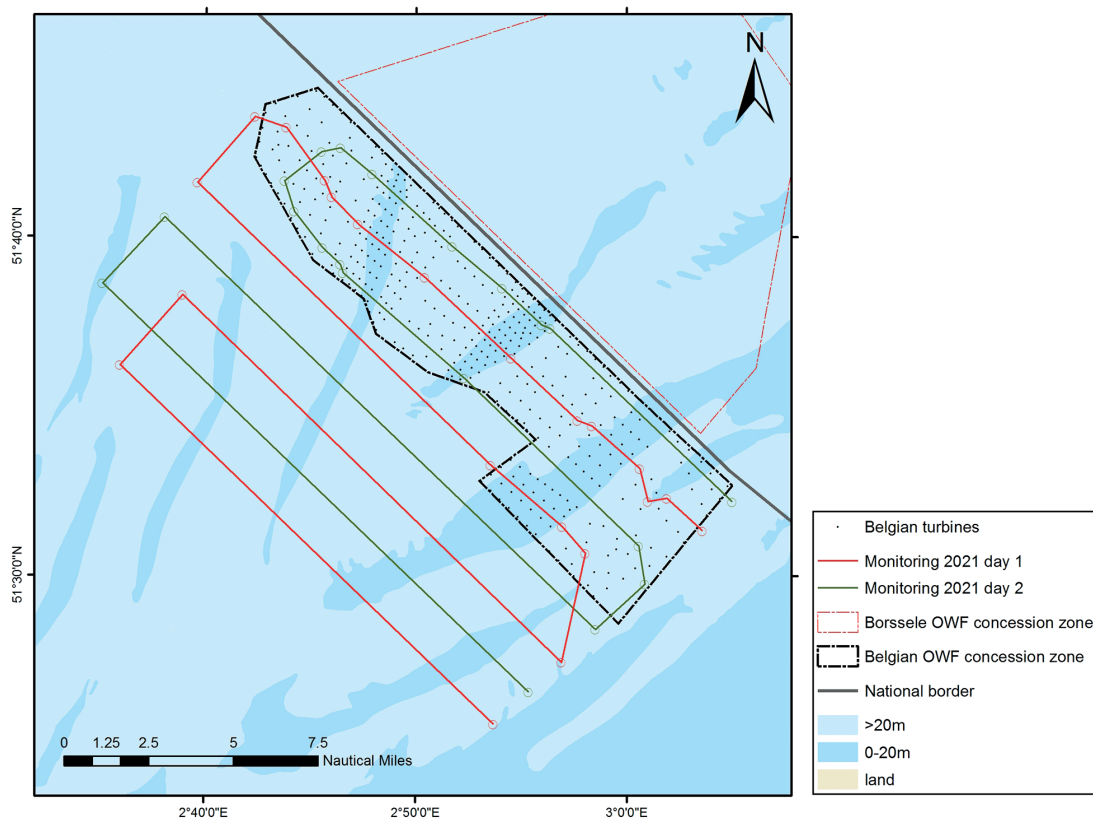
### 3. Ship-based monitoring of seabird displacement in the Belgian OWF concession zone

#### 3.1. Methods

Since the end of 2020, the Belgian OWF concession zone is fully operational. This new context allows seabird monitoring across the concession zone without any access restrictions due to construction works. In the feasibility study of last year (Vanermen *et al.* 2020), a new monitoring strategy was therefore outlined (Fig. 7), aiming to continue assessing species-specific displacement rates by means of ship-based counts and meanwhile looking for correlations with wind farm configuration characteristics.

Ship-based seabird counts are conducted according to a standardised and internationally applied method, combining a ‘transect count’ for birds in contact with the water and repeated ‘snapshot counts’ for flying birds (Tasker *et al.* 1984). For the ‘transect count’, the focus

is on a 300 m wide transect along one side of the ship’s track, and while steaming at a speed of about 10 knots, all birds in touch with the water (swimming, dipping, diving) within this transect are counted. The distance to each observed bird (group) is estimated, allowing to correct for decreasing detectability with increasing distance afterwards. The transect is thus divided in four distance categories (A=0-50 m; B=50-100 m; C=100-200 m; D=200-300 m). Counting all flying birds inside the transect, however, would cause an overestimation and would be a measure of bird flux rather than bird density (Tasker *et al.* 1984). The density of flying birds is therefore assessed through one-minute interval counts of birds flying within a quadrant of 300 by 300 m inside the transect (the so-called ‘snapshot counts’). As the ship covers a distance of approximately 300 m per minute when sailing the prescribed speed of 10 knots, the full transect is covered by means of these subsequent ‘snapshots’.



**Figure 7.** The new seabird displacement monitoring route, which can be covered in the course of two (preferably consecutive) days and is planned to be sailed five times per year.



### 3.2. Results

The newly proposed monitoring route was sailed for the first time on the 23<sup>rd</sup> and 24<sup>th</sup> of February 2021, two days with favourable conditions (wind force of at most 5 Beaufort and significant wave heights below 1 m). Below, the count results for six key seabird species will be discussed by showing distribution maps and comparing the densities encountered inside versus outside the concession zone.

#### 3.2.1. Northern gannet

No less than 84 northern gannets (*Morus bassanus*) were observed between the turbines of the Belgian OWF concession zone (Fig. 8). Most were observed in the south-east part of the wind farm zone, coinciding with increased razorbill densities. Outside the concession zone, northern gannets were most common in the north-western part of the study area, near active fishery activity. Likely due to the latter, densities of northern gannet were eventually much higher outside compared to inside the wind farms (0.8 versus 0.3 birds/km<sup>2</sup>, respectively, see Table 2).

#### 3.2.2. Large gulls

The numbers of large gulls were generally low inside the wind farm concession zone (Figs 9 to 11), with lesser black-backed gull being the most numerous species (0.4 birds/km<sup>2</sup>). In contrast, gull densities were particularly high in the north-western part of the study area, near active beam trawlers.

Overall, lesser black-backed gull reached a density of 14.3 birds/km<sup>2</sup> outside the OWF concession zone. For herring and great black-backed gull (*Larus argentatus* and *marinus*) as well, densities were clearly higher outside compared to inside the wind farms (Table 2).

#### 3.2.3. Auks

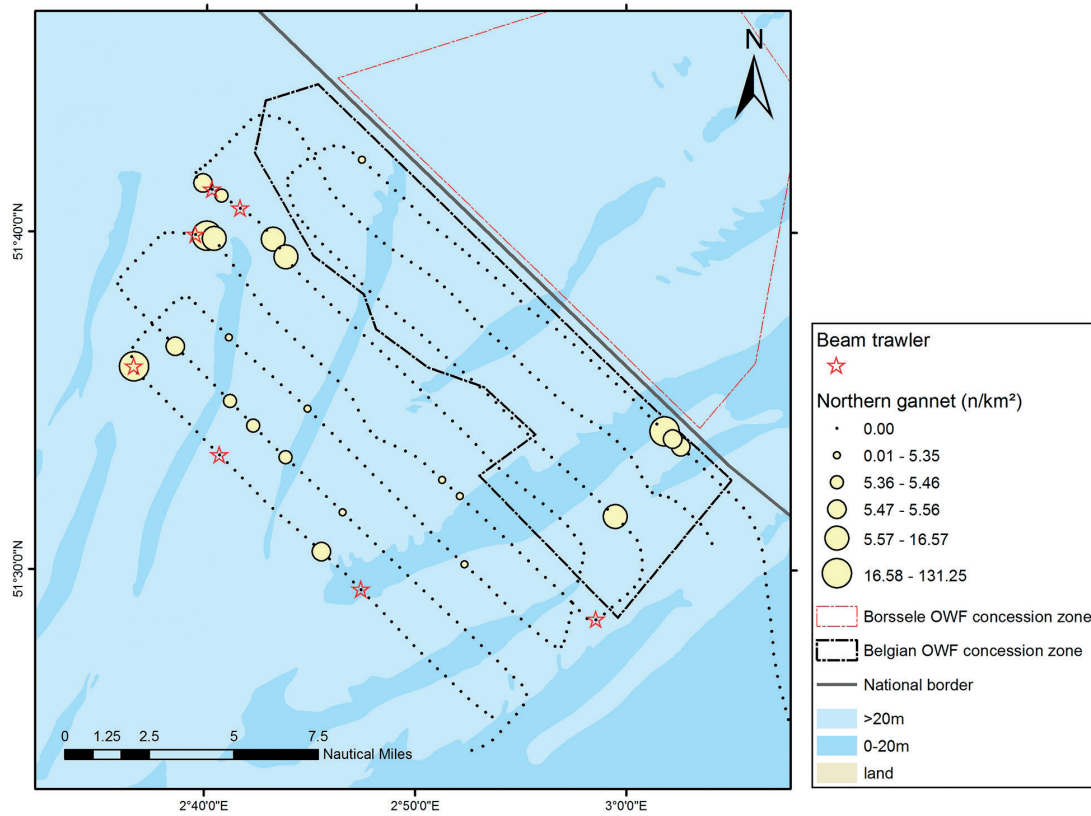
The south-east edge of the Thornton Bank held particularly high densities of razorbill (*Alca torda*), both in- and outside the OWF concession zone (Fig. 13). Overall, densities inside the concession zone appeared about twice as high compared to densities outside (4.59 versus 2.36 birds/km<sup>2</sup> respectively, see Table 2). Common guillemot (*Uria aalge*) occurred more homogenously spread across the study area (Fig. 12), with comparable densities inside and outside the concession zone (1.2 and 1.0 birds/km<sup>2</sup> respectively).

#### 3.2.4. Summarising table

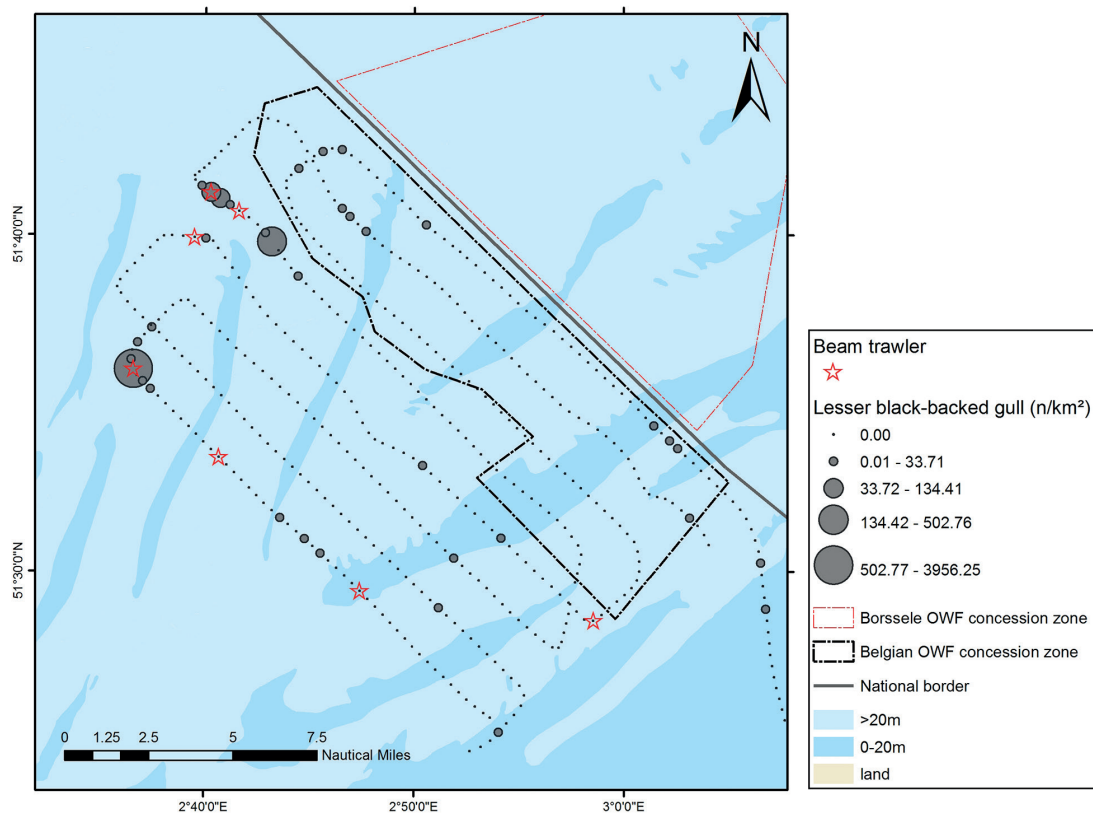
All species known to aggregate near fishing vessels showed clearly increased densities outside the wind farm concession zone. During our campaign, seven fishing vessels were active near our monitoring route (see Figs 8 to 11), with high numbers of associated gulls and gannets near some of them. Inside the wind farms, gulls occurred much more dispersed, while northern gannets concentrated in the south-east part of the concession zone, alongside feeding flocks of razorbill. Worth mentioning also is the relatively large number of yellow-legged gulls (*Larus michahellis*) encountered in the

**Table 2.** Densities (n/km<sup>2</sup>) of six key seabird species inside and outside the wind farm concession zone; bold figures indicate where the species reaches its highest density.

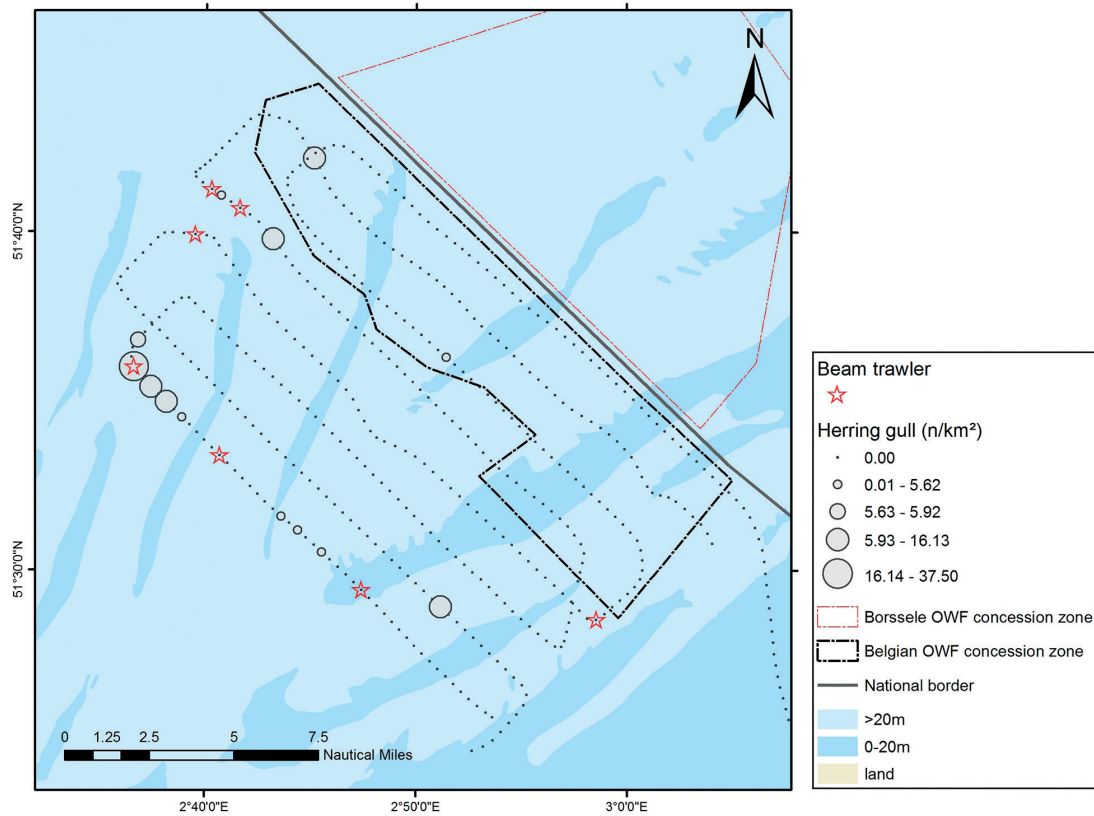
	Inside	Outside
Northern gannet	0.29	<b>0.80</b>
Lesser black-backed gull	0.43	<b>14.27</b>
Herring gull	0.10	<b>0.37</b>
Great black-backed gull	0.00	<b>0.11</b>
Common guillemot	<b>1.18</b>	1.03
Razorbill	<b>4.59</b>	2.36



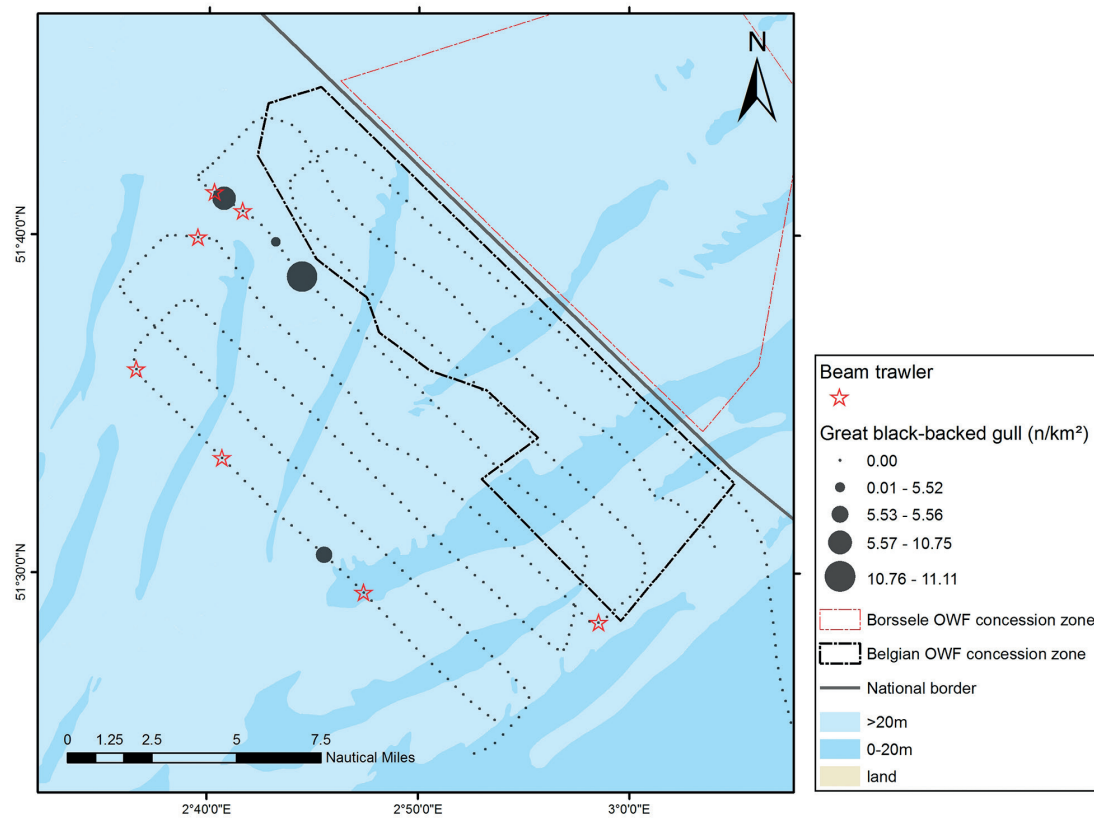
**Figure 8.** Northern gannet densities encountered during the two-day seabird displacement monitoring on 23 & 24/02/2021.



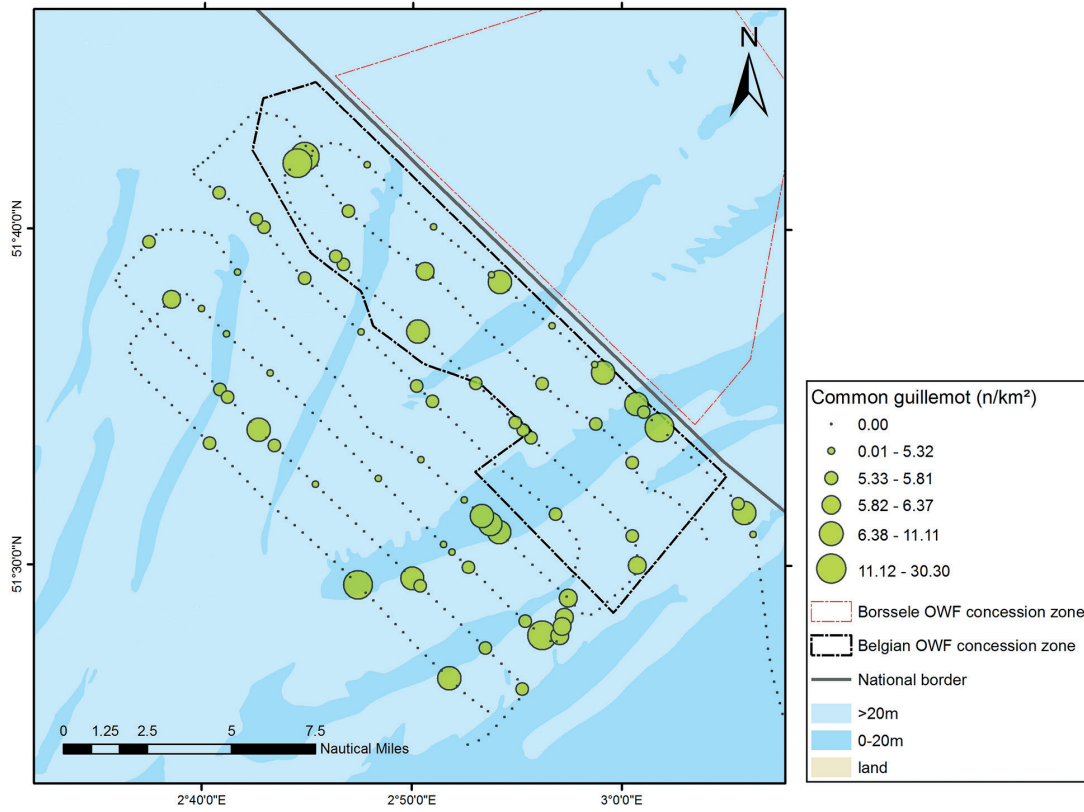
**Figure 9.** Lesser black-backed gull densities encountered during the two-day seabird displacement monitoring on 23 & 24/02/2021.



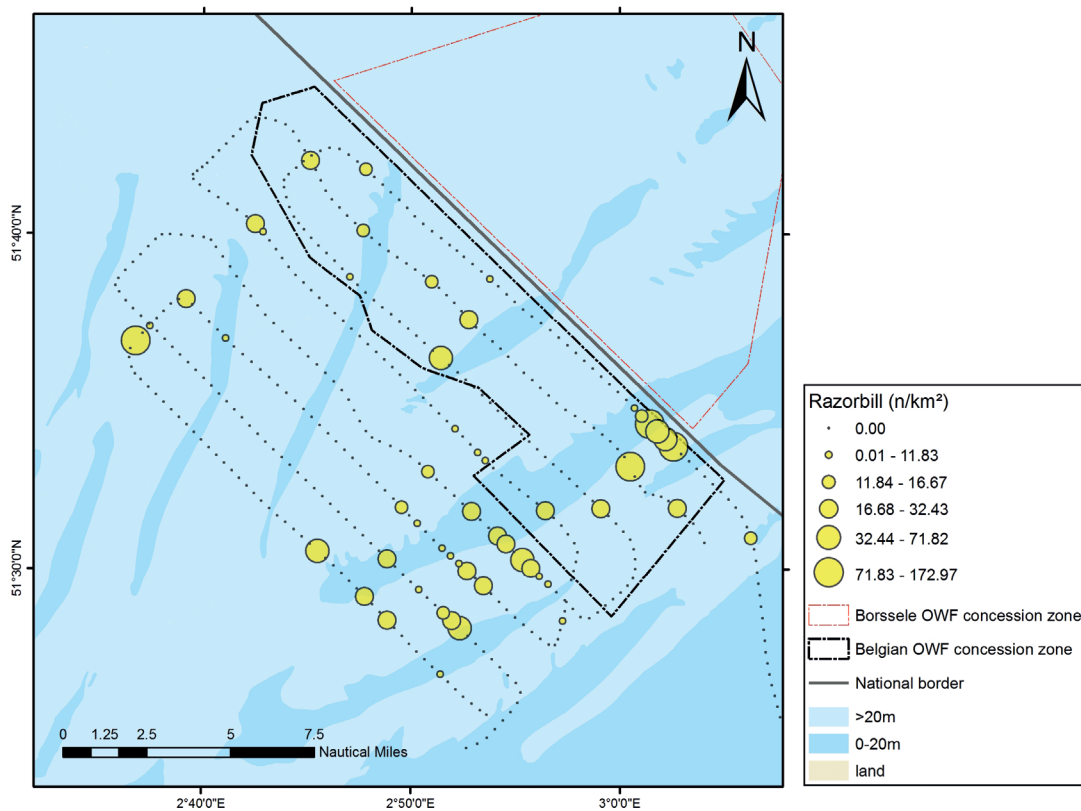
**Figure 10.** Herring gull densities encountered during the two-day seabird displacement monitoring on 23 & 24/02/2021.



**Figure 11.** Great black-backed gull densities encountered during the two-day seabird displacement monitoring on 23 & 24/02/2021.



**Figure 12.** Common guillemot densities encountered during the two-day seabird displacement monitoring on 23 & 24/02/2021.



**Figure 13.** Razorbill densities encountered during the two-day seabird displacement monitoring on 23 & 24/02/2021.

course of the two monitoring days, totalling 31 individuals (14 inside compared to 17 outside the concession zone).

No less than 396 auks were observed between the turbines. When transforming the counted numbers to densities, the density of razorbill was almost twice as high inside compared to outside the wind farms. For common guillemot, densities inside and outside are comparable, yet slightly higher between the turbines (see Table 2).

### 3.3. Discussion ship-based seabird displacement monitoring

Clearly, the results from one monitoring survey are insufficient to perform statistical analyses, nor to draw any firm conclusions. On the other hand, the first findings are quite remarkable considering the relatively large numbers of auks and gannets observed in the concession zone (razorbill in particular), species generally perceived to actively avoid OWFs across European waters (reviewed in Vanermen & Stienen 2019). This could be a sign of habituation, whether or not in combination with a scale effect. One can indeed imagine how the same birds tending to avoid single wind farms might find it harder to avoid wind farm areas as extensive as the Belgian OWF concession zone. Birds that are now ‘forced’ into the wind farms in turn can be expected to increasingly habituate to their presence. For low-flying species such as common guillemot and razorbill, this can be regarded as good news as it might cancel out the potential impact of habitat loss, while the increased densities are not expected to lead to more collision victims. This, however, is

not the case for northern gannet, a much more airborne species. About 7% of gannet flight movements are known to occur at collision risk height (Johnston *et al.* 2014), implying that habituation and increased presence between wind turbines might lead to a higher collision mortality. It will be very interesting to see whether coming surveys can confirm these first findings, and to perform spatial analyses on the resulting data. These analyses should further take in account the effect of active beam trawling on bird distribution in the area, which is now somehow blurring the raw results.

### Acknowledgements

First of all, we want to thank all offshore wind farm concession holders for financing the environmental monitoring program, as well as the Management Unit of the North Sea Mathematical Models (MUMM) for assigning the seabird displacement study to INBO. A special word of gratitude goes out to the Belgian Science Policy (BELSPO) for providing ship time on RV Belgica. We wish to thank all crew members of the RV Belgica as well as Robin Brabant, Steven Degraer and Lieven Naudts for their logistic support and cooperation.

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### References

- Akaike, H. 1974. A new look at the statistical model identification. *IEEE Transactions on Automatic Control* 19: 716-723. <https://doi.org/10.1109/TAC.1974.1100705>
- Bouten, W., Baaij, E.W., Shamoun-Baranes, J. & Camphuysen, C.J. 2013. A flexible GPS tracking system for studying bird behavior at multiple scales. *Journal of Ornithology* 154: 571-580. <https://doi.org/10.1007/s10336-012-0908-1>



- Johnston, A., Cook, A.S.C.P., Wright, L.J., Humphreys, E.M. & Burton, N.H.K. 2014. Modelling flight heights of marine birds to more accurately assess collision risk with offshore wind turbines. *Journal of Applied Ecology* 51: 31-41. <https://doi.org/10.1111/1365-2664.12191>
- Ross-Smith, V.H., Thaxter, C.B., Masden, E.A., Shamoun-Baranes, J., Burton, N.H.K., Wright, L.J., Rehfish, M.M. & Johnston, A. 2016. Modelling flight heights of lesser black-backed gulls and great skuas from GPS: a Bayesian approach. *Journal of Applied Ecology* 53: 1676-1685. <https://doi.org/10.1111/1365-2664.12760>
- Shamoun-Baranes, J., Burant, J.B., van Loon, E.E., Bouten, W. & Camphuysen, C.J. 2017. Short distance migrants travel as far as long distance migrants in lesser black-backed gulls *Larus fuscus*. *Journal of Avian Biology* 48: 49-57. <https://doi.org/10.1111/jav.01229>
- Stienen, E.W.M., Desmet, P., Aelterman, B., Courtens, W., Feys, S., Vanermen, N. & Verstraete, H. 2016. GPS tracking data of Lesser Black-backed Gulls and Herring Gulls breeding at the southern North Sea coast. *ZooKeys* 555: 115-124. <https://doi.org/10.3897/zookeys.555.6173>
- Tasker, M.L., Jones, P.H., Dixon, T.J. & Blake, B.F. 1984. Counting seabirds at sea from ships: a review of methods employed and a suggestion for a standardised approach. *Auk* 101: 567-577. <https://doi.org/10.1093/auk/101.3.567>
- Vanermen, N. & Stienen, E. 2019. Seabird displacement. In: Perrow M.R. (ed.) *Wildlife and Wind Farms, Conflicts and Solutions – Offshore: Potential Effects*. Pelagic Publishing, Exeter, pp. 174-205.
- Vanermen, N., Courtens, W., Daelemans, R., Lens, L., Müller, W., Van de walle, M., Verstraete, H. & Stienen, E.W.M. 2019a. Attracted to the outside: a meso-scale response pattern of lesser black-backed gulls at an offshore wind farm revealed by GPS telemetry. *ICES Journal of Marine Science*. <https://doi.org/10.1093/icesjms/fsz199>
- Vanermen, N., Courtens, W., Van de walle, M., Verstraete, H. & Stienen, E.W.M. 2019b. Seabird monitoring at the Thornton Bank offshore wind farm: final displacement results after 6 years of post-construction monitoring and an explorative Bayesian analysis of common guillemot displacement using INLA. In: Degraer S. et al. (eds) *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Marking a Decade of Monitoring, Research and Innovation. Memoirs on the Marine Environment*. Royal Belgian Institute of Natural Sciences, Brussels, pp. 85-116.
- Vanermen, N., Courtens, W., Van de walle, M., Verstraete, H. & Stienen, E.W.M. 2020. Belgian seabird displacement monitoring programme: A feasibility study on future research possibilities. In: Degraer S. et al. (eds) *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Empirical Evidence Inspiring Priority Monitoring, Research and Management*. Royal Belgian Institute of Natural Sciences, Brussels, pp. 53-60.

# CHAPTER 4

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## OCCURRENCE OF INTENSE BIRD MIGRATION EVENTS AT ROTOR HEIGHT IN BELGIAN OFFSHORE WIND FARMS AND CURTAILMENT AS POSSIBLE MITIGATION TO REDUCE COLLISION RISK

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### Abstract

Songbirds are known to cross the North Sea in large numbers during autumn and spring migration. When flying at rotor height, these migrating birds are at risk of collision with turbine blades. This risk can increase when weather conditions deteriorate during these long migration flights over sea. Such deteriorating conditions can result in large numbers of possibly disoriented, weakened birds flying at rotor height and possibly to large numbers of bird collisions. An effective measure to reduce the number of collisions with wind turbines during intense migration events, is to temporarily idle turbines. Offshore wind farms in the Dutch Borssele area, adjacent to the Belgian wind farms, will need to idle turbines from 2023 onwards when the flux of birds exceeds 500 birds.  $\text{km}^{-1}.\text{hour}^{-1}$  at rotor height. Continuous bird radar surveys were performed in a Belgian offshore wind farm to record intense bird migration events. Such events, here defined by a bird flux higher than 500 birdtracks.  $\text{km}^{-1}.\text{hour}^{-1}$  at rotor height occurred 14 times

during autumn 2019 (maximum of 995 birdtracks.  $\text{km}^{-1}.\text{hour}^{-1}$ ) and did not occur in spring 2021 (maximum of 261 birdtracks.  $\text{km}^{-1}.\text{hour}^{-1}$ ). All intense bird migration events occurred at night and comprised nocturnally migrating songbirds. Applying a collision risk model on the detected bird flux, a total estimated number of 761 songbird collisions would have been avoided if the turbines of all Belgian offshore wind farms would have been idled during the 14 hours in autumn 2019 when the bird flux exceeded 500 birdtracks.  $\text{km}^{-1}.\text{hour}^{-1}$  at rotor height. The uncertainty of the collision risk model results and the fact that we do not exactly know which species were registered by the radar does not allow to assess the significance of the number of songbird collisions with wind turbines in the Belgian part of the North Sea. It is however unlikely that this has a significant effect at population level. If this will still be the case for the cumulative effects of all planned wind farms in the (southern) North Sea is unknown.

## 1. Introduction

The southern North Sea is part of one of the main European migration flyways for large numbers of seabirds (Stienen *et al.* 2007) and non-marine birds (Buurma 1987; Alerstam 1990; Lensink *et al.* 2002; Bradarić *et al.* 2020; Manola *et al.* 2020). Estimates of the number of birds seasonally travelling through the southern North Sea vary from 85 million (Lensink *et al.* 2002) up to several hundreds of million (estimates of Helgoland mentioned in Hüppop *et al.* 2006), of which the vast majority are non-marine birds (Krijgsveld *et al.* 2011; Bradarić *et al.* 2020). During migration, birds fly at greater altitudes than when foraging or commuting between sites (Garthe & Hüppop 2004; Krijgsveld *et al.* 2011) and choose the altitude stratum in which their energy costs are lowest (Hüppop *et al.* 2006), ranging from sea-level up to 10 km. A general phenomenon is that birds fly high with tailwind and that they fly at a lower altitude with headwind (Alerstam 1990; Buurma 1987; Lensink *et al.* 2002).

Peaks of intense migration occur during good weather with favourable, supporting wind conditions (Bradarić *et al.* 2020). During these relatively long flights, birds can be overtaken by deteriorating weather conditions and will lower their flight altitude (Lensink *et al.* 2002). Such conditions result in large numbers of possibly disoriented, weakened birds flying at rotor height and possibly to large numbers of bird collisions. Lensink *et al.* (1999) reported three of these events in the period from 1978 until 1990, but concluded, based on limited data at sea, that these ‘falls’ occur at a yearly base in the southern North Sea.

The development of offshore wind farms (OWFs) in the North Sea might impact these migrating birds as they risk colliding with the turbines, resulting in an increased mortality rate. Fijn *et al.* (2015) reported on the magnitude of bird fluxes at rotor height during migration in the Dutch part of the North Sea. The majority of these fluxes consisted of gull species during the day and migrating

songbirds at night. An effective measure to reduce the number of collisions with wind turbines during intense migration events, is to temporarily idle turbines (Cook *et al.* 2011; May 2017). This is, for example, foreseen as a mandatory condition for the exploitation of the wind farms in the Dutch Borssele area. When the flux of birds exceeds 500 birds.km<sup>-1</sup>.hour<sup>-1</sup> at rotor height, the number of rotations of the wind turbines must be reduced to less than one revolution per minute (rpm; Rijkswaterstaat 2019). This requires continuous monitoring of the intensity of bird migration by radar and has been estimated to result in approximately 30 hours of turbine downtime annually, i.e., 3 to 4 nights per year. The aim is to apply this measure from January 1<sup>st</sup>, 2023, onwards.

The goal of this report is to assess the number of hours the flux of birds flying at rotor height exceeds 500 birds.km<sup>-1</sup>.hour<sup>-1</sup> in the Belgian OWFs and to assess the significance of curtailment in reducing collision risk.

## 2. Material and methods

### 2.1. Research strategy

We used a vertically mounted bird radar with automated bird tracking software to assess the intensity of bird migration in the Belgian part of the North Sea (BPNS) during two migration seasons. We then assessed the frequency of occurrence of intense bird migration events at rotor height, here defined as a bird flux exceeding 500 birdtracks.km<sup>-1</sup>.hour<sup>-1</sup>. This is the threshold value used in the Dutch Borssele wind farms to idle the turbines. We finally estimated the number of collision victims that would have been avoided if the Belgian OWFs would have idled the turbines during these intense migration events with a collision risk model.

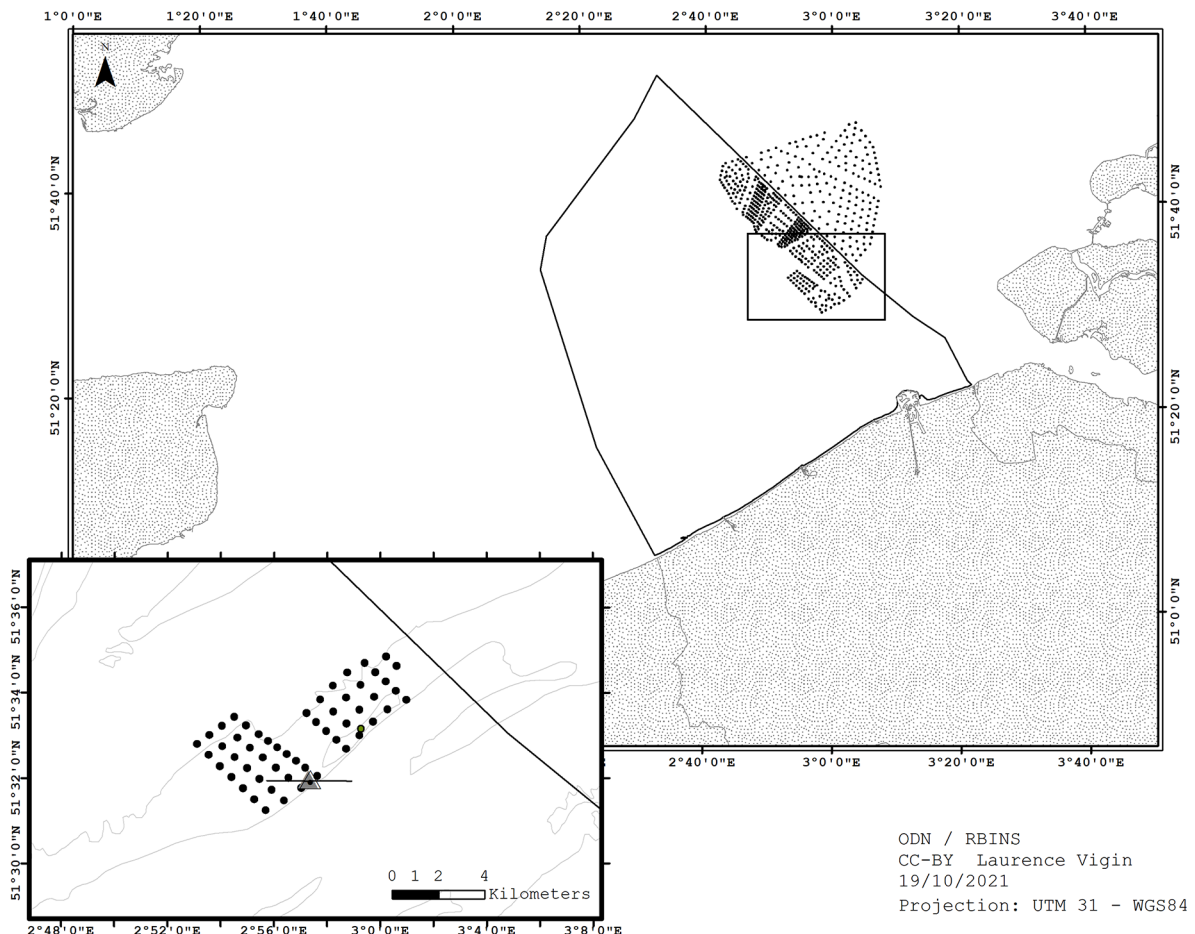
### 2.2. Radar hardware

Radar is a valuable tool to obtain data on the intensity of bird movements and their flight altitudes. Radar observations greatly contribute to the understanding of bird migration because of the ability to register

birds continuously at large spatial scale and at high altitudes (Eastwood 1967; Bruderer 1997a, 1997b; Gauthreaux & Belser 2003; Liechti *et al.* 2019; Nilsson *et al.* 2019). There are several advantages compared to visual observations as radar is not limited to lower altitudes, daylight or good visibility and does not suffer from observer bias. However, radar systems also have some limitations and the recorded data should be handled cautiously (Schmaljohann *et al.* 2008; Fijn *et al.* 2015). Radars are unable to distinguish species and do not always allow to differentiate between single birds and bird groups.

Bird flux and flight altitude data were collected by a vertically mounted 25 kW marine surveillance radar (JRC JMA-5320-7, X-band ( $9.41 \pm 3.0$  KHz), nominal beam angle:  $20^\circ$ ,

rotation speed: 24 rpm). The radar antenna rotates in the vertical plane and as such, scans a vertical ‘radar screen’ that registers all the targets moving through that screen. As this ‘radar screen’ is narrow, every registration can be an individual bird or a flock of birds passing through that area. The flux of birds is expressed as migration traffic rate (MTR), i.e., number of birds that pass across a one kilometer line during an hour ( $\text{birds.km}^{-1}.\text{hr}^{-1}$ ; Schmaljohann *et al.* 2008). As the radar is not able to differentiate individual birds from a small flock of birds, the MTR for this type of radar is actually the number of bird groups.  $\text{km}^{-1}.\text{hour}^{-1}$  or a minimum estimate of the number of  $\text{birds.km}^{-1}.\text{hour}^{-1}$  (Fijn *et al.* 2015). Therefore the results are further presented as birdtracks  $\text{km}^{-1}.\text{hour}^{-1}$ .



**Figure 1.** Map of the Belgian part of the North Sea (black polygon) with indication of the Belgian wind farms. The adjacent Borssele wind farms in the Dutch part of the North Sea are shown to the East of the Belgian wind farms. The location of the individual turbines (dots) and the radar location on the transformer platform (triangle) in the C-Power wind farm on the Thorntonbank are shown in the inset. The black line indicates the orientation of the vertical radar from East to West.



The radar antenna is installed on the offshore platform inside the C-Power wind farm on the Thorntonbank in the BPNS since 18 September 2019, after Brabant & Degraer (2017) concluded that the S-band antenna, previously used on the Thorntonbank, was not performing optimally, and had to be replaced by an X-band magnetron radar. Since then, the radar has been performing well and the data presented here are collected with that new vertically mounted antenna. The orientation of the radar is East to West (Fig. 1).

### 2.3. Bird tracking software and data post-processing

The radar operates continuously year-round and is remotely controlled. The system is operated by the Merlin software (DeTect Inc., Florida USA) which is specifically designed to track individual birds (DeTect Inc. 2010; Brabant *et al.* 2012). The Merlin software links consecutive registrations of a target, and thus registers the flight path of a moving target. Within the Merlin software the range of detection can be specified. This is the range of the radar beam that is being processed by the Merlin tracking software. In this study, the range is set at one nautical mile (nm, 1.852 km), which means an area of one nm on both sides of the radar position and an altitude up to 2 nm is being processed by the bird tracking software.

However, these processed data still contain some non-bird tracks coming from different sources (e.g., rain, wind turbines, side lobes). As we use the radar data to determine the flux of birds in the area, clutter has to be removed as accurately as possible. Precipitation was manually removed from the database by visually scanning visualisations of 15 minutes of data and removing rain events. Turbines were removed from the data based on their geographic position. All objects above 2000 m were also removed from the dataset.

The manual post-processing of the radar data to remove non-bird echoes (mainly rain

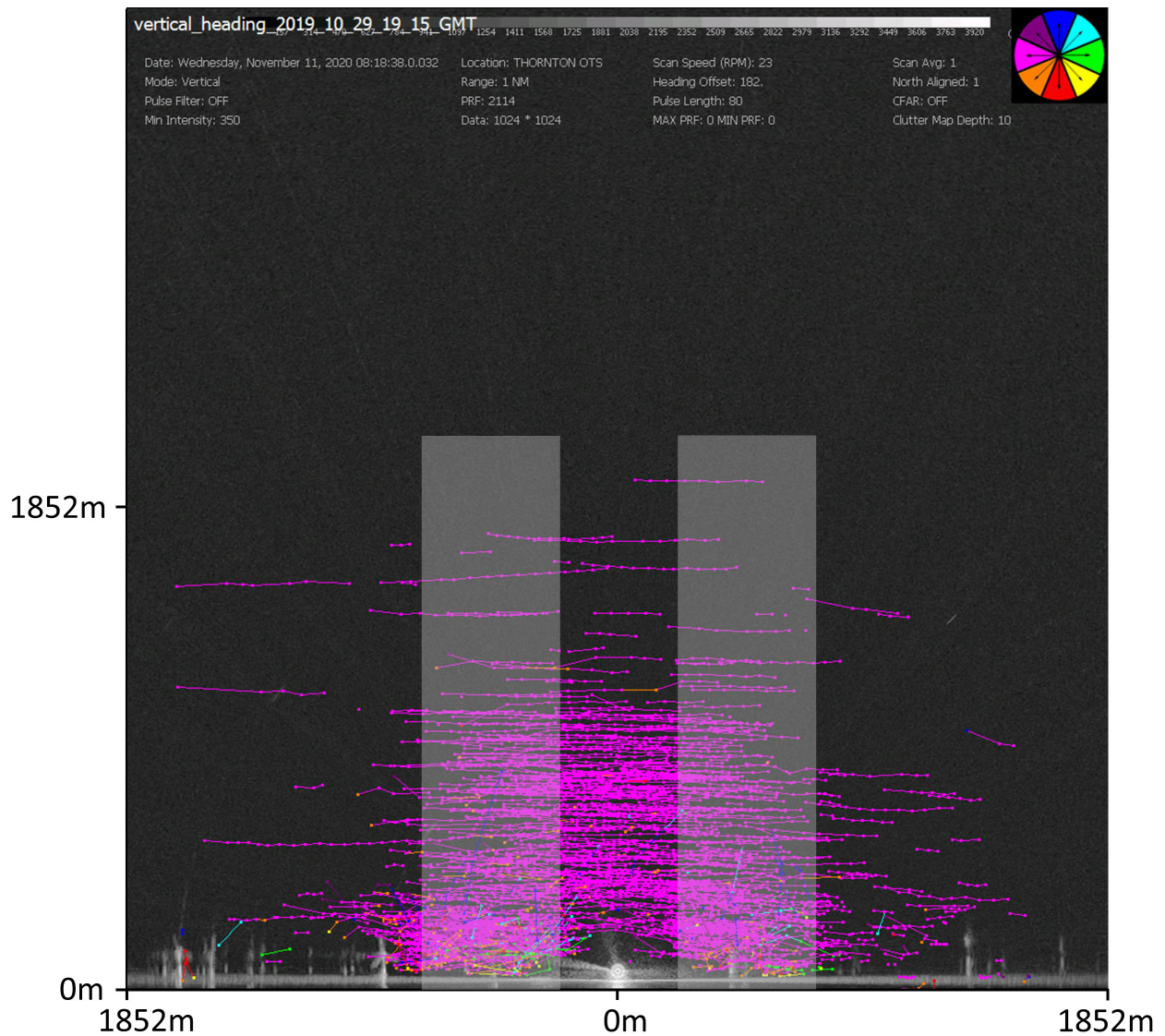
events) from the data is not 100% effective, resulting in occasional noise present in the data at rotor height. After visually reviewing the complete dataset it could be concluded that this noise was never to that extent that it affects the number of hours where MTR exceeds 500 birdtracks.km<sup>-1</sup>.hour<sup>-1</sup>. In the near future, a filtering model will be developed to remove noise automatically based on radar echo characteristics, as was already effectively done for the S-band radar system (Brabant *et al.* 2016).

The MTR was calculated as the sum of the number of bird tracks per hour, registered in two columns of 500 m wide selected from the entire measurement volume (Fig. 2; at 150 to 650m distance from the radar, both to the east and west; following the approach of Fijn *et al.* 2015). In doing so, we avoided using the data close to the radar location, which is saturated with reflections of the radar platform, and further than 650 m from the radar to avoid detection loss at further distance from the radar (Fijn *et al.* 2015). Fijn *et al.* (2015) describe that for a magnetron radar, similar to the one used in this study, this detection loss starts at 900 m for smaller birds.

We calculated MTR values for every hour in these study periods per altitude layer of 50 m and also between 24 and 193 m, being the lowest point and highest point of turbine rotors in the Belgian OWFs, to determine the MTR at rotor height.

For this analysis, we used data from two migration seasons, i.e., autumn/winter 2019 (20 September until 15 December) and winter/spring 2021 (7 January until 15 May). The radar was continuously operational throughout both survey periods, autumn/winter 2019 and winter/spring 2021, except from 11 to 15 of April 2021 when the radar system was shut down because of high wind conditions. Data from 2020 were not continuous because of several technical issues and were therefore not used.





**Figure 2.** Visualisation of 15 minutes of bird radar data from October 29<sup>th</sup>, 2019 19:15 until 19:30 UTC. Each bird track represents a single bird or a group of birds. The radar position is in the bottom centre of the image (0 m). The radar range (1852 m) is indicated to the East and West of the radar position. The color of the bird tracks represents the direction of flight within the radar beam (e.g., from West to East is purple). The gray columns, at 150 m to 650 m from the radar position and up to 2000 m, indicate the radar data which is used to determine the migration traffic rate (MTR, birds.km<sup>-1</sup>.hr<sup>-1</sup>).

#### 2.4. Collision risk modelling

Collision risk model (CRM) allows to estimate the number of bird collisions at sea, where carcass searches are impossible. CRM uses the technical wind farm and turbine specifications, bird-related variables and bird densities to calculate the collision risk per species. The calculations were carried out with the basic collision risk model of Band (2012). The extended CRM of Band (2012) could not be used, because that extension

requires detailed information on species-specific flight height distribution throughout the rotor height, which is lacking in our dataset.

As the radar detections are not species-specific, it is not possible to do species-specific CRM estimates. We however know that the highest bird migration peaks occur at night-time (Brabant *et al.* 2017; Nilsson *et al.* 2019) and are mainly terrestrial birds (Alerstam 1990; Krijgsveld *et al.* 2011).

**Table 1.** Average dimensions of thrushes, used as bird related input data for the collision risk model.

Species	Body_Length (m) <sup>1</sup>	Wingspan (m) <sup>1</sup>	Flight_Speed (m/s) <sup>2</sup>	Nocturnal_Activity (% of diurnal activity)	Flight	Proportion in Flight
Thrushes <i>Turdus</i> sp.	0.24	0.36	12.4	1	flapping	1

<sup>1</sup>Cramp (1977–1985); <sup>2</sup>Alerstam *et al.* (2007).

**Table 2.** Average wind farm and turbine related input data of the Belgian offshore wind farms used for bird collision risk modelling.

N of turbines	Width (km)	Latitude (°)	tidal offset (m)	turbine model (MW)	n of blades	rotor radius (m)	air gap (m)	max blade width (m)	rotor speed (rpm)	Pitch (°)
399	35	51.6	4.3	6.9	3	73	26.9	5.0	12.11	5.5

Therefore, we used average sizes of thrushes, a species group that is known to migrate in huge numbers at night, for the bird-related input data in the CRM (Table 1).

We calculated the number of expected collisions when the MTR at rotor height exceeded 500 birdtracks.km<sup>-1</sup>.hour<sup>-1</sup> for the nine Belgian OWFs in the area. For simplicity we used average wind turbine dimensions for the Belgian OWFs (Table 2). More details on input variables used in the BPNS can be found in Brabant & Vanermen (2020). Rotor speed and pitch were taken from Gyimesi *et al.* (2018). Information on turbine activity per month were taken from Masden (2015).

The CRM also includes a micro-avoidance rate, accounting for last-minute avoidance actions of birds. The avoidance rate is a very important factor in CRM and has a large impact on the outcome. It has proven difficult to quantify and is likely to vary in response to a wide range of environmental and ecological factors, as well as the configuration of the wind farm. Based on the available evidence, it is widely accepted that total avoidance levels amongst birds are likely to be high (Chamberlain *et al.* 2006; Krijgsveld *et al.* 2011; Everaert 2014), commonly higher than 98% and for many seabirds above 99% (Cook *et al.* 2012), also at night (Welcker *et al.*

2017). Most probably, this rate is species-specific and may also depend on weather conditions. Based on the available evidence, it is widely accepted that total avoidance levels amongst birds are likely to be high (Chamberlain *et al.* 2006; Krijgsveld *et al.* 2011; Everaert, 2014), commonly higher than 98% and for many seabirds above 99% (Cook *et al.* 2012), also at night (Welcker *et al.* 2017). Most probably, this rate is species-specific and may also depend on weather conditions. As the radar data are not species-specific, we applied the general micro-avoidance value of 97.6% determined by Krijgsveld *et al.* (2011), based on their extensive radar research in a comparable offshore environment. This rate was also used by Poot *et al.* (2011) to estimate songbird collisions in Dutch OWFs.

Calculations and graphs were made in R version 3.2.2. (R Core Team 2015), making use of the packages ggplot2 (Wickham 2016), cowplot (Wilke 2016), reshape2 (Wickham 2007) and plyr (Wickham 2011).

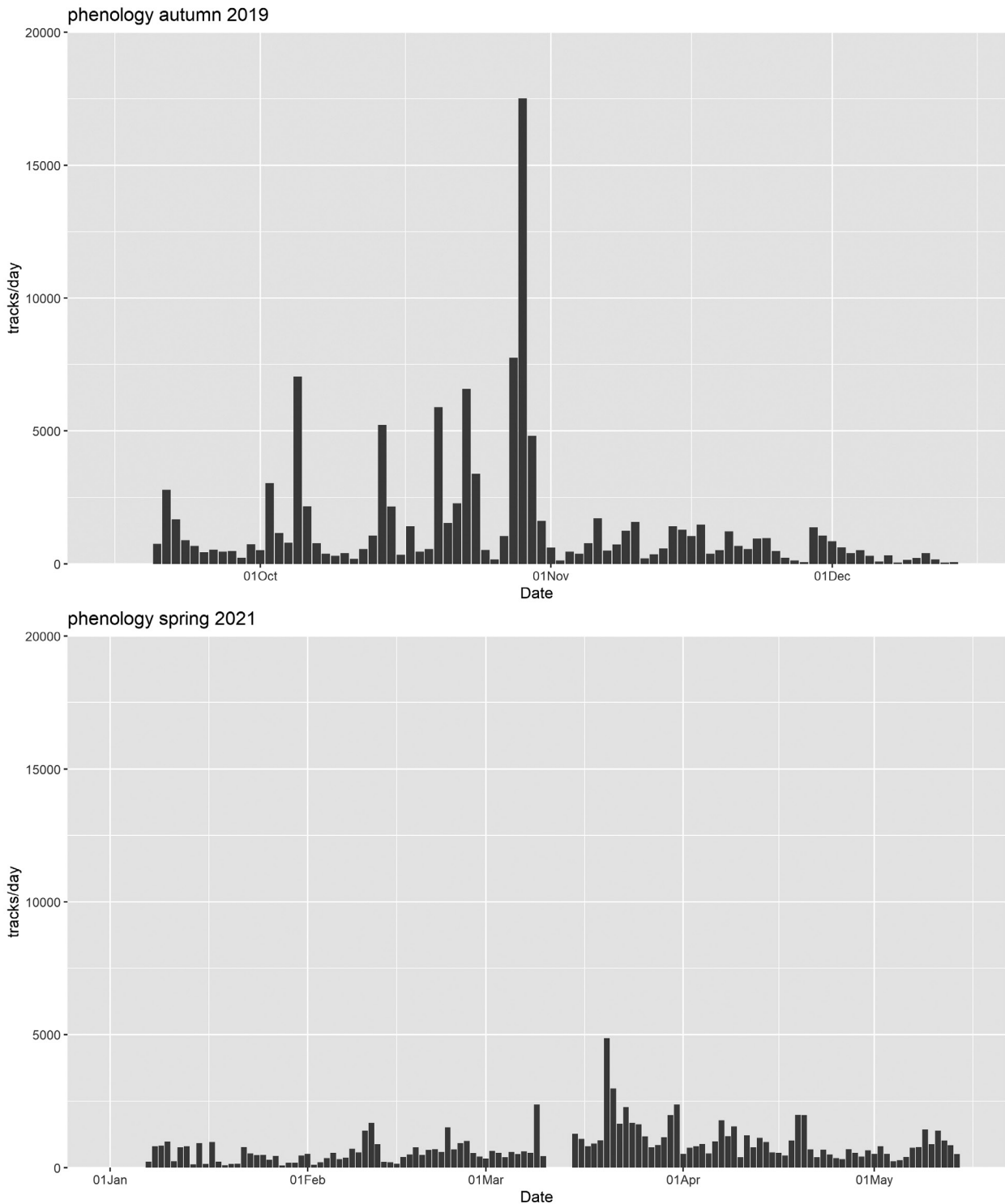
### 3. Results

The highest migration intensity was observed in the month October 2019 (Fig. 2 and Fig. 3, upper panel), with a maximum of 17511 tracks/day on October 29<sup>th</sup>. In spring

2021, the maximum number of tracks in one day was 4870 on March 20<sup>th</sup> (Fig. 3, lower panel).

Both in autumn 2019 and spring 2021, the number of bird tracks decreased with altitude (Fig. 4). 11.9% of all bird tracks

recorded in autumn 2019 were detected in the lowest 50 m. In Spring 2021, this is even 22.7%. The percentage of bird tracks detected at rotor height (24-193 m) is similar in both study periods, being 41.4% in autumn 2019 and 38.2% in spring 2021.

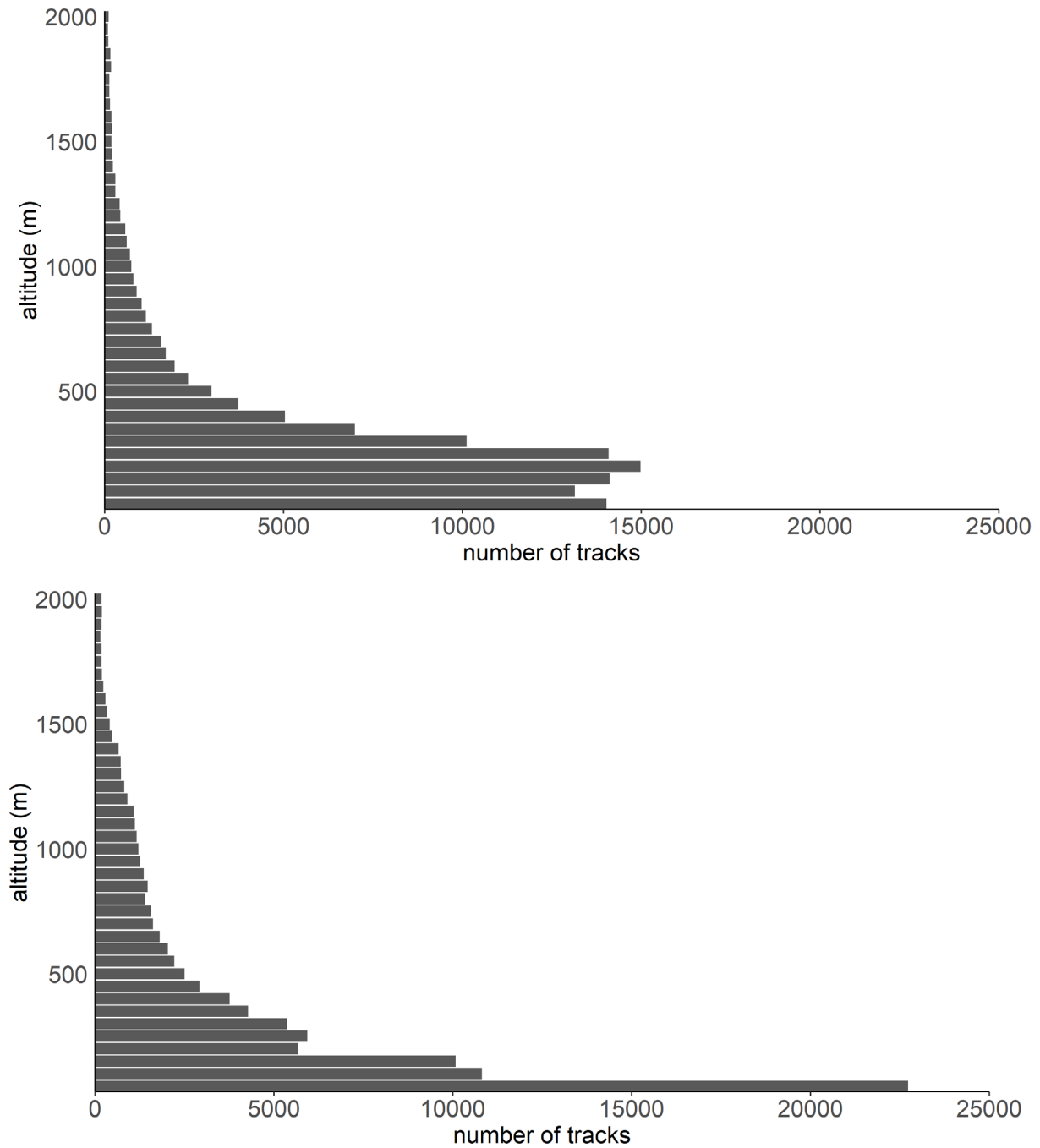


**Figure 3.** Number of bird tracks per day, recorded by the radar, for autumn 2019 (upper panel) and spring 2021 (lower panel).

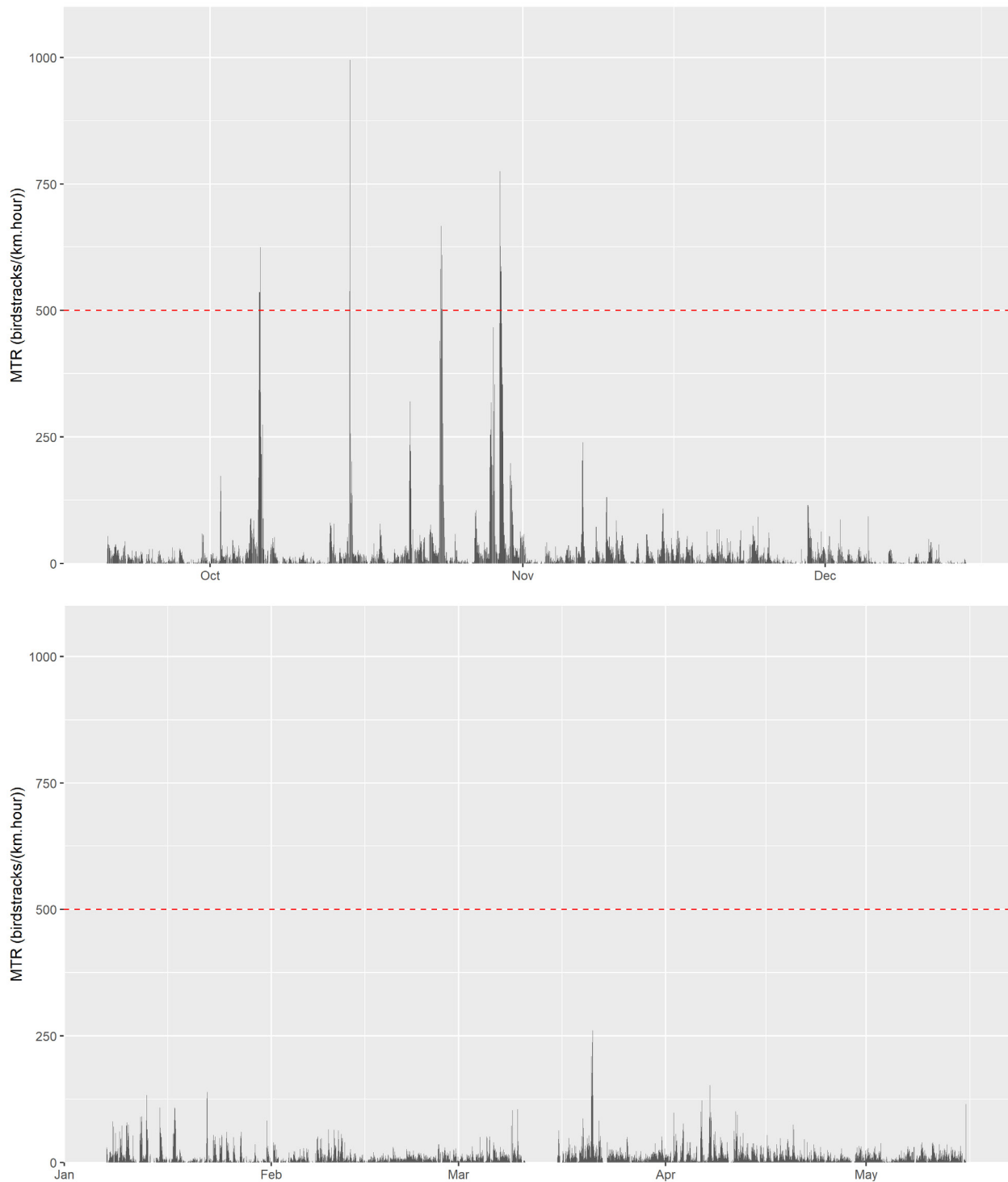
During the entire study period, the MTR at rotor height exceeded 500 birdtracks.km<sup>-1</sup>.hour<sup>-1</sup> during 14 hours. These all occurred in October 2019 after sunset. The highest registered MTR at rotor height was 995 birdtracks.km<sup>-1</sup>.hour<sup>-1</sup> on October 14<sup>th</sup> between 22:00 and 23:00 CET. In the first half of 2021, the MTR at rotor height was never higher than 500 birdtracks.km<sup>-1</sup>.hour<sup>-1</sup> (Fig. 5). The

highest recorded flux during that period was 261 birdtracks.km<sup>-1</sup>.hour<sup>-1</sup>.

During the 14 hours in autumn 2019 when the MTR exceeded the threshold value of 500 birdtracks.km<sup>-1</sup>.hour<sup>-1</sup>, a total estimated number of 761 collisions would have been avoided if the turbines of the Belgian OWFs had been idled.



**Figure 4.** Total number of bird tracks per 50 m altitude layer for autumn 2019 (upper panel) and spring 2021 (lower panel).



**Figure 5.** MTR (birdtracks.km<sup>-1</sup>.hour<sup>-1</sup>) at rotor height (24–193 m) for autumn 2019 (upper panel) and spring 2021 (lower panel). The dashed red line indicates the threshold for curtailing the turbines in the Dutch Borssele wind farm area, being 500 birdtracks.km<sup>-1</sup>.

#### 4. Discussion

The highest bird fluxes were logically registered during the main bird migration months, being September, October, March and April. Although we have no data from our

site during the summer months, we know from previous radar studies (Brabant *et al.* 2017) and radar studies in the adjacent Dutch part of the North Sea (Krijgsveld *et al.* 2011) that the bird flux in summer is lower than in migration



seasons. We can therefore assume that the MTR threshold value of 500 birdtracks.km<sup>-1</sup>.hour<sup>-1</sup> would not have been exceeded during summer months. The number of hours during the study period during which the threshold was surpassed is rather low (14 hours) and about half of the Dutch estimate of 30 hours per year, based on the results of Krijgsveld *et al.* (2011). All these events occurred at night and most likely are nocturnal passerine migration events. Especially Blackbird *Turdus merula*, Song Thrush *Turdus philomelos*, Redwing *Turdus iliacus* and Robin *Erithacus rubecula* migrate in high numbers at night (Krijgsveld *et al.* 2011; Fijn *et al.* 2015). These are most likely birds that winter in the UK and mainly originate from Scandinavia and NE-Europe (Bourne 1980; Buurma 1987; Alerstam 1990; Lensink *et al.* 2002; Leopold *et al.* 2014; Nilsson *et al.* 2019). The intense migration events in our dataset coincide with departures of large numbers of birds towards the UK, seen on bird- and meteorological radars from coastal sites in Belgium and the Netherlands (pers. comm. Hans van Gasteren). Although, part of our radar detections can also be birds crossing the North Sea directly from Scandinavia, which is also a known migration route for passerines (Buurma 1987; Lensink *et al.* 2002).

A high portion of the detected birds flew at rotor height, being 41.4% in autumn 2019 and 38.2% in spring 2021, and as such, were at risk of collision with the turbine rotors. An estimated number of 682 collisions could have been avoided in autumn 2019, if turbines in the Belgian OWFs would have been idled during peaks of intense bird migration. These CRM results are based on several assumptions (e.g., avoidance rate, flight speed) and should therefore be handled with care and be considered as an estimate of the order of magnitude of the expected number of collisions. Also, the radar cannot reliably differentiate individual birds from small bird flocks (Fijn *et al.* 2015), meaning that the MTR values used as input for the CRM bird density data are underestimating the actual MTR. Fijn *et al.* (2015) expect, based

on visual validation of radar recordings, that this results in underestimating the MTR with maximum 10%. The uncertainty of the CRM results and the fact that we do not exactly know which species were registered by the radar does not allow to assess whether the number of migrating songbirds colliding with wind turbines at sea could have a significant effect at population level. Poot *et al.* (2011) used a Potential Biological Removal (PBR) approach to assess the cumulative collision effects of 11 OWFs in the Dutch part of the North Sea (hypothetical scenario). They concluded that a worst-case scenario would not cause negative population trends in the considered passerine species. If this is still the case for cumulative effects of all planned wind farms in the (southern) North Sea is unknown.

To reduce the number of collisions with wind turbines during such events, an effective measure is to idle the turbines (Cook *et al.* 2011; Marques *et al.* 2014; May 2017; McClure *et al.* 2021). These curtailment measures are often applied in onshore wind farms for local and migrating raptors and soaring birds. To our knowledge, no such stand-still procedures are currently being applied in OWFs. The Borssele measure, which imposes wind farm operators to idle turbines when the bird flux exceeds 500 birds.km<sup>-1</sup>.hour<sup>-1</sup> at rotor height, will be applied as from January 1<sup>st</sup>, 2023.

Our results demonstrate that we can monitor in near real-time if the bird flux at rotor height exceeds the Borssele threshold to idle turbines. However, using the threshold value for a near-real time application has proved impossible after consultation of the wind farm operators (pers. comm. Jos de Visser, Rijkswaterstaat). For the sake of not posing risks to the stability of the electricity network, offshore wind farm operators need to know at least 24 hours in advance, and preferably 48 hours, if turbines need to be idled. To remedy this, the University of Amsterdam is now developing a prediction model of intense bird migration, based on meteorological and bird

radar data. The main focus is to predict intense migration events, based on which idling wind turbines can be carefully planned for well in advance. To collect sufficient data in the area for the development of this model, the Dutch government invested in a network of dedicated bird radars at sea. Rijkswaterstaat has purchased six Robin Radar Max (3D) systems (personal comm. Jos de Visser, Rijkswaterstaat). One is already installed on the Borssele alpha platform. A second one will be installed in the Ørsted OWF in the North of the Borssele area and another one in Gemini OWF. The other three locations are to be decided. The Belgian radar data are also

available for the development of this model, if needed.

Currently, there is no stand-still procedure imposed in Belgian OWFs during intense bird migration. If no stand-still procedure would be imposed in the OWFs in Belgian waters, the Borssele wind turbines will be idled during events of intense bird migration, while Belgian turbines on the other side of the border are not. The environmental permits of the Belgian OWFs however foresee the possibility to start with such a procedure, so measures on both sides of the border could be aligned in the future.

## References

- Alerstam T. 1990. Bird migration. Cambridge University Press, Cambridge, pp. 420.
- Alerstam, T., Rose'n, M., Bäckman, J., Ericson, P.G.P. & Hellgren, O. 2007. Flight speeds among bird species: allometric and phylogenetic effects. *PLoS Biology* 5 (8): e197. <https://doi.org/10.1371/journal.pbio.0050197>
- Band, B. 2012. *Using a Collision Risk Model to Assess Bird Collision Risks for Offshore Wind Farms*. British Trust for Ornithology.
- Brabant, R. & Degraer, S. 2017. Autumn bird migration registered with vertical radar at the Thorntonbank 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*. Chapter 8: 115-127. Royal Belgian Institute of Natural Sciences, Brussels.
- Brabant, R. & Vanermen, N. 2020. Collision risk for six seabird species in the first Belgian offshore wind farm zone, 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* Chapter 4: 43-53. Royal Belgian Institute of Natural Sciences, Brussels.
- Brabant, R., Vigin, L., Stienen, E.W.M., Vanermen, N. & Degraer, S. 2012. Radar research on the impact of offshore wind farms on birds: preparing to go offshore. In: Degraer, S., Brabant, R. & Rumes, B. (eds) *Offshore Wind Farms in the Belgian Part of the North Sea – Heading for an Understanding of Environmental Impacts*: 111-126. Management Unit of the North Sea Mathematical Models – Marine Ecosystem Management Unit, Brussels.
- Brabant, R., Vidao, J., Smith, A. & Degraer, S. 2016. Bird radar study in the Belgian part of the North Sea: Developments to improve bird detection. In: Degraer, S., Brabant, R., Rumes, B. & Vigin, L. (eds) *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea. Environmental Impact Monitoring Reloaded* Chapter 13: 223-232. Royal Belgian Institute of Natural Sciences, Brussels.

- Bourne, W.P.R. 1980. The midnight descend, dawn ascent and reorientation of landbirds migrating across the North Sea in autumn. *Ibis* 122: 536-540.  
<https://doi.org/10.1111/j.1474-919X.1980.tb00915.x>
- Bradarić, M., Bouten, W., Fijn, R.C., Krijgsveld, K.L. & Shamoun-Baranes, J. 2020. Winds at departure shape seasonal patterns of nocturnal bird migration over the North Sea. *Journal of Avian Biology* 51 (10): e02562. <https://doi.org/10.1111/jav.02562>
- Bruderer B. 1997a. The study of bird migration by radar. Part I: the technical basis. *Naturwissenschaften* 84: 1-8.
- Bruderer B. 1997b. The study of bird migration by radar. Part II: major achievements. *Naturwissenschaften* 84: 45-54.
- Buurma L.S. 1987. Patronen van hoge vogeltrek boven het Noordzeegebied in oktober. *Limosa* 60: 63-74.
- Chamberlain, D.E., Rehfisch, M.R., Fox, A.D., Desholm M. & Anthony, S.J. 2006. The effect of avoidance rates on bird mortality predictions made by wind turbine collision risk models. *Ibis* 148: 198–202. <https://doi.org/10.1111/j.1474-919X.2006.00507.x>
- Cook, A.S.C.P., Ross-Smith, V.H, Roos, S., Burton, N.H.K., Beale, N., Coleman, C., Daniel, H., Fitzpatrick, S., Rankin, E., Norman, K. & Martin, G. 2011. Identifying a range of options to prevent or reduce avian collision with offshore wind farms using a UK-based case study. *BTO Research Report* 580: 197. British Trust for Ornithology, Norfolk, UK.
- Cramp, S. (ed), 1977-1985. *The birds of the Western Palearctic. Handbook of the Birds of Europe, the Middle East and North Africa, Vol. 1, 3 & 4.* Oxford University Press, Oxford.
- DeTect Inc. 2010. Merlin/Harrier Target Tracking Algorithm. P10-012, Revision B. pp. 19.
- Eastwood E. 1967. Radar ornithology. London, UK, Methuen, pp. 278.
- Everaert, J., 2014. Collision risk and micro-avoidance rates of birds with wind turbines in Flanders. *Bird Study* 61: 220–230. <https://doi.org/10.1080/00063657.2014.894492>
- Fijn, R.C., Krijgsveld, K.L., Poot, M.J.M. & Dirksen, S. 2015. Bird movements at rotor heights measured continuously with vertical radar at a Dutch offshore wind farm. *Ibis* 157 (3): 558-566.  
<https://doi.org/10.1111/ibi.12259>
- Garthe, S. & Hüppop, O. 2004. Scaling possible adverse effects of marine wind farms on seabirds: developing and applying a vulnerability index. *Journal of Applied Ecology* 41 (4): 724-734.  
<https://doi.org/10.1111/j.0021-8901.2004.00918.x>
- Gauthreaux, S.A. & Belser, C.G. 2003. Radar ornithology and biological conservation. *The Auk* 120 (2): 266-277.
- Gyimesi, A., de Jong, J.W., Potiek A. & Bravo Rebolledo, E.L. 2018. Actualisatie van KEC vogelaanvaring berekeningen volgens Routekaart 2030. Rapportnr. 18-290, Rapport Bureau Waardenburg, Culemborg.
- Hüppop, O., Dierschke, J., Exo, K.-M., Fredrich, E. & Hill, R. 2006. Bird migration studies and potential collision risk with offshore wind turbines. *Ibis* 148 (s1): 90-109.  
<https://doi.org/10.1111/j.1474-919X.2006.00536.x>

- Krijgsveld, K., Fijn, R., Japink, M., van Horssen, P., Heunks, C., Collier, M., Poot, M., Beuker, D. & Dirksen, S. 2011. Effect studies offshore wind farm Egmond aan Zee - Final report on fluxes, flight altitudes and behaviour of flying birds. Report No. OWEZ\_R\_231\_T1\_20111114\_flux&flight, Report by Bureau Waardenburg bv, pp. 334.
- Lensink, R., Camphuysen, C.J., Jonkers, D.A., Leopold, M.F., Schekkerman, H. & Dirksen, S. 1999. Falls of migrant birds, an analysis of current knowledge. Report No. 99.55, Bureau Waardenburg bv, Culemborg, Netherlands.
- Lensink, R., van Gasteren, H., Hustings, F., Buurma, L.S., van Duin, G., Linnartz, L., Vogelzang, F. & Witkamp, C. 2002. Vogeltrek over Nederland 1976-1993. Schuyt & Co, Haarlem.
- Leopold, M.F., Boonman, M., Collier, M. P., Davaasuren, N., Jongbloed, R. H., Lagerveld, S., van der Wal, J.T. & Scholl, M.M. 2014. A first approach to deal with cumulative effects on birds and bats of offshore wind farms and other human activities in the Southern North Sea.
- Liechti, F., Aschwanden, J., Blew, J., Boos, M., Brabant, R., Dokter, A.M., Kosarev, V., Lukach, M., Maruri, M., Reyniers, M., Schekler, I., Schmaljohann, H., Schmid, B., Weisshaupt, N. & Sapir, N. 2019. Cross-calibration of different radar systems for monitoring nocturnal bird migration across Europe and the Near East. *Ecography* 42 (5): 887-98. <https://doi.org/10.1111/ecog.04041>
- Manola, I., Bradarić, M., Groenland, R., Fijn, R., Bouten, W. & Shamoun-Baranes, J. 2020. Associations of synoptic weather conditions with nocturnal bird migration over the North Sea. *Frontiers in Ecology and Evolution* 8: 542438. <https://doi.org/10.3389/fevo.2020.542438>
- Marques, A.T., Batalha, H., Rodrigues, S., Costa, H., Pereira, M. J. R., Fonseca, C., Mascarenhas, M. & Bernardino, J. 2014. Understanding bird collisions at wind farms: An updated review on the causes and possible mitigation strategies. *Biological Conservation* 179: 40-52. <https://doi.org/10.1016/j.biocon.2014.08.017>
- Masden, E. 2015. Developing an avian collision risk model to incorporate variability and uncertainty. *Scottish Marine and Freshwater Science* 6 (14): pp. 43. <https://doi.org/10.7489/1659-1>
- May, R.F. 2017. Mitigation for birds. In: Perrow, M.R. (ed.) *Wildlife and Windfarms, Conflicts and Solutions. Volume 2: Monitoring and Mitigation*: 124-144.
- McClure, C.J.W., Rolek, B.W., Dunn, L., McCabe, J.D., Martinson, L. & Katzner T. 2021. Eagle fatalities are reduced by automated curtailment of wind turbines. *Journal of Applied Ecology* 58 (3): 446-452. <https://doi.org/10.1111/1365-2664.13831>
- Nilsson, C., Dokter, A.M., Verlinden, L., Shamoun-Baranes, J., Schmid, B., Desmet, P., Bauer, S., Chapman, J., Alves, J.A., Stepanian, P.M, Sapir, N., Wainwright, C., Boos, M., Górska, A., Menz, M.H.M, Rodrigues, P., Leijnse, H., Zehndjiev, P., Brabant, R., Haase, G., Weisshaupt, N., Ciach, M. & Liechti, F. 2019. Revealing patterns of nocturnal migration using the European weather radar network. *Ecography* 42 (5): 876-86. <https://doi.org/10.1111/ecog.04003>
- Poot, M.J.M., van Horssen, P.W., Collier, M.P., Lensink, R. & Dirksen, S. 2011. *Effect Studies Offshore Wind Egmond aan Zee: Cumulative Effects on Seabirds. A modelling Approach to Estimate Effects on Population Levels in Seabirds*. NoordzeeWind Report OWEZ\_R\_212\_20111021\_Cumulative\_Effects. Bureau Waardenburg report, 11-026.
- R Core Team, 2015. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. URL Available from <https://www.R-project.org/>.
- Rijkswaterstaat, 2019. *Kavelbesluit V windenergiegebied Hollandse Kust (noord)*. pp. 113.

- Schmaljohann, H., Liechti, F., Bächler, E., Steuri, T. & Bruderer, B. 2008 Quantification of bird migration by radar – a detection probability problem. *Ibis* 150: 342-355.  
<https://doi.org/10.1111/j.1474-919X.2007.00797.x>
- Stienen, E.W.M., Van Waeyenberge, J., Kuijken, E. & Seys, J. 2007. Trapped within the corridor of the Southern North Sea: the potential impact of offshore wind farms on seabirds. *In: de Lucas, M., Janss, G.F.E. & Ferrer, M. (eds) Birds and Wind Farms - Risk Assessment and Mitigation: 71-80. Quercus, Madrid.*
- Welcker, J., Liesenjohann, M., Blew, J., Nehls, G. & Grünkorn, T., 2017. Nocturnal migrants do not incur higher collision risk at wind turbines than diurnally active species. *Ibis* 159: 366-373.  
<https://doi.org/10.1111/ibi.12456>
- Wickham, H. 2007. Reshaping Data with the reshape Package. *Journal of Statistical Software* 21 (12): 1-20. Available from <http://www.jstatsoft.org/v21/i12/>.
- Wickham, H. 2011. The Split-Apply-Combine Strategy for Data Analysis. *Journal of Statistical Software* 40 (1): 1–29. Available from <http://www.jstatsoft.org/v40/i01/>.
- Wickham, H. 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York. Available from <https://ggplot2.tidyverse.org>.
- Wilke, C.O. 2016. cowplot: Streamlined Plot Theme and Plot Annotations for ‘ggplot2’. R package version 0.6.2. Available from <http://CRAN.R-project.org/package=cowplot>.



# CHAPTER 5

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## CONTINUED EXPANSION OF THE ARTIFICIAL REEF EFFECT IN SOFT-SEDIMENT EPIBENTHOS AND DEMERSAL FISH ASSEMBLAGES IN TWO ESTABLISHED (10 YEARS) BELGIAN OFFSHORE WIND FARMS

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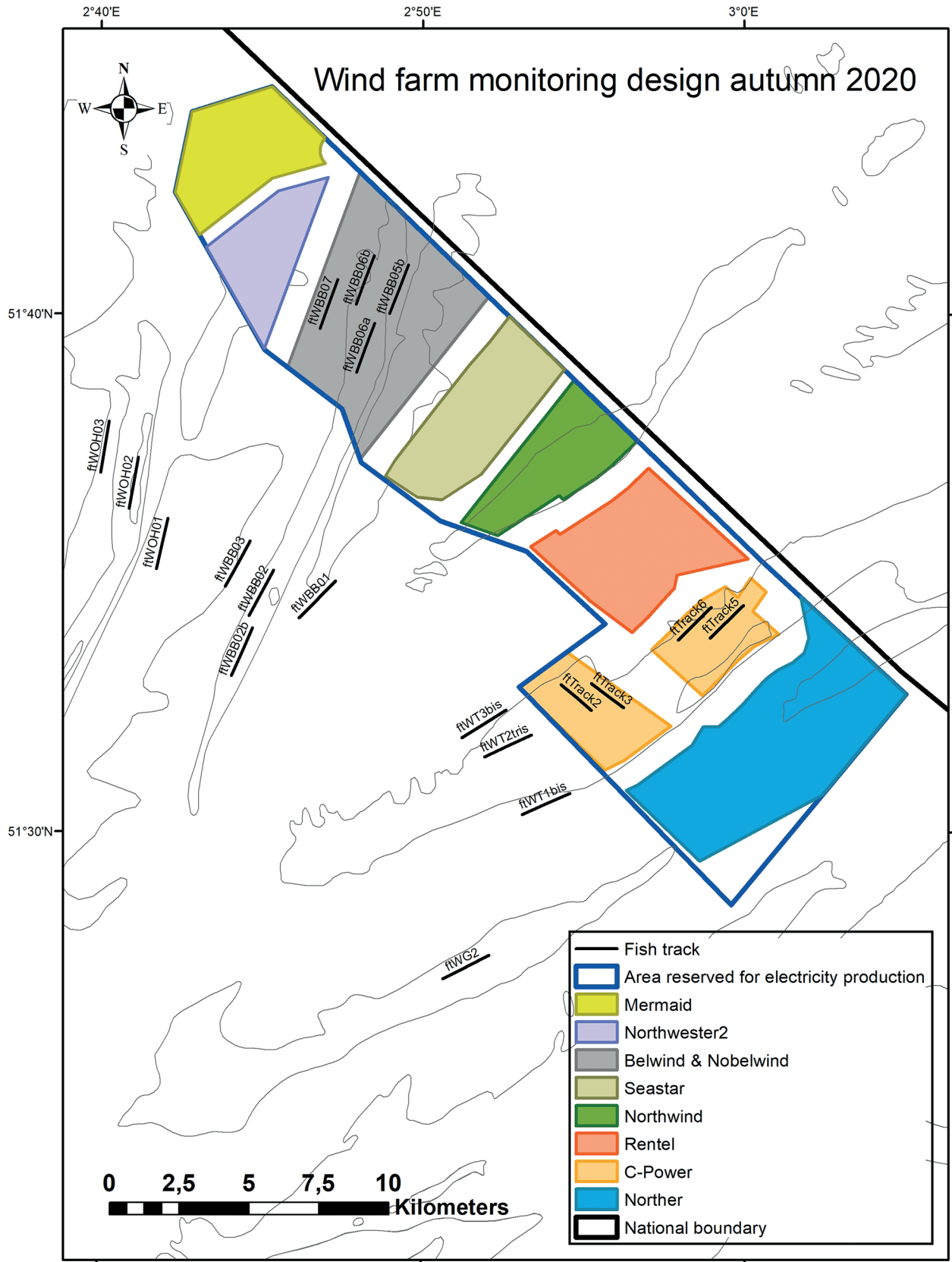
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Since 2005, the effect of offshore windfarms (OWFs) on the soft sediment epibenthos and demersal fish assemblages is being monitored in the Belgian part of the North Sea. Long-term yearly monitoring campaigns in C-Power (54 turbines) and Belwind (56 turbines) allow us to evaluate how the soft sediment ecosystem in between the turbines responds to the introduction of hard substrates. Two major changes are expected: an ‘artificial reef effect’ (e.g. Coolen *et al.* 2020) and a fisheries exclusion or local ‘refugium effect’ (Handley *et al.* 2014). Changes related to the artificial reef effect are most obvious at turbine scale and their near surroundings (Dannheim *et al.* 2019, 2020). Although an expansion of the reef effect beyond the immediate vicinity of the turbines is possible (Degraer *et al.* 2020). De Backer *et al.* (2020) observed such a reef effect expansion seven years after the construction of OWFs C-Power and Belwind, as suggested by significantly increased densities of epifouling species (blue mussel *Mytilus edulis* and anemones *Anthozoa* spp.) and an increased occurrence of other hard substrate-associated species on the soft sediments in between the turbines (>200 m).

Additionally, slightly increased densities were recorded within C-Power OWF for some common soft sediment-associated fish species in between the turbines, hinting towards the first signs of a refugium effect, probably resulting from a combination of fisheries exclusion and increased food availability, partly related to the artificial reef effect.

This short communication describes whether these observations (*i.e.* expansion of the reef effect and first signs of a refugium effect on the soft sediments in between the turbines) remain valid, using the results of our 2020 sampling campaign, respectively nine (C-Power) and ten (Belwind) years after construction. Epibenthos and bottom-dwelling fish were sampled at 19 locations (four within C-Power, four within Belwind and eleven reference locations) with an 8-meter shrimp beam trawl (22 mm mesh in the cod end) equipped with a bolder chain (Fig. 1). The net was towed for 15 minutes at an average speed of 4 knots over approximately 1 nautical mile. Several metadata were recorded (time, coordinates, trajectory, sampling depth, etc.) to allow for a correct conversion towards a standardized sampling area (1000 m<sup>2</sup>). All fish



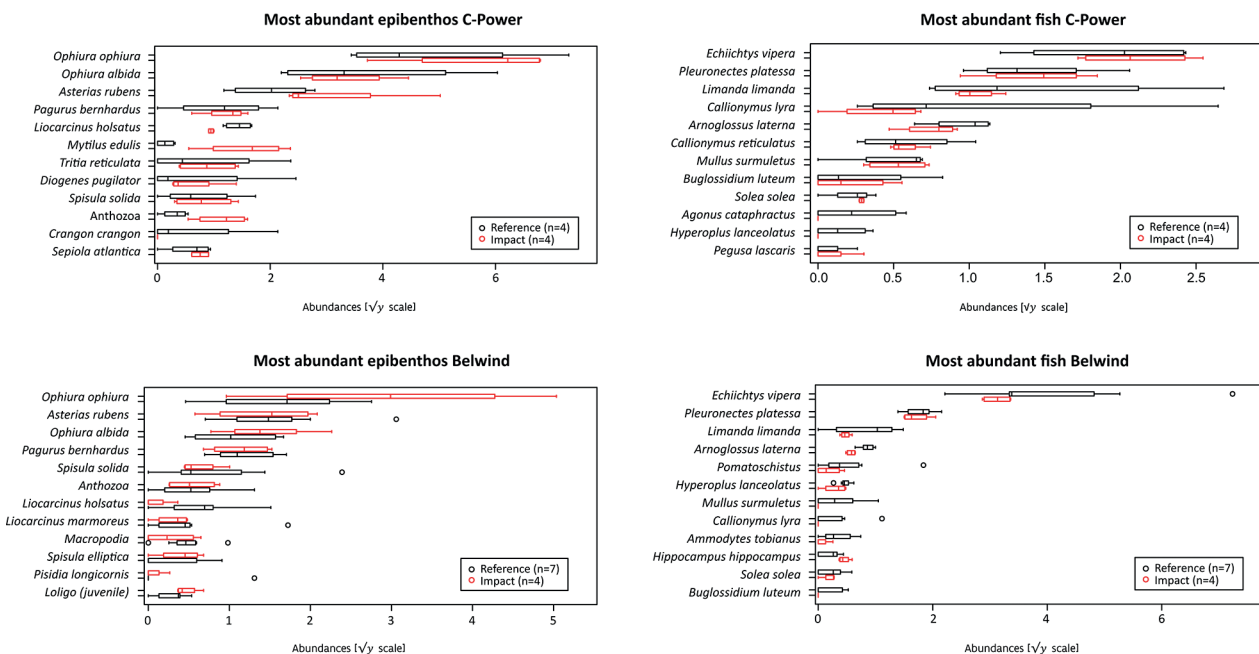
**Figure 1.** Overview map showing the 2020 trawl locations at the C-Power and Belwind concession area and the respective reference locations.

and epibenthos species were identified and counted, bulk wet weights were registered for all epibenthos species, and all fish, shrimps and crabs were measured. As pelagic fish (e.g. mackerel, horse mackerel, herring, sprat, anchovy) and jellyfish are not quantitatively sampled with a beam trawl, these were further excluded from all analyses. As such, throughout this chapter the term fish refers to both demersal and benthic-pelagic fish species.

Several univariate variables (species number, total density and total biomass; the latter only for epibenthos) were calculated per ecosystem component and for the combined hard substrate-associated species (see further). Type III Analyses of Variance (ANOVA) using the Wald F test and Kenward-Roger degrees of freedom (R package ‘Car’) were ran on linear mixed-effect models (lmer), with wind farm (Belwind and C-Power), impact factor (reference vs impact) and their interaction as fixed effects, and position on the sandbank (top or gully) as random effect. The univariate response variables were log-transformed where necessary to meet model requirements. The interaction (OWF\*Impact) was omitted

when not significant, prior to running the ANOVA, whereas in case the interaction was significant, a pairwise test using the lsmeans function with Kenward-Roger degrees of freedom was performed. Furthermore, multivariate model-based approaches were performed with the package ‘mvabund’ (Wang *et al.* 2012), to explore differences in species composition. Square root transformed multivariate species abundance data were fitted against the impact factor for each OWF separately using the *manyglm* function with ‘negative binomial’ family. The mean-variance assumption was checked by plotting residuals versus fits. Subsequently, univariate tests were run per species to investigate individual species effects. All analyses were done using R version 4.0.3 (2020-10-10).

Based on the 2020 dataset, no significant differences could be noted between impact and reference samples for both epibenthos and fish assemblages, not for C-Power (*manyglm*,  $p=0.11$  and  $p=0.39$ , respectively) nor for Belwind (*manyglm*,  $p=0.14$  and  $p=0.07$ , respectively) (Fig. 2). Comparably, no significant effects were observed in number of species (S) for both ecosystem components



**Figure 2.** Box-and-whisker-plots showing minimum, maximum, 0.25 percentile, 0.75 percentile and median sqrt densities for most abundant epibenthos and demersal fish species in reference (black) and impact (red) samples for C-Power and Belwind offshore wind farms, sampled in September-October 2020. Outliers are visualized as circles.

**Table 1.** Average and standard deviation (SD) for epibenthos and fish species richness (S), overall density (N) and biomass (W) for the reference and impact samples gathered in 2020 in C-Power and Belwind offshore wind farms.

Ecosystem component	OWF	Impact	Avg. S±SD	Avg. N±SD (ind.1000 m <sup>-2</sup> )	Avg. W±SD (g WW.1000 m <sup>-2</sup> )
<b>Epibenthos</b>	C-Power	Reference	18±1	60±26	1957±553
		Impact	20±3	69±19	2825±562
	Belwind	Reference	14±4	14±10	870±695
		Impact	14±2	20±12	730±290
<b>Fish</b>	C-Power	Reference	12±2	13±7	–
		Impact	9±1	10±2	–
	Belwind	Reference	12±5	27±12	–
		Impact	8±1	14±2	–

in both OWFs (Impact,  $p=0.05$ ) (Table 1). This corroborates our earlier findings that the soft sediment epibenthos and fish assemblage in between the turbines underwent no drastic changes due to the presence of OWFs (De Backer & Hostens 2017; De Backer *et al.* 2020).

On the other hand, the overall epibenthos density (N) and biomass (W) were significantly affected by the presence of the OWFs (Table 1), with significantly higher densities in between the turbines for both OWFs (Impact,  $p=0.001$ ), and significantly higher overall epibenthos biomass within C-Power (pairwise  $p=0.02$ ). This overall higher density is mainly attributed to increased abundances (although not significant) of some dominant epibenthic species in the impact samples compared to the reference samples (Fig. 2). Especially, densities of common starfish *Asterias rubens* were higher in between the turbines of C-Power compared to the reference samples (average  $10.8\pm 8.3$  and  $4.4\pm 2.6$  ind.  $1000\text{ m}^{-2}$ , respectively). We also observed increased densities of blue mussel *Mytilus edulis* within C-Power (avg.  $2.9\pm 1.96$  and  $0.08\pm 0.02$  ind.  $1000\text{ m}^{-2}$ , respectively for impact and reference), and anemones *Anthozoa* spp. (most probably *Metridium* spp.) also displayed higher values in the impact samples (avg.  $1.5\pm 0.9$  and  $0.2\pm 0.1$  ind.  $1000\text{ m}^{-2}$  respectively). Blue mussel and anemones (most probably *Metridium* spp.) are likely drop-offs from the turbines

since they are known to foul on the turbine foundations (De Mesel *et al.* 2015; Krone *et al.* 2013; Kerckhof *et al.* 2019). Starfish are known to predate on mussels (Kautsky *et al.* 1990; Norberg & Tedengren 1995; Reimer & Tedengren 1996), so higher starfish densities are probably the result of an attraction to the increased presence of blue mussel.

Higher epibenthos densities in Belwind OWF were only recorded for the brittle star *Ophiura albida* (avg.  $11.2\pm 9.1$  and  $3.2\pm 2.5$  ind.  $1000\text{ m}^{-2}$ , respectively, for impact and reference) (Fig. 2). This species is typically associated with soft sediments, showing stationary burrowing behaviour and predominantly feeding on infaunal organisms (Boos *et al.* 2010). It remains unclear whether the higher densities in Belwind can be attributed to an OWF effect, related to changed food availability (*e.g.* changes in macrobenthos species) or changed predation pressure (*e.g.* changes in fish abundances). Up till now, no clear indications of such changes were recorded in Belwind (Lefaible *et al.* 2019; De Backer *et al.* 2020), so we assume that the increased density mainly reflects natural variation.

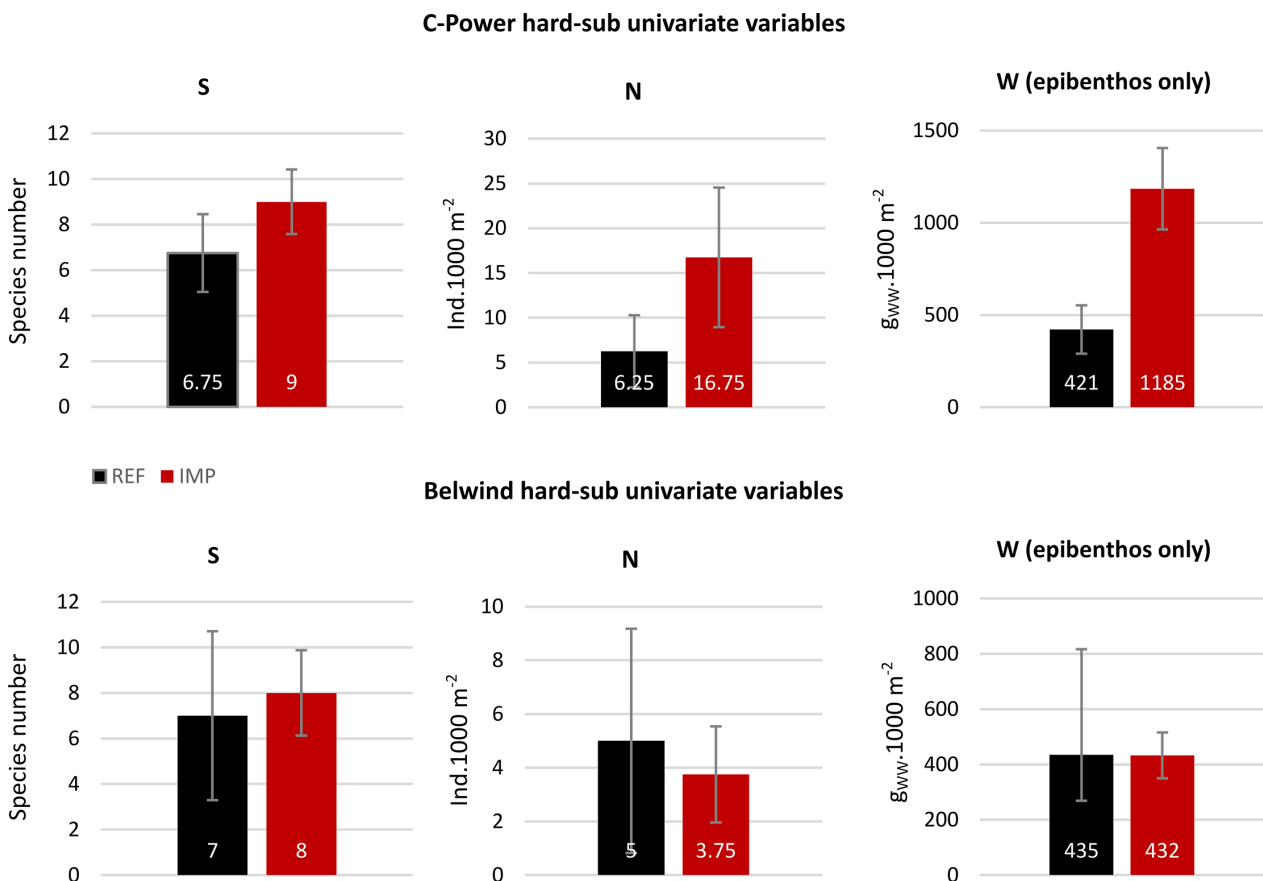
In contrast to epibenthos, the overall fish density was significantly lower in the impact samples compared to the reference samples for both OWFs (Impact,  $p=0.02$ ) (Table 1), although at the individual species level no such differences could be discerned for the 2020 data (Fig. 2). These observations may

partly negate the first sign of a refugium effect that was noted for C-Power based on the longer time series analysis (De Backer *et al.* 2020). Of course, fish are mobile species, and the high standard deviations (especially in the reference samples), partly related to the low number of samples, suggest that the real refugium effect might have been obscured in 2020. This warrants further investigation and especially an extended time series is needed to assess the refugium effect.

The expansion of the artificial reef effect in the soft sediment habitat comprises several factors, such as the drop-off of hard substrate species, organic enrichment through faecal deposits of suspension feeders and changes in habitat structure (*e.g.* presence of empty mussel shells) (Degraer *et al.* 2020). For this study, we had a closer look into the presence of such drop-offs and other typical hard substrate-associated species (assignment

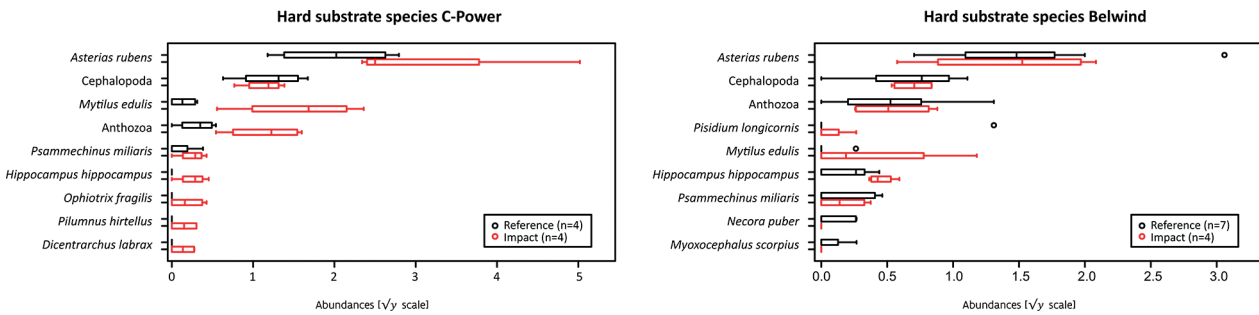
based on species-identification.org, www.sealifebase.ca and www.marlin.ac.uk). A significantly higher number of hard substrate-species (S) was observed in between the turbines compared to the reference samples for both OWFs (impact,  $p=0.02$ ), where the response was again most pronounced in C-Power (Fig. 3). Also the hard substrate-species composition was significantly different in C-Power impact vs reference samples (manyglm,  $p=0.013$ ) (Fig. 4).

Aside the number of species, also significantly higher densities ( $p=0.0007$ ) and biomass values ( $p=0.0034$ ), were recorded for C-Power impact vs reference samples (Fig. 3). At species level, all hard substrate-species, such as blue mussel, Anthozoa, sea-urchin *Psammechinus miliaris*, short-snouted seahorse *Hippocampus hippocampus*, brittle star *Ophiothrix fragilis*, hairy crab *Pilumnus hirtellus*, European seabass *Dicentrarchus*



**Figure 3.** Average species richness (S), density (N) and biomass (W) ( $\pm$  standard deviation) for hard-sub associated species (fish, epibenthos and cephalopods), for impact and reference samples in C-Power and Belwind, gathered in September-October 2020. Numbers within each barplot are the respective average values.





**Figure 4.** Box-and-whisker-plots showing minimum, maximum, 0.25 percentile, 0.75 percentile and median sqrt densities for all hard substrate species (fish, epibenthos, and cephalopods) in reference (black) and impact (red) samples for C-Power and Belwind taken during autumn 2020. Outliers are visualized as circles.

*labrax*, displayed higher densities in the C-Power impact samples (Fig. 4). However, this was only significant for blue mussel ( $p=0.022$ ) and nearly significant for *Anthozoa* spp. ( $p=0.07$ ). For Belwind, the patterns for hard substrate-associated species were again more subtle, with slightly higher densities for only a few species (blue mussel, sea horse and long-clawed porcelain crab *Pisidia longicornis*) in the OWF samples (Fig. 4).

For this part of the study, we also included the cephalopods (*Alloteuthis subulata*, *Loligo vulgaris*, juvenile *Loligo* sp., *Sepia officinalis* and *Sepiolo atlantica*) as hard substrate-associated species. These species are known to attach their eggs to hard substrates (Mapes & Nuetzel 2009), which might influence their presence on the soft sediments in between the turbines. However, no obvious differences were noted for this group of benthopelagic organisms in 2020 (Fig. 4).

Overall, the results for 2020 corroborate our earlier findings of an artificial reef effect expansion in the OWFs towards the soft sediments in between the turbines ( $> 200$  m distance), which started about seven years after construction (De Backer & Hostens 2017; De Backer *et al.* 2020). Epibenthic organisms like Anthozoa and blue mussel, which are known to foul on the turbines (Kerckhof *et al.* 2019), other epibenthic organisms (*e.g.* *Ophiotrix fragilis*, *Pilumnus hirtellus*) that appear in higher densities on the scour protection layer surrounding the turbines, and fish species that are attracted to the ‘reef’ structures

(*e.g.* seahorse and seabass), all seem to be expanding into the soft sediments, albeit in relatively low densities. This proves that changes induced by OWFs are not restricted to the turbines and scour protection layer, but may also extend in four dimensions (Degraer *et al.* 2020).

Introducing artificial structures into a soft-sediment ecosystem will alter diverse cause-effect pathways that operate over different spatial and temporal scales (Dannheim *et al.* 2020). On the long term, local turbine-scale effects may cascade into further environmental responses. Furthermore, the observed effects were most pronounced in C-Power compared to Belwind OWF, suggesting that the environmental responses in epibenthic and demersal benthopelagic fish assemblages to the installation of OWFs is likely to be site-specific. Therefore, extrapolation of the results to other OWFs should be done with care, while monitoring need to be continued to grasp any further spatial distribution of the artificial reef and refugium effects.

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## References

- Boos, K., Gutow, L., Mundry, R. & Franke, H.-D. 2010. Sediment preference and burrowing behaviour in the sympatric brittlestars *Ophiura albida* Forbes, 1839 and *Ophiura ophiura* (Linnaeus, 1758)(Ophiuroidea, Echinodermata). *Journal of Experimental Marine Biology and Ecology* 393 (1-2): 176-181. <https://doi.org/10.1016/j.jembe.2010.07.021>
- Coolen, J.W., Van Der Weide, B., Cuperus, J., Blomberg, M., Van Moorsel, G.W., Faasse, M.A., Bos, O.G., Degraer, S. & Lindeboom, H.J. 2020. Benthic biodiversity on old platforms, young wind farms, and rocky reefs. *ICES Journal of Marine Science* 77 (3): 1250-1265. <https://doi.org/10.1093/icesjms/fsy092>
- Dannheim, J., Degraer, S., Elliot, M., Smyth, K. & Wilson, J.C. 2019. Seabed communities. In: Perrow, M.R. (ed.) *Wildlife and Wind Farms, Conflicts and Solutions. Volume 3 Offshore: Potential Effects*. Pelagic Publishing, Exeter, pp. 64-85.
- Dannheim, J., Bergström, L., Birchenough, S.N., Brzana, R., Boon, A.R., Coolen, J.W., Dauvin, J.-C., De Mesel, I., Derweduwen, J. & Gill, A.B. 2020. Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research. *ICES Journal of marine Science* 77 (3): 1092-1108. <https://doi.org/10.1093/icesjms/fsz018>
- De Backer, A. & Hostens, K. 2017. Effects of Belgian offshore windfarms on soft sediment epibenthos and fish: an updated time series. In: Degraer, S. et al. *Environmental Impacts of offshore Wind Farms in the Belgian Part of the North Sea: A continued Move towards Integration and Quantification*. pp. 59-71.
- De Backer, A., Buyse, J. & Hostens, K. 2020. A decade of soft sediment epibenthos and fish monitoring at the Belgian offshore wind farm area. In: Degraer, S. et al. *Environmental Impacts of offshore Wind Farms in the Belgian Part of the North Sea: Empirical Evidence inspiring Priority Monitoring*. pp. 79-113.
- Degraer, S., Carey, D.A., Coolen, J.W., Hutchison, Z.L., Kerckhof, F., Rumes, B. & Vanaverbeke, J. 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning: A synthesis. *Oceanography* 33 (4): 48-57. <https://doi.org/10.5670/oceanog.2020.405>
- 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: 1-14. <https://doi.org/10.1007/s10750-014-2157-1>
- Handley, S.J., Willis, T.J., Cole, R.G., Bradley, A., Cairney, D.J., Brown, S.N. & Carter, M.E. 2014. The importance of benchmarking habitat structure and composition for understanding the extent of fishing impacts in soft sediment ecosystems. *Journal of Sea Research* 86: 58-68. <https://doi.org/10.1016/j.seares.2013.11.005>
- Kautsky, N., Johannesson, K. & Tedengren, M. 1990. Genotypic and phenotypic differences between Baltic and North Sea populations of *Mytilus edulis* evaluated through reciprocal transplantations. I. Growth and morphology. *Marine Ecology Progress Series*: 203-210. <https://doi.org/10.3354/meps059203>
- Kerckhof, F., Rumes, B. & Degraer, S. 2019. About “mytilisation” and “slimeification”: A decade of succession of the fouling assemblages on wind turbines off the Belgian coast. In: Degraer et al. *Environmental Impacts of offshore Wind Farms in the Belgian Part of the North Sea: marking a Decade of Monitoring, Research and Innovation*. pp. 73-84.

- Krone, R., Gutow, L., Joschko, T. & Schröder, A. 2013. Epifauna dynamics at an offshore foundation - Implications of future wind power farming in the North Sea. *Marine Environmental Research* 85: 1-12. <https://doi.org/10.1016/j.marenvres.2012.12.004>
- 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. et al. *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: marking a Decade of Monitoring, Research and Innovation. Memoirs on the Marine Environment*. pp. 47-63.
- Mapes, R.H. & Nuetzel, A. 2009. Late Palaeozoic mollusc reproduction: cephalopod egg-laying behavior and gastropod larval palaeobiology. *Lethaia* 42 (3): 341-356. <https://doi.org/10.1111/j.1502-3931.2008.00141.x>
- Norberg, J. & Tedengren, M. 1995. Attack behaviour and predatory success of *Asterias rubens* L. related to differences in size and morphology of the prey mussel *Mytilus edulis* L. *Journal of Experimental Marine Biology and Ecology* 186 (2): 207-220. [https://doi.org/10.1016/0022-0981\(94\)00158-A](https://doi.org/10.1016/0022-0981(94)00158-A)
- Reimer, O. & Tedengren, M. 1996. Phenotypical improvement of morphological defences in the mussel *Mytilus edulis* induced by exposure to the predator *Asterias rubens*. *Oikos*: 383-390. <https://doi.org/10.2307/3545878>
- Wang, Y., Naumann, U., Wright, S.T. & Warton, D.I. 2012. Mvabund – an R package for model-based analysis of multivariate abundance data. *Methods in Ecology and Evolution* 3 (3): 471-474. <https://doi.org/10.1111/j.2041-210X.2012.00190.x>

# CHAPTER 6

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## SMALL-SCALE DISTRIBUTION PATTERNS OF FLATFISH ON ARTIFICIAL HARD SUBSTRATES IN A BELGIAN OFFSHORE WIND FARM

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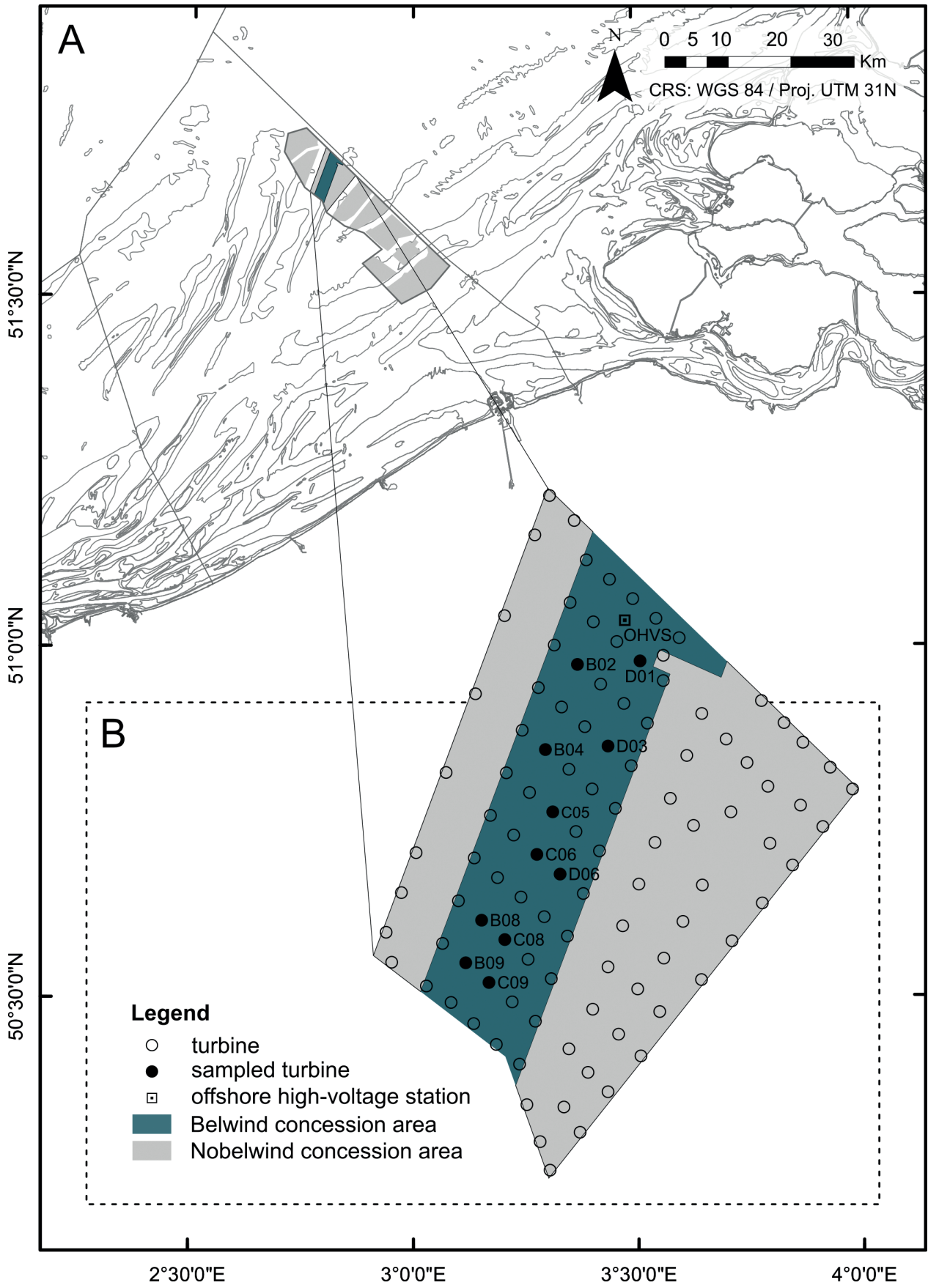
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Since the last decade, many large-scale offshore wind farms are being built in European waters (Soares-Ramos *et al.* 2020). The majority of the turbines (81%) are fixed in the bottom with monopile foundations and accommodated with a scour protection layer (SPL) to keep the surrounding soft sediments in place (WindEurope 2021). The turbines and SPL's provide new habitats, especially in soft-sediment areas, influencing the local marine environment and its associated biota in various ways (Lindeboom *et al.* 2015; Degraer *et al.* 2020). A pronounced effect of introduced hard substrates is the attraction and concentration of fish and epifaunal organisms, generally referred to as the 'artificial reef effect' (Petersen *et al.* 2006). Significantly higher densities of round fish species such as cod *Gadus morhua* and pouting *Trisopterus luscus* (Reubens *et al.* 2013), but also crustaceans (e.g. European lobster *Homarus gammarus* and edible crab *Cancer pagurus*) (Krone *et al.* 2017), have been recorded near turbines and their foundations compared to the surrounding sediments, which is commonly explained by an increase in feeding and/or shelter opportunities (Bergström *et al.* 2013; Degraer *et al.* 2020).

Up till now, there are no indications that such an artificial reef effect also exists

for flatfish species. Most studies that looked at the attraction of fish towards turbines and the surrounding SPL find no significant effect for flatfish species or even suggest avoidance behaviour in relation to hard substrates (Krone *et al.* 2017; van Hal *et al.* 2017). However, their sampling design did not specifically focus on flatfish, whose passive behaviour is very different from more active benthopelagic and pelagic species, and therefore a sampling bias could have occurred (Gibson 1997). Moreover, most mandatory monitoring programmes mainly focus on the effects on the soft sediment habitat at a distance of ca. 200 m from the turbines, while attraction to the hard substrate habitat often takes place at a much smaller scale (Bergström *et al.* 2013; Wilber *et al.* 2018).

The current study investigated the OWF artificial reef effect for different flatfish species, through 20 visual diving transects in the Belgian Belwind OWF. We focused on small-scale (< 50 m) distribution patterns in flatfish abundance around the turbines, covering both SPL and the nearby soft-sediment. The Belwind OWF is located on the Bligh Bank at a distance of 46-52 km from the Belgian coast where water depth varies between 15 and 37 m (Fig. 1). The Belwind OWF was constructed between August



**Figure 1.** Location of the Belwind wind farm within the offshore wind concession area in the Belgian part of the North Sea (BPNS) (A) and overview of sampled turbines (●) in the Belwind wind farm (B).

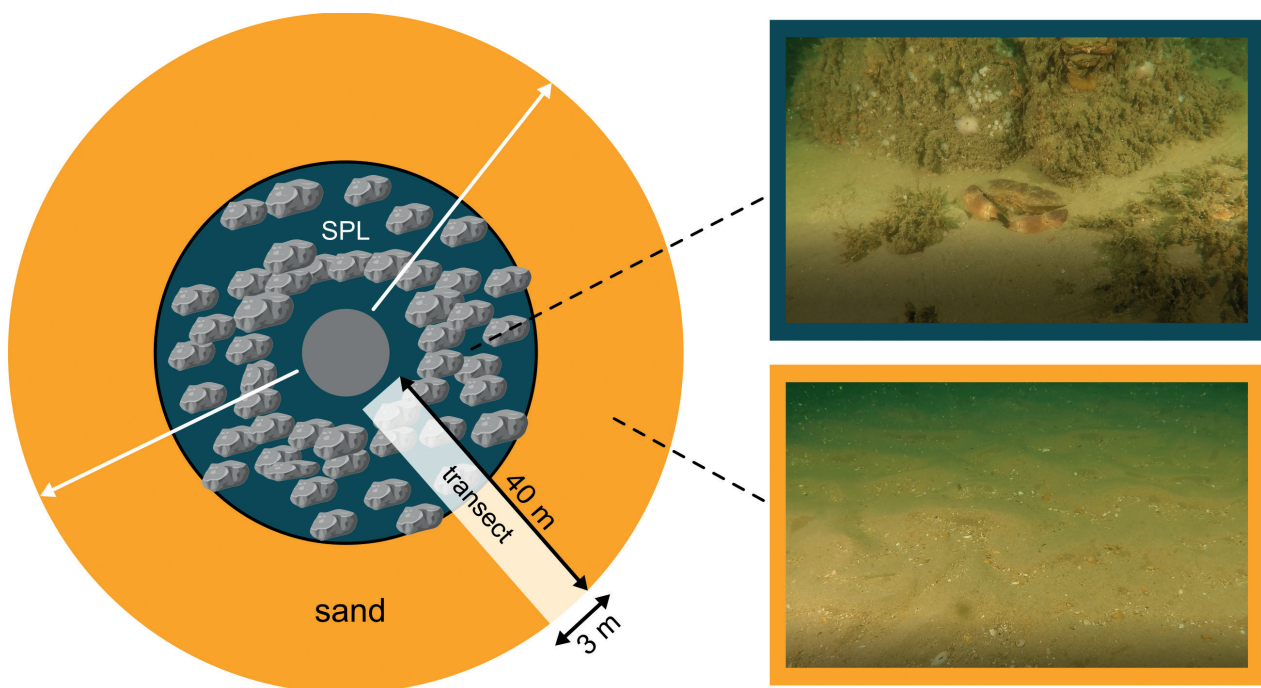


2009 and December 2010 and consists of 56 turbines (55 monopile foundations - Vestas 3 MW and 1 jacket foundation - Haliade 6 MW, built in 2013), each surrounded by a rocky SPL. Between July and August 2019, we surveyed flatfish around 11 randomly chosen turbines, which were completely surrounded by other turbines to avoid any fringe effects.

Depending on the prevailing conditions such as visibility and current speed, one to three diving transects in different directions from the turbine were covered within each dive (Fig. 2). Two divers descended along the turbine, secured a measuring tape at the bottom of the monopile and started swimming in a straight line away from the turbine. As the SPL's had different dimensions, a fixed distance of 40 m was covered during each transect to standardize the data. One diver visually scanned the area for flatfish individuals at both sides of the measuring tape (covering approx. 3 m width), while the other diver filmed the transect with a GoPro

camera. Flatfish individuals were visually identified and the habitat (SPL or sand) and its distance to the turbine were noted on a waterproof writing board. Also, water temperature, visibility and transect direction were noted for each dive. Since the number of transects varied per dive/turbine, the total searched area per habitat type (SPL/sand) per turbine was calculated as a measure for sampling effort. Subsequently, the number of individuals per species per habitat type (SPL/sand) was summed for each turbine.

A general linear mixed model (GLMM) with a Poisson distribution was fitted with the species count data as response variable, habitat type (SPL/sand) as explanatory variable, turbine as a random factor and the log-transformed search area per habitat type as offset variable to correct for the variation in sampling effort. For visualisation purposes, count data was standardised to ind.100 m<sup>-2</sup>. All data exploration, modelling and validation was carried out in R version 4.0.3 (R Core



**Figure 2.** Schematic representation of the diving transects around a turbine in the Belwind wind farm. The blue circle represents the the scour protection layer (SPL) consisting of the visible armoured layer and sand in between the rocks, while the yellow circle represents the sand surrounding the SPL, where no rocks are present. The density of the armoured layer is higher closer to the turbine, but is more or less absent right next to it. White arrows indicate possible transect lines conducted by the divers during one dive. The white rectangle shows a schematic representation of a diving transect with a length of 40 m and width of 3 m. Pictures show the typical habitat at the indicated location. ©Film Johan Devolder

**Table 1.** Total number of individuals per flatfish species observed along the diving transects on the scour protection layer (SPL) and the surrounding sand.

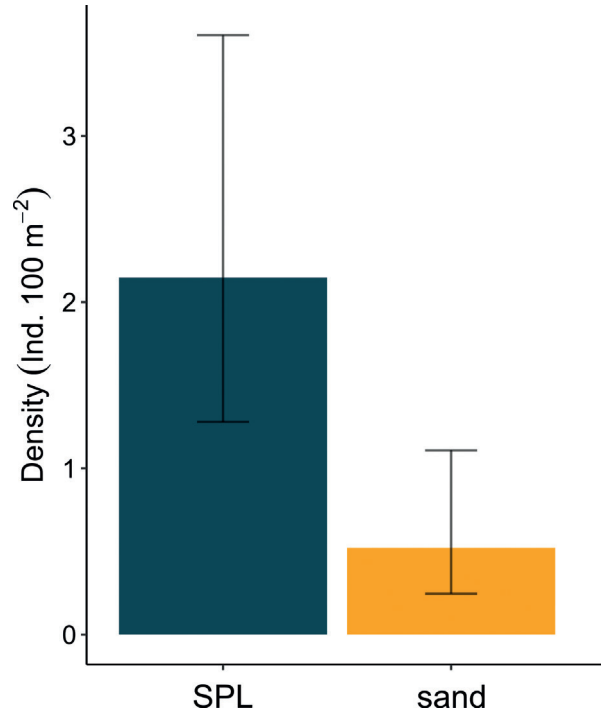
Species	English name	SPL	sand
<i>Pleuronectes platessa</i>	plaice	23	8
<i>Microstomus kitt</i>	lemon sole	4	–
<i>Solea solea</i>	common sole	3	–
<i>Limanda limanda</i>	dab	1	–
<i>Platichthys flesus</i>	European flounder	1	–
Pleuronectiformes juv.	flatfish juvenile	–	1
<b>Total</b>		<b>32</b>	<b>9</b>
Total covered surface area (m <sup>2</sup> )		982	1360

Team 2020). Five different flatfish species and a total of 41 individuals were detected during the 20 visual transects (Table 1). Plaice *Pleuronectes platessa* had by far the most sightings (n=31), followed by lemon sole *Microstomus kitt* (n=4) and common sole *Solea solea* (n=3). On average 2.05 ( $\pm 1.50$ ) or 1.74 ( $\pm 1.34$ ) ind.100 m<sup>-2</sup> were sighted per transect and almost 80% of the flatfish were found on the SPL, while only 9 individuals were seen on the nearby sand surrounding the SPL. The mean length of the scour protection layer over all transects was 16.37 m ( $\pm 8.41$ ).

Plaice was the only species with high enough abundances to fit a GLMM (Fig. 3). The model showed a highly significant effect of habitat type ( $p < 0.001$ ), with four times more plaice found on the SPL ( $2.15 \pm 0.57$  ind.100 m<sup>-2</sup>) than on the surrounding sand ( $0.52 \pm 0.20$  ind.100 m<sup>-2</sup>). These results suggest a strong attraction of plaice towards the SPL, meaning there is an artificial reef effect present. As stated above, this might be explained by increased feeding and shelter possibilities (Bergström *et al.* 2013; Degraer *et al.* 2020). Leonhard *et al.* (2006) estimated a 50 times increased food availability for fish after the introduction of hard substrates in Danish wind farms. Video footage taken by divers in a Dutch wind farm showed that cod *Gadus morhua* and pouting *Trisopterus luscus* actively used the hard substrates for shelter and food (Lindeboom *et al.* 2011), which was also observed near gravity based foundations in a Belgian wind farm (Reubens *et al.* 2013). Follow-up studies, including stomach content

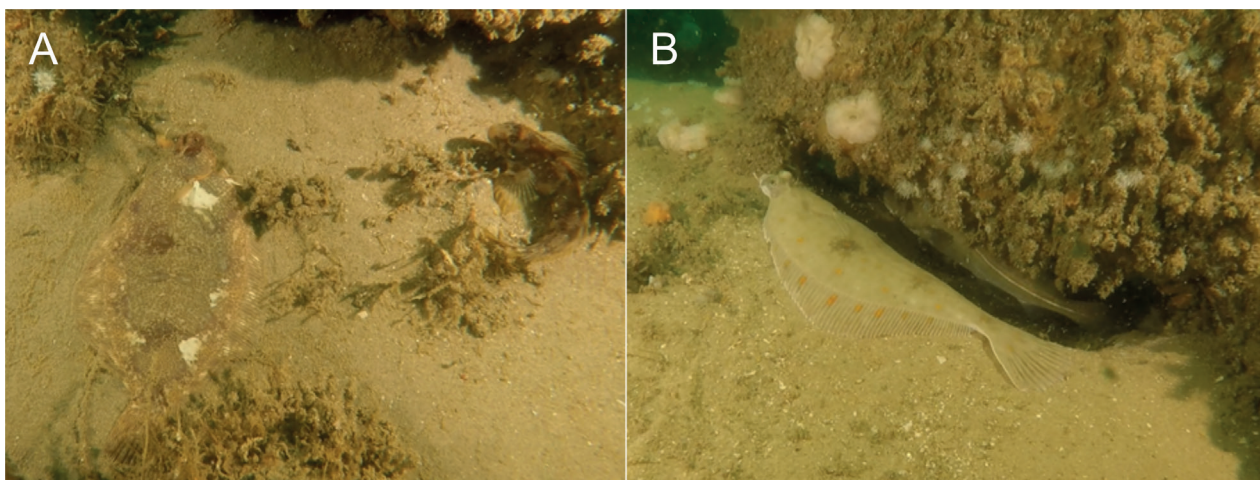
analyses and high-resolution acoustic tagging, will further investigate how plaice uses this new SPL-habitat in the Belwind OWF and how this influences its distribution on small (turbine) and wider (wind farm) spatial scales.

The higher plaice abundances on the SPL compared to the surrounding sand seem to contradict the findings of other studies. Many wind farm monitoring programmes focus on a larger spatial scale and use trawling devices 200 m away from the turbines (Lindeboom *et al.* 2011; Stenberg *et al.* 2015; Wilber *et al.*

**Figure 3.** Least-squares means for the final GLMM model showing the number of plaice per 100 m<sup>2</sup> for both habitat types (SPL = scour protection layer). Error bars represent 95%-confidence intervals.

2018), which may mask small-scale attraction at the turbine scale (Bergström *et al.* 2013; Vandendriessche *et al.* 2015). However, studies that did look at small-scale attraction of plaice also found no effect or even demonstrated avoidance behavior in relation to the hard substrate (Krone *et al.* 2017; van Hal *et al.* 2017). Most probably, this discrepancy with our results is linked to the configuration of the SPL. In the Belwind wind farm, the rock density of the SPL is sufficiently low (or sedimentation sufficiently high), at least further away from the turbines and closer to the edge of the SPL, to allow for the (natural) development of sandy patches. Actually, all flatfish observed by the divers in the SPL zone were found on these sandy patches, which benefits the burrowing behaviour of flatfish species (Fig. 4). In the study of Krone *et al.* (2017), the scour protection around the monopiles in the Riffgat wind farm are described as ‘closed rock fields’, which is in clear contrast with the configuration of the Belwind SPL. Furthermore, video footage and pictures of the SPL at other European wind farms, such as OWEZ (NL) and Horns Rev (DK), showed much higher densities of rocks with no visible sediment patches (Leonhard *et al.* 2006; Lengkeek *et al.* 2017), which may explain the lower presence of flatfish on the SPL in these wind farms.

The rock density hypothesis is further supported by the flatfish distribution pattern observed in relation to the distance from the turbine. Flatfish densities were high very close to the turbine, much lower just a few meters further away, followed by increasing densities with distance from the turbine till the edge of the SPL (Fig. 5A). The observed numbers of flatfish on the surrounding sand, at distances between 20 and 40 m from the turbine, were again much lower. This distribution pattern can be largely correlated with the density of the rocks (and sandy patches) of the SPL layer (see Fig. 2): almost no rocks are present in the immediate surroundings of the turbine, as the armoured SPL layer was deployed after the installation of the turbines; a few meters from the turbine, the rocks are stacked on top of each other leaving no patches of sand in between them; with increasing distance from the turbines, the rock density decreases until the edge of the SPL merges into natural sandy habitat. Following this rationale, it is plausible that over time an attraction effect of flatfish to the hard substrate may appear in other wind farms as well, if sedimentation rates are high enough to allow for the formation of sandy patches in between the rocks. As for now, it remains unclear whether higher abundances of plaice (and other flatfish species) on the SPL also lead to an increased production or only results in an aggregation of individuals



**Figure 4.** Pictures of (A) lemon sole *Microstomus kitt* and tompot blenny *Parablennius gattorugine*; (B) plaice *Pleuronectes platessa* and juvenile cod *Gadus morhua*, taken during a diving transect over the scour protection layer at turbine D3 in the Belwind wind farm. ©Film Johan Devolder.

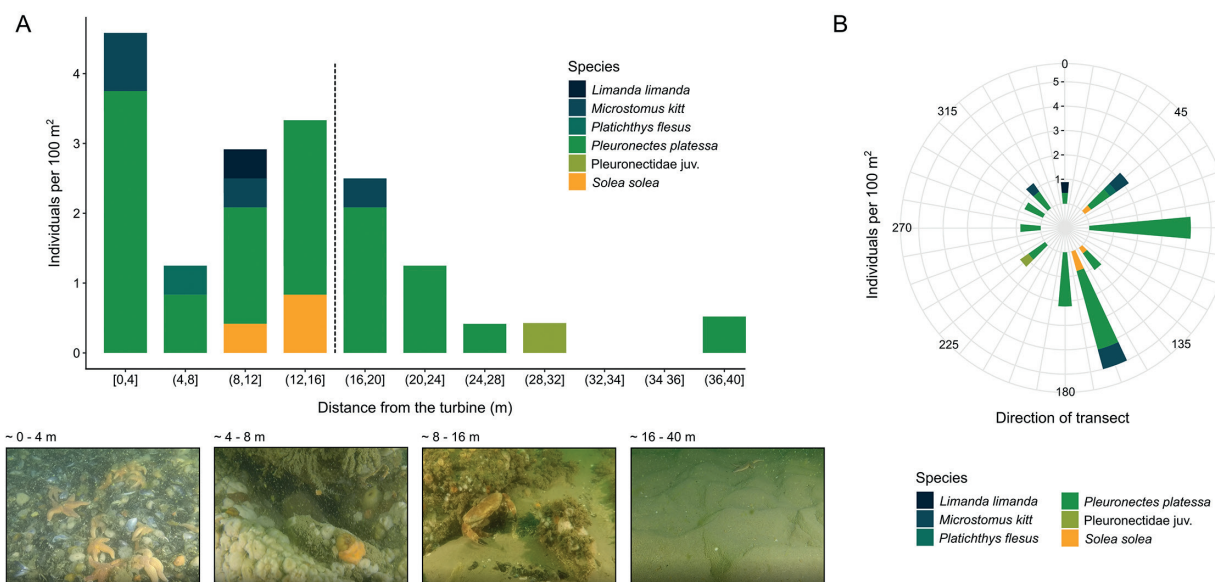


from the surrounding areas (Andersson *et al.* 2010; Reubens *et al.* 2013; Degraer *et al.* 2020). Long-term monitoring of the SPL is therefore recommended.

When looking at the relation with transect direction, flatfish species do not seem to clearly prefer a particular side or direction of the turbine, although slightly higher densities might be discerned on the eastern side of the turbines (Fig. 5B). However, diving was always performed around slack tide and the direction of the tidal current was taken into account as well when deciding which transect to swim, which might have influenced the results. More data need to be collected over a longer time period to further investigate the potential effects of water currents on the SPL and the presence of flatfish. The use of acoustic telemetry may be beneficial in this, as electronic tags could register flatfish movements independent of the prevailing currents.

Our findings are important when a nature-inclusive design is opted for in new offshore wind energy developments (Degraer *et al.*

2020). The SPL ‘eco-designing’ is already mandatory for the construction of offshore wind farms in the Netherlands (Ministerie van Economische Zaken 2019). However, different species have different needs when it comes to, for example, the size of the crevices or the scour material. If the goal is to promote flatfish species, and specifically plaice, the advice would be to construct a SPL with a rock density that is sufficiently low so that sediment patches can develop in between the rocks. Therefore, eco-designing of future wind farm projects will need separate discussions concerning which species to promote. Ideally, the focus lies on a couple of umbrella species, because measures taken for such species will benefit the larger community (Lengkeek *et al.* 2017). Such discussions should preferably be conducted in a quadruple helix framework involving not only scientists, but also the industry, policy makers as well as the general public. This is necessary, as the outcomes of these discussions will not only have ecological implications, but may equally affect recreational and commercial fisheries (Gill *et al.* 2020).



**Figure 5.** Barplot showing the number of flatfish per 100 m<sup>2</sup> found at different distances from the turbine (A) and at different directions in relation to the turbine (B). The mean length of the scour protection layer over all transects was 16.37 m, which is shown by the dashed black line. Colours represent the different species that were observed along the transect. The pictures show what the typical habitat looks like at the defined distances from the turbine, but some variation exists between turbines. ©Film Johan Devolder/A. Norro/RBINS 2019.

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## References

- Andersson, M.H. & Öhman, M.C. 2010. Fish and sessile assemblages associated with wind-turbine constructions in the Baltic Sea. *Marine and Freshwater Research* 61 (6): 642-650. <https://doi.org/10.1071/MF09117>
- Bergström, L., Sundqvist, F. & Bergström, U. 2013. Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community. *Marine Ecology Progress Series* 485 : 199-210. <https://doi.org/10.3354/meps10344>
- Degraer, S., Carey, D.A., Coolen, J.W.P., Hutchison, Z.L., Kerckhof, F., Rumes, B. & Vanaverbeke, J. 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning: a synthesis. *Oceanography* 33 (4): 48-57. <https://doi.org/10.5670/oceanog.2020.405>
- Gibson, R.N. 1997. Behaviour and the distribution of flatfishes. *Journal of Sea Research* 37 (3-4): 241-256. <https://doi.org/dsk89s>
- Gill, A.B., Degraer, S., Lipsky, A., Mavraki, N., Methratta, E. & Brabant, R. 2020. Setting the context for offshore wind development effects on fish and fisheries. *Oceanography* 33 (4): 118-127. <https://doi.org/10.5670/oceanog.2020.411>
- Krone, R., Dederer, G., Kanstinger, P., Krämer, P., Schneider, C. & Schmalenbach, I. 2017. Mobile demersal megafauna at common offshore wind turbine foundations in the German Bight (North Sea) two years after deployment - increased production rate of *Cancer pagurus*. *Marine Environmental Research* 123: 5361. <https://doi.org/10.1016/j.marenvres.2016.11.011>
- Lengkeek, W., Dideren, K., Teunis, M., Driessen, F., Coolen, J.W.P., Bos, O.G., Vergouwen, S.A., Raaijmakers, T.C., de Vries, M.B. & van Koningsveld, M. 2017. *Eco-friendly Design of scour Protection: potential Enhancement of ecological Functioning in offshore Wind Farms*. Ministry of Economic Affairs, Department of Nature & Biodiversity. pp. 98. Available from <https://edepot.wur.nl/411374>
- Leonhard, S.B. & Pedersen, J. 2006. *Benthic Communities at Horns Rev Before, During and After Construction of Horns Rev Offshore Wind Farm - Final Report, Annual Report 2005*. Available from <https://tethys.pnnl.gov/publications/benthic-communities-horns-rev-during-after-construction-horns-rev-offshore-wind-farm>
- Lindeboom, H., Degraer, S., Dannheim, J., Gill, A.B. & Wilhelmsson, D. 2015. Offshore wind park monitoring programmes, lessons learned and recommendations for the future. *Hydrobiologia* 756 (1): 169-180. <https://doi.org/10.1007/s10750-015-2267-4>
- Lindeboom, H.J., Kouwenhoven, H.J., Bergman, M.J.N., Bouma, S., Brasseur, S., Daan, R., Fijn R.C., de Haan, D., Dirksen, S. & van Hal, R. 2011. Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environmental Research Letters* 6 (3): 035101. <https://doi.org/10.1088/1748-9326/6/3/035101>



- Ministerie van Economische Zaken. 2019. Kavelbesluit V windenergiegebied Hollandse Kust (noord). *Staatscourant* 2019: 24545.
- Petersen, J.K. & Malm, T. 2006. Offshore windmill farms: Threats to or possibilities for the marine environment. *Ambio* 35 (2): 75-80. <https://doi.org/csz76x>
- R Core Team 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available from <https://www.R-project.org/>
- 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. <https://doi.org/10.1016/j.fishres.2012.10.011>
- Soares-Ramos, E.P.P., de Oliveira-Assis, L., Sarrias-Mena, R. & Fernández-Ramírez, L.M. 2020. Current status and future trends of offshore wind power in Europe. *Energy* 202: 117787. <https://doi.org/10.1016/j.energy.2020.117787>
- Stenberg, C., Støttrup, J.G., Van Deurs, M., Berg, C.W., Dinesen, G.E., Mosegaard, H., Grome, T.M. & Leonhoard, S.B. 2015. Long-term effects of an offshore wind farm in the North Sea on fish communities. *Marine Ecology Progress Series* 528: 257-265. <https://doi.org/10.3354/meps11261>
- 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. <https://doi.org/10.1007/s10750-014-1997-z>
- van Hal, R., Griffioen, A.B. & van Keeken, O.A. 2017. Changes in fish communities on a small spatial scale, an effect of increased habitat complexity by an offshore wind farm. *Marine Environmental Research* 126: 26-36. <https://doi.org/10.1016/j.marenvres.2017.01.009>
- Wilber, D.H., Carey, D.A. & Griffin, M. 2018. Flatfish habitat use near North America's first offshore wind farm. *Journal of Sea Research* 139: 24-32. <https://doi.org/10.1016/j.seares.2018.06.004>
- WindEurope 2021. *Offshore Wind in Europe: Key Trends and Statistics 2020*. Available from <https://windeurope.org/intelligence-platform/product/offshore-wind-in-europe-key-trends-and-statistics-2020/>

# CHAPTER 7

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

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### 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<sup>2</sup>, 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<sup>-2</sup>), 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, epifaunal 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

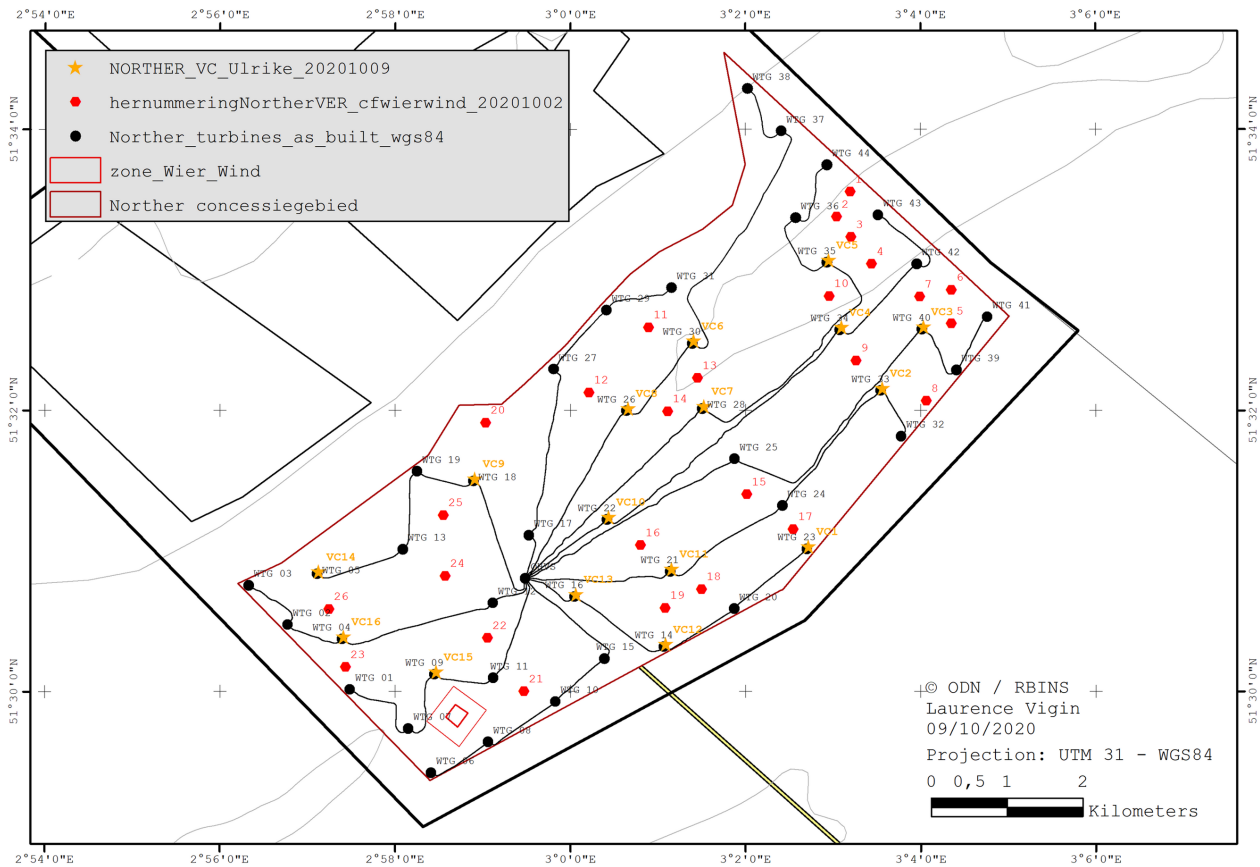
Within the Belgian part of the North Sea (BPNS), sampling was conducted in the concession area of the recently developed Norther OWF. The OWF is situated 23 km from the Belgian coastline (port of Zeebrugge) and is positioned southeast of the Thornton Bank, therefore constituting the most nearshore OWF 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<sup>2</sup> 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<sup>-2</sup>), 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 ( $379 \pm 83 \mu\text{m}$ ) and relatively high fine sand fractions ( $19.70 \pm 18.06\%$ ), fine gravel/granule fractions ( $10.51 \pm 10.75\%$ ) and total organic matter content ( $1.04 \pm 0.68\%$ ). 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  $\mu\text{m}$ , 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  $\mu\text{m}$ , min: 10% - max: 22%) and silt (<63  $\mu\text{m}$ , min: 14% - max: 29%) were detected. Therefore, this group of samples will

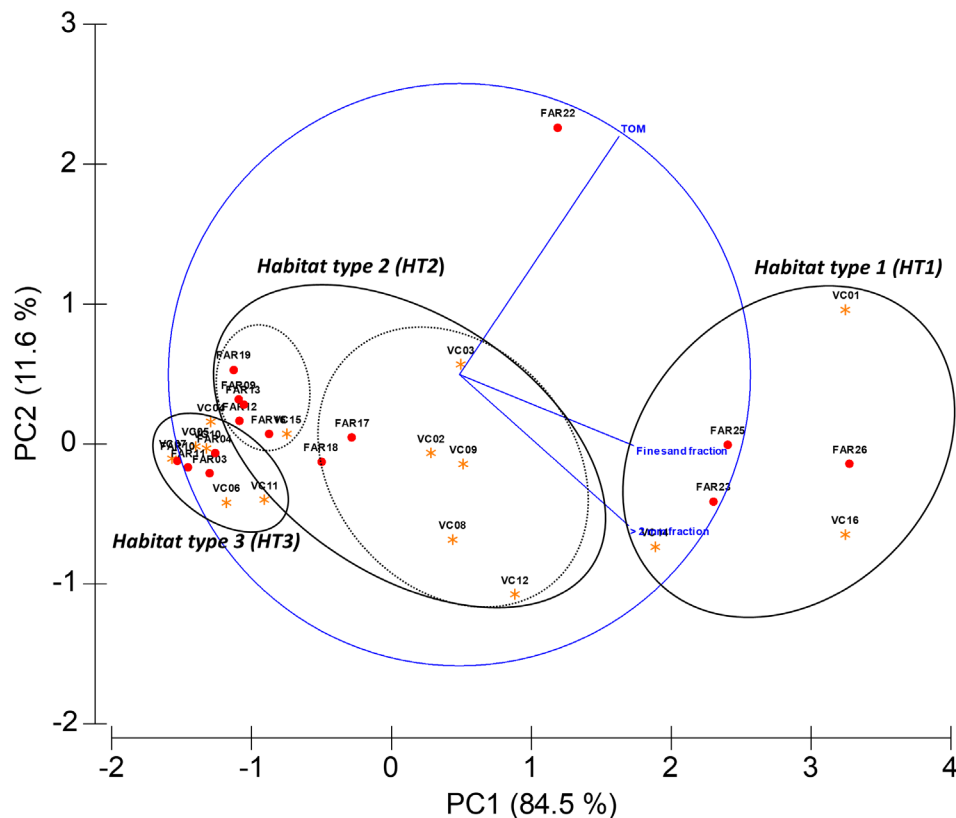
**Table 1.** Classification of the three habitat types found within the Norther site, with a description, overview of samples (Very Close; VC and Far samples) and average values ( $\pm$  SD) for the abiotic parameters within each habitat type.

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

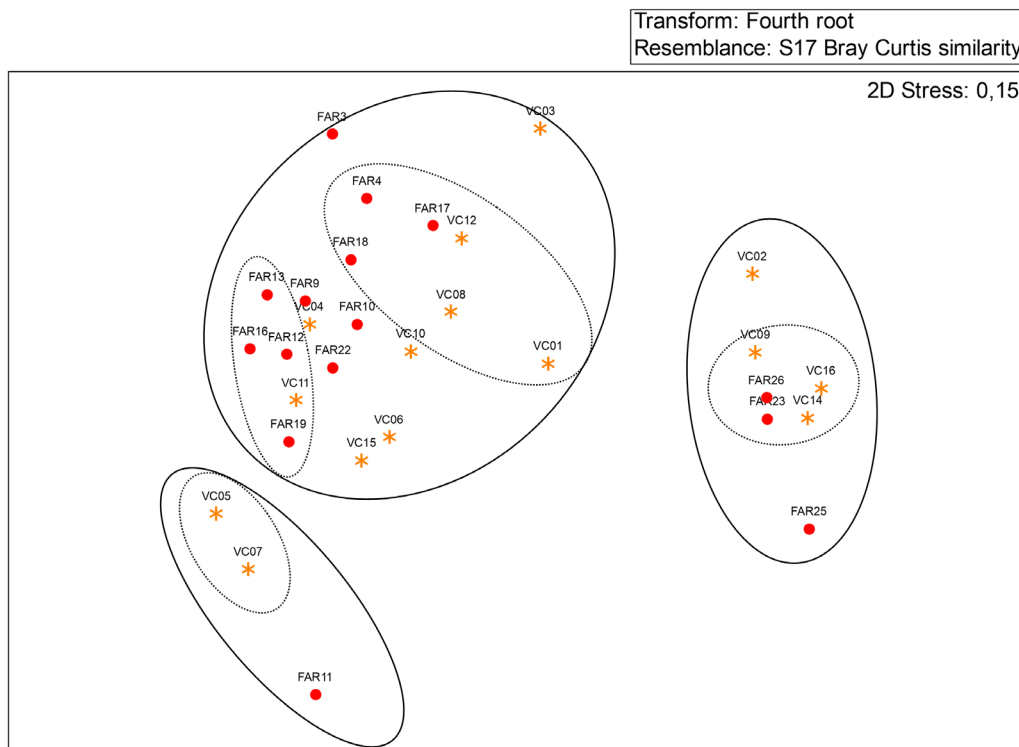


**Figure 2.** Ordination plot obtained for normalized environmental data after PCA analysis.

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 macroinvertebrate abundances, species richness and Shannon-Wiener diversity. However, it can be stated that the area is characterized by relatively high abundances ( $1408 \pm 1899$  ind.  $m^{-2}$ ) and diversity ( $S: 17 \pm 12$ ,  $H': 2.04 \pm 0.55$ ). 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<sup>-2</sup>) 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<sup>-2</sup>) 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<sup>-2</sup>) 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

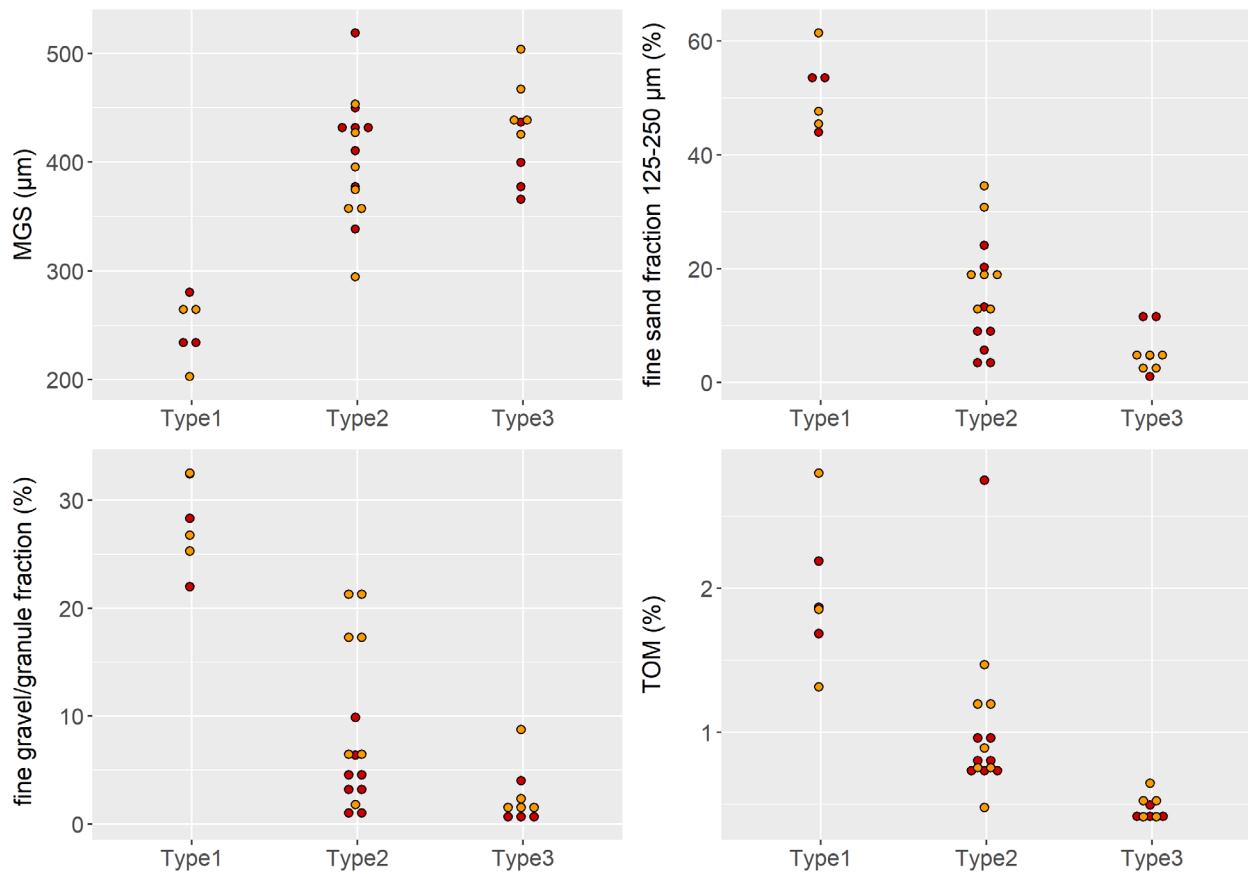
can be concluded that HT 1 harbors abundant and diverse assemblages of group 1, but these can also be encountered within transitional samples from HT 2. Assemblages found within HT 2 and HT 3 are less distinct from each other and contain the less abundant and diverse assemblages of groups 1 and 2, with 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 ( $\pm$  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.

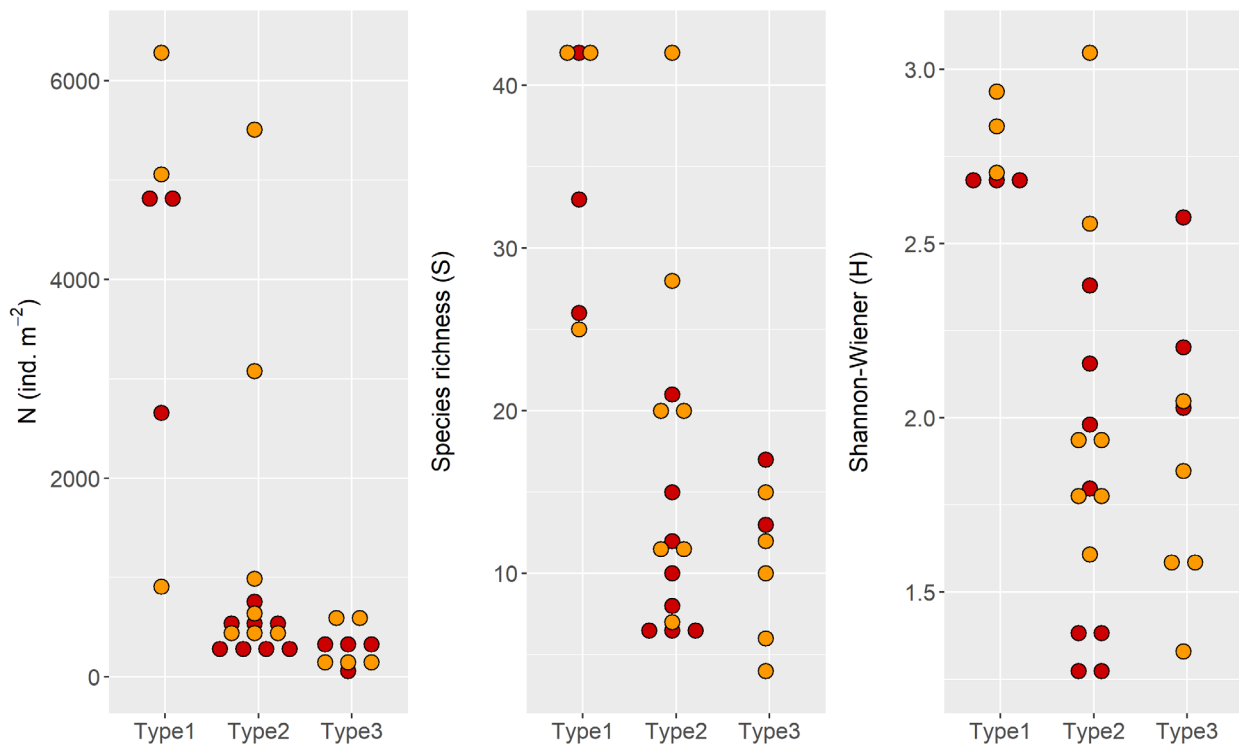
**Table 2.** Overview of calculated abiotic sediment and community descriptors (mean  $\pm$  SD) for the spatial comparison between both distances from turbines within Norther (2020) for every habitat type. Average values are also added from the far samples during the baseline assessment (2016).

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

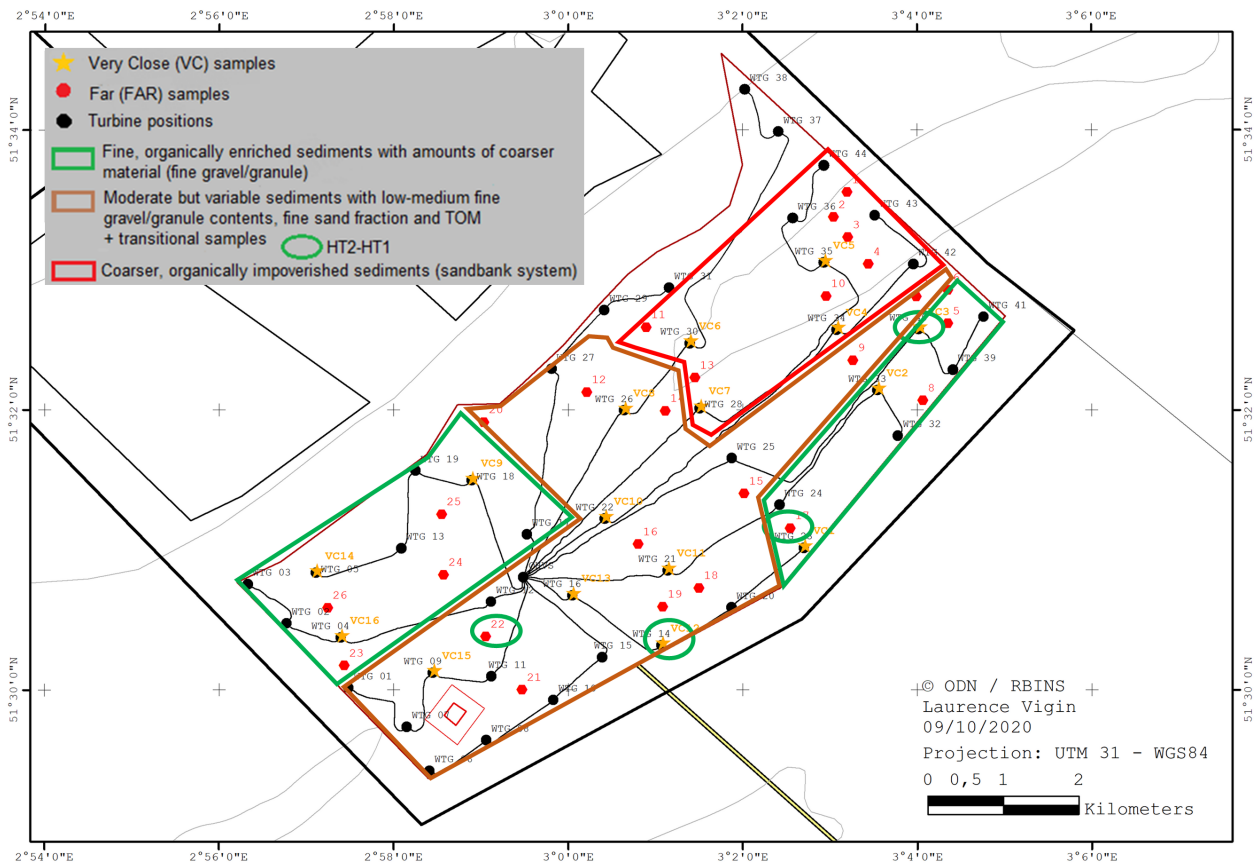
## 4. Discussion

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 heterogeneous 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. Macrobenthos 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>

# CHAPTER 8

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## BLUE MUSSEL *MYTILUS EDULIS* AS HABITAT PROVIDER ON OFFSHORE WIND TURBINE FOUNDATIONS

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### Abstract

We compare the species composition of the early (mussels not prevalent) and mature (mussels prevalent) subtidal colonizing communities at offshore wind turbine foundations with special attention to the mobility and habitat preferences of the colonizing species. We identified 47 species belonging to nine different phyla from the samples of the mature community, including 21 species unique to the secondary substratum provided by the mussel shell, all of them are sessile species. Only 17 of the 37 species identified from the early subtidal colonizing community were present in the mature community. The main phyla present in both the early and mature samples were Mollusca, Arthropoda, and Annelida.

Our findings confirm the hypothesis that mussels counteract the impoverishment of total species richness on wind turbines, caused by the abundant presence of *Metridium senile* in mature artificial hard substratum communities by providing secondary substratum for colonization by sessile and hemi-sessile epifauna. The species assemblage found on these mussels is different from the one previously found on the piles, and only seven-

teen species (~36%) present in the mature community were already present in the first year after installation. In 2020, all bryozoan species (7) were exclusively observed on the secondary substratum provided by the shells of the mussels. However, these species were previously encountered on the scour protection or on the shells of other bivalves. This may be due to the fact that the secondary substratum provided by the mussels differs in physical properties (e.g., microhabitat complexity) from the primary (vertical) substratum of the pile.

### 1. Introduction

Offshore wind turbine foundations, like all submerged man-made structures, are rapidly colonised by fouling organisms (Degraer *et al.* 2020) that successively develop assemblages which may or may not resemble epibioses of natural hard substrata (Kerckhof *et al.* 2017). The effects of the introduction of artificial hard substrata on the surrounding marine environment – the so-called artificial reef effect – is considered as a major effect caused by offshore wind farms (Petersen & Malm 2006). In 2019, we described three succession stages of the

subtidal fouling assemblages at two types of offshore wind turbine foundations (i.e., concrete gravity-based and steel monopile foundation) off the Belgian coast in the first decade after the installation (Kerckhof *et al.* 2019). Installation of the turbine foundations was followed by rapid colonization and a relatively short pioneer stage (~2 years), a more diverse intermediate stage characterised by large numbers of suspension feeders, and a third *Metridium senile*-dominated stage, which was reached after 10 years on the concrete gravity-based foundations, whereas the assemblage on the steel monopiles of the more offshore site was co-dominated by *M. senile* and *Mytilus edulis*.

*Metridium senile* is a strong competitor for space and can have a strong structuring effect on the fouling community by rapidly colonising new substrata, covering large areas, preventing other species' propagules to settle, consuming free-living larvae and smothering new recruits (Kaplan 1984; Nelson & Craig 2011). On natural reefs in the Dutch North Sea *Metridium*-dominated samples were found to be relatively low in species richness compared to samples with low numbers of *Metridium* (Coolen *et al.* 2015, 2018). At the offshore wind farms, a strong reduction in species richness (> 50% reduction compared to earlier stages) was, however, only observed in the *M. senile*-dominated assemblages on the deep subtidal part of the concrete gravity-based foundations (De Mesel *et al.* 2015; Kerckhof *et al.* 2019). The fact that no such reduction was observed on the steel monopiles studied here, may be due to the presence of large (> 5 cm) *M. edulis*. Mussels are known to increase habitat heterogeneity by providing secondary substratum (Tsuchiya & Nishihira 1985; Albrecht & Reise 1994), creating interstitial cavities (Yager *et al.* 1993) and functioning as a sediment trap (Yager *et al.* 1993). Habitat modification by *M. edulis* has often led to very diverse assemblages on hard substrata (Suchanek 1985; Tsuchiya & Nishihira 1985; Lintas & Seed 1994).

In this study, we focus on the effect of blue mussels *M. edulis* on the epifaunal species diversity at the vertical parts of the turbine foundations in an offshore wind farm located in shallow coastal waters in the southern North Sea. We hypothesize that blue mussels counteract the local impoverishment of species richness caused by the abundant presence of *Metridium senile* in mature artificial hard substratum communities because the living mussels provide secondary substratum for colonization by attached (i.e., sessile and hemi-sessile) epifauna. Secondly, we hypothesize that the species found on these mussels would also be different from those previously found on the piles because mussels do not only provide secondary substratum but also differ in physical properties (e.g., microhabitat complexity) from the primary substratum.

## 2. Material and methods

### 2.1. Research strategy

We compared the species composition of the early (mussels not prevalent) and mature (mussels prevalent) subtidal colonizing communities at offshore wind turbine foundations with special attention to the mobility and habitat preferences of the colonizing species.

### 2.2. Study site and data collection

We collected subtidal hard substrata macrofauna from the Belwind offshore wind farm, located at about 50 km offshore in the Belgian offshore renewable energy zone (see Chapter 1). The Belwind wind farm is situated on the Bligh Bank and is entirely located in clear English Channel water (M'harzi *et al.* 1998; Lacroix *et al.* 2004).

As part of the long-term environmental monitoring, on 12 October 2020, Scuba divers collected four scrape samples from the steel monopile foundation of the BBB8 turbine (originally installed on the 21<sup>st</sup> of October 2009) by scraping fouling organisms from a square sampling surface area of



6.3 dm<sup>2</sup> (Kerckhof *et al.* 2010). Samples were collected at -15 m which is considered representative for the assemblages of most of the subtidal part of the foundations (Fig. 1; Kerckhof *et al.* 2010).

The scraped material was collected in plastic bags that were sealed, subsequently preserved in buffered formalin 10% and transported to the laboratory for sieving over a 1 mm sieve. Individual organisms were sorted and identified to the lowest taxonomic level possible (mostly species level; further called “species”). Density was determined for non-colonial species, while percentage cover was assessed for the crust forming and erect (bushy) colonial epifaunal species such as hydrozoans, bryozoans and sponges. We assigned the observed species to be mobile, hemi-sessile or sessile based on the mobility of the life stage observed in the samples. Hemi-sessile organisms are organisms that usually remain attached in the same place (e.g., *Jassa herdmani*, *Mytilus edulis*), but have limited mobility, whereas sessile organisms, such as adult barnacles, live permanently attached to the substratum and are unable to move. All data were transformed

to the SACFOR scale to allow for integrating relative abundances of colonial and non-colonial species (Connor & Hiscock 1996). Specimens of *M. edulis* were separated during sorting, lightly rinsed, measured (lengthwise) and classified according to their length (small: < 30 mm, medium: 31-60 mm, large: > 61 mm). Associated organisms were sorted and identified to the lowest taxonomic level possible, and the percentage cover of the mussel shells (medium and large as the few smaller mussels present in the samples were devoid of epifauna) by fouling organisms was estimated for all species in four broad categories (1: 1-4%, 2: 5-19%, 3: 20-40%, 4: >40%). The commensal species *Pinnotheres pisum* was excluded from further analysis.

To compare the epifaunal composition on the mussel shells (= secondary habitat) with that of the initial epifauna that settled directly on the turbine foundations (= primary habitat), we used the dataset on epifauna observed in 2010 on the Belwind monopiles (i.e., three scrape samples collected on 18 August 2010, i.e., nine months after installation of the turbine foundation) as compiled by Kerckhof *et al.* (2019).



**Figure 1.** Sampling square and scraper at a Belwind monopile. Note the presence of *Mytilus edulis* clumps in between and under *Metridium senile* (left). Example of a mussel fully covered by fouling organisms (right).



### 2.3. Statistical methods

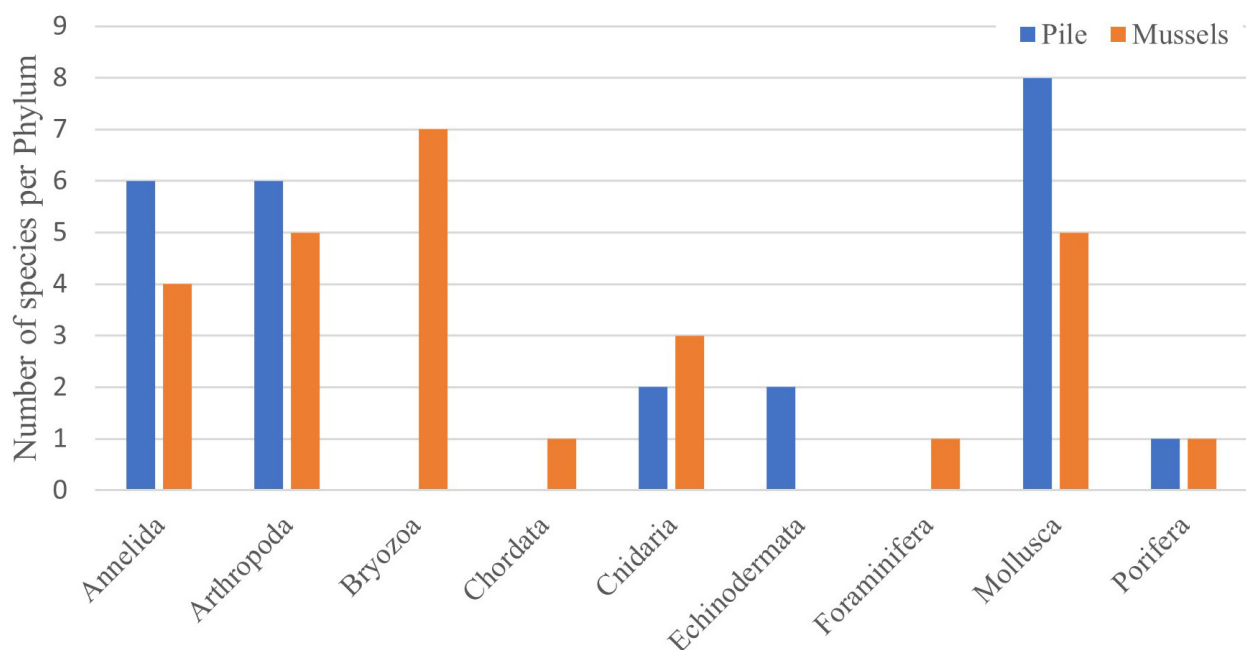
We applied the Spearman rank correlation coefficient to relate mussel length and, both the number of associated species and cumulative percentage cover. However, because multiple mussels had the same length, exact p-values could not be computed. Species accumulation curves (SAC; or species-richness curves) and extrapolated species richness (Chao 1987) were used to estimate the total number of species associated with these mussels and visualized using the R package *vegan* (Oksanen *et al.* 2019). All data analyses were performed in R (R Core Team 2020).

## 3. Results

We identified 47 species belonging to nine different phyla in the 2020 samples (Fig. 2): 24 sessile species, 5 hemi-sessile species and 18 mobile species (Table 1). The main phyla present in the samples were Mollusca (11 species), Arthropoda (11 species), Annelida (8 species), and Bryozoa (7 species) (Fig. 2). Twenty species were exclusively found on the pile, i.e., the primary substratum (17 mobile, 1 hemi-sessile and 2 sessile species). On the

mussels, i.e., the secondary substratum, we found 21 unique species all of them sessile species. Six species were found on both the primary and secondary substratum (3 sessile, 2 hemi-sessile and 1 mobile species). The three species most frequently observed on the mussels were the encrusting annelid *Spirobranchus triqueter* (present on 34 out of 38 mussels), hemi-sessile anemones (mostly *Metridium*, on 29 out of 38 mussels) and the encrusting barnacle *Verruca stroemia* (on 25 out of 38 mussels, Table 1). The species observed on the mussels have all been found previously, e.g., on the stones of the scour protection or on shells of other bivalves (dataset Kerckhof *et al.* 2019). All bryozoan species were exclusively observed on the secondary substratum.

The 37 species observed in the August 2010 samples comprised 26 mobile, 2 hemi-sessile and 9 sessile species (dataset Kerckhof *et al.* 2019). The main phyla present in the samples were Arthropoda (12 species), Mollusca (8 species), Annelida (8 species), and Echinodermata (3 species). Most of the sessile (7/9) and half of the hemi-sessile species (1/2) observed on the primary



**Figure 2.** Number of taxa per phylum present on the primary substratum -pile - (blue) or on the secondary substratum – mussels - (orange) in 2020 (pooled samples).

**Table 1.** Overview of the species encountered in the 2020 scrape samples, the mobility of the life stage observed (M = mobile; H = hemi-sessile; S = sessile), location where they were encountered (P = on primary substratum; M = on mussels), the frequency with which they were encountered on individual mussels, and whether they were previously observed in 2010.

Species	Phylum	Mobility of observed life stage	Location encountered	Frequency on mussels	Previously observed in August 2010
<i>Eulalia aurea</i>	Annelida	M	P		
<i>Eulalia sp.</i>	Annelida	M	P & M	1/38	X
<i>Eunereis longissima</i>	Annelida	M	P		X
<i>Lanice conchilega</i>	Annelida	S	M	1/38	X
<i>Lepidonotus squamatus</i>	Annelida	M	P		X
<i>Sabellaria spinulosa</i>	Annelida	H	M	10/38	
<i>Spirobranchus triqueter</i>	Annelida	S	P & M	34/38	
<i>Subadyte pellucida</i>	Annelida	M	P		
<i>Balanus crenatus</i>	Arthropoda	S	M	19/38	X
<i>Balanus perforatus</i>	Arthropoda	S	M	5/38	X
<i>Corophium sextonae</i>	Arthropoda	H	M	19/38	
<i>Gitana sarsi</i>	Arthropoda	M	P		
<i>Harmothoe extenuata</i>	Arthropoda	M	P		X
<i>Jassa herdmani</i>	Arthropoda	S	P & M	19/38	X
<i>Phtisica marina</i>	Arthropoda	M	P		X
<i>Pilumnus hirtellus</i>	Arthropoda	M	P		X
<i>Pisidia longicornis</i>	Arthropoda	M	P		X
<i>Stenothoe monoculoides</i>	Arthropoda	M	P		
<i>Verruca stroemia</i>	Arthropoda	S	M	25/38	X
<i>Alcyonidium mytilii</i>	Bryozoa	S	M	2/38	
<i>Callopora dumerilii</i>	Bryozoa	S	M	7/38	
<i>Celleporella hyalina</i>	Bryozoa	S	M	8/38	
<i>Conopeum reticulum</i>	Bryozoa	S	M	7/38	
<i>Electra pilosa</i>	Bryozoa	S	M	8/38	
<i>Membranipora tenuis</i>	Bryozoa	S	M	3/38	X
<i>Microporella ciliata</i>	Bryozoa	S	M	6/38	
<i>Diplosoma listerianum</i>	Chordata	S	M	23/38	
<i>Actiniaria</i>	Cnidaria	H	P & M	29/38	
<i>Alcyonium digitatum</i>	Cnidaria	S	M	2/38	
<i>Clytia hemisphaerica</i>	Cnidaria	S	M	5/38	
<i>Obelia bidentata</i>	Cnidaria	S	P		
<i>Ophiothrix fragilis</i>	Echinodermata	M	P		
<i>Psammechinus miliaris</i>	Echinodermata	M	P		X
<i>Planorbulina mediterraneensis</i>	Foraminifera	S	M	1/38	
<i>Aequipecten opercularis</i>	Mollusca	H	P		X
<i>Crepidula fornicata</i>	Mollusca	S	P & M	1/38	X
<i>Doto sp.</i>	Mollusca	M	P		
<i>Epitonium clathratulum</i>	Mollusca	M	P		
<i>Euspira nitida</i>	Mollusca	M	P		
<i>Heteranomia squamula</i>	Mollusca	S	M	14/38	X
<i>Hiatella arctica</i>	Mollusca	S	M	1/38	
<i>Mytilus edulis</i>	Mollusca	H	P & M	18/38	X
<i>Odostomia turrata</i>	Mollusca	M	P		
<i>Ostrea edulis</i>	Mollusca	S	M	1/38	
<i>Trivia monacha</i>	Mollusca	M	P		
<i>Cliona celata</i>	Porifera	S	M	1/38	
<i>Dysidea fragilis</i>	Porifera	S	P		

substratum in 2010 were present on the secondary substratum in 2020. In contrast, only two sessile species (*Crepidula fornicata* and *Jassa herdmani*) present in 2010, were also observed on the primary substratum in 2020. Only a single mobile species (*Eulalia* sp.) observed in 2010 was recovered from the secondary substratum in 2020.

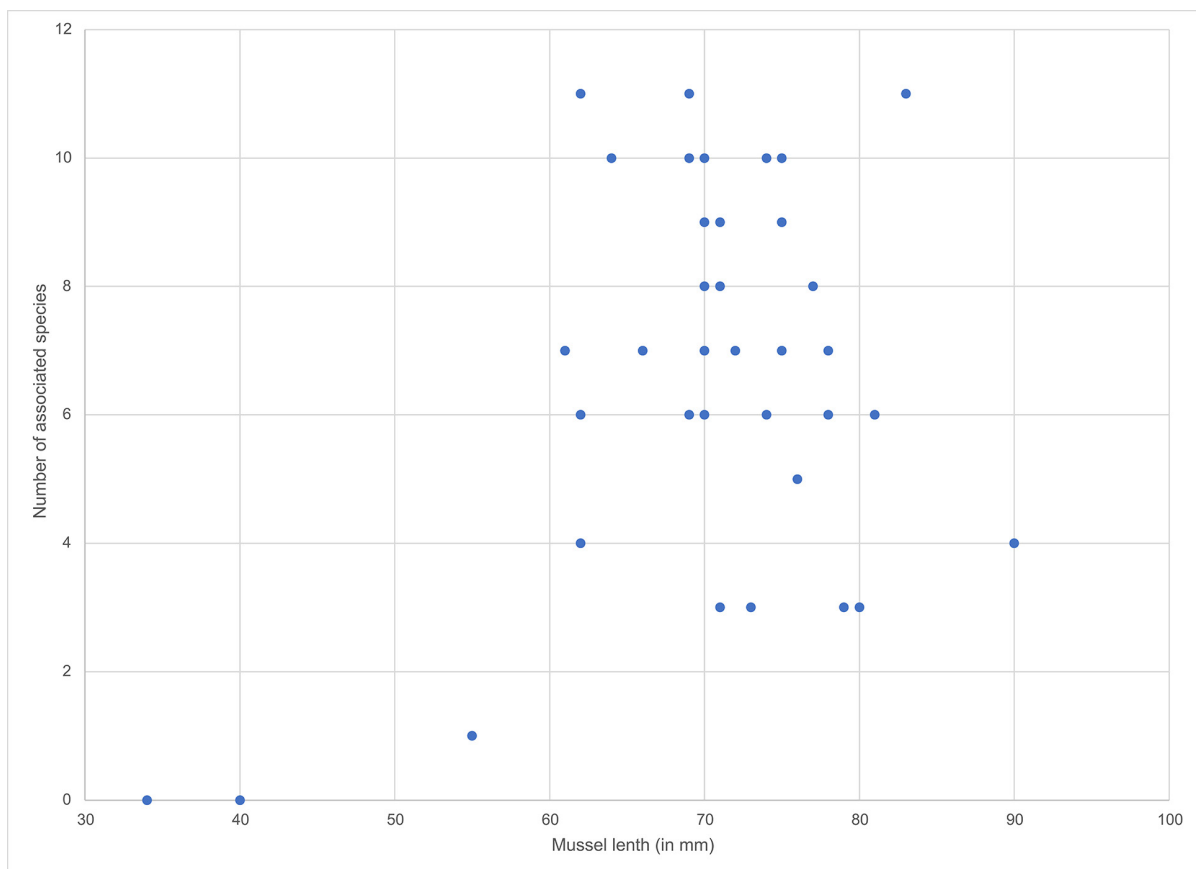
We found no correlation between the length of the mussels and the number of species on the mussel (Fig. 3; correlation coefficient: 0.08) and only a weak correlation between the length of the mussels and their cumulative percentage of cover by epifauna (Fig. 4, correlation coefficient: 0.39). No species were found on small mussels (< 30 mm), and maximally one species was associated with medium mussels (31-60 mm). It would appear that the mussels have to be of a certain size or age before they can be colonized by epifauna. Nearly all large

mussels were covered, often entirely (Fig. 4), by fouling fauna.

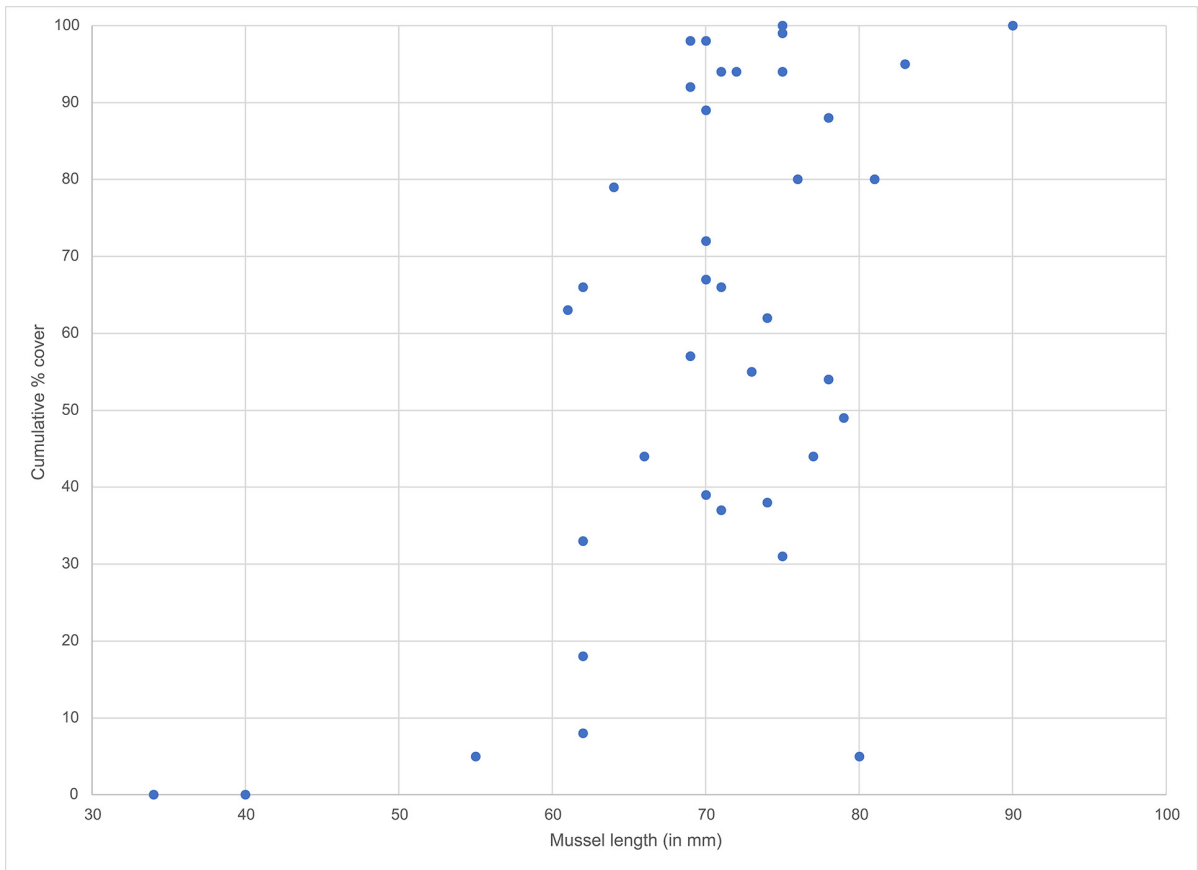
The four replicates each contained between 5 and 17 medium to large-sized mussels with 12 up to 18 mussel-associated species per replicate. A single replicate thus contained less than half to up to 2/3<sup>rd</sup> of the observed number of species associated with the mussels (27 spp.). Each individual medium to large-sized mussel was associated with 0 to 11 species (mean: 6.6 spp., SD: 3.0, Fig. 5). The extrapolated maximum number of species associated with mussels on the turbine foundation was estimated to be 35.

#### 4. Discussion

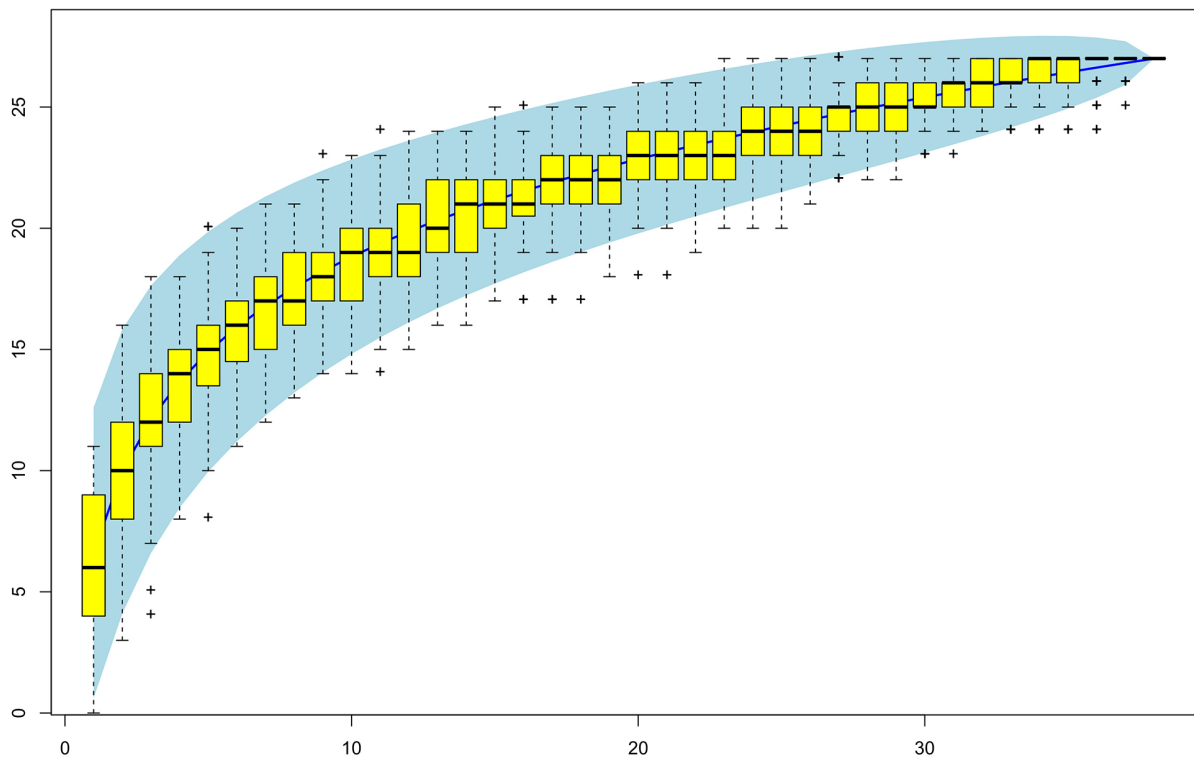
Out of the 47 species in the 2020 samples, 21 species were only observed on the shells of mussels, all of them sessile species. This suggests that ten years after initial colonisation, shells of large mussels



**Figure 3.** Number of associated species as a function of *Mytilus edulis* length (n = 38). Note that the ~55 mm mussel was colonized exclusively by *Metridium senile*.



**Figure 4.** Cumulative percentage cover by associated species as a function of *Mytilus edulis* length (n = 38).



**Figure 5.** Species accumulation curve of the number of species associated with mussels for the number of mussels studied (box represents 1<sup>st</sup> and 3<sup>rd</sup> quartile, whiskers showing minimum and maximum values, with outliers as '+').

provide a specific secondary substratum for sessile species within the mature subtidal epifaunal community.

At this offshore wind farm, initial settling of blue mussels was observed in 2010 (i.e., ~6 months after installation), predominantly in the intertidal zone where the mussel population developed into a typical intertidal mussel belt similar to those described in Joschko *et al.* (2008) for the German Bight. As a mussel population further develops, the mussels grow and start occupying more space, but do not necessarily increase in numbers (Suchanek 1985). In established intertidal mussel beds, individual mussels can gradually move to outside of the patches. A similar thinning effect likely also happened on the foundations with individual large mussels gradually moving downwards, which may explain the presence of solitary larger mussels on the permanently submerged parts of the piles (e.g., -15 m as observed in this study). Even after 11 years, relatively low numbers of mussels are observed below the intertidal zone which is in marked contrast with findings elsewhere (Krone *et al.* 2013; Hutchison *et al.* 2020). This may be due to foundation type as jacket structures are often entirely covered by mussels (Hutchinson 2020; personal observations on the jacket structures in C-Power phase 2 and 3), the location further offshore resulting in lower numbers of spat in the water column or a combination of both.

Natural aggregations of mussels, which generally form horizontal intertidal aggregations, are bioengineered microhabitats that are structurally more complex than the surrounding, often soft sediment, substratum (Suchanek 1985). Such mussel beds consist of three major components: the mussel matrix, a diverse assemblage of associated organisms and accumulated detritus at the base of the mussel bed (Suchanek 1985). In our study, on the vertical surface of the foundation, two of the three aforementioned components are presumably of reduced importance due to

the tidal position of the investigated mussel bed. Because the subtidal mussel population on the turbine foundation is composed of solitary large individuals that have likely moved down the foundation as a result of the thinning effect, these mussel aggregations are characterized by a loose matrix structure. This may cause detrital particles such as faeces and pseudofaeces, to wash out easily instead of accumulating between the byssus of the mussels. This is also the case for inorganic components such as shell debris. This, together with the strong currents, may explain the lower number of mobile species looking for shelter or dwelling among the mussels to feed, e.g., *Harmothoe* spp., *Eulalia* spp., as observed in this study. It is likely that sample manipulation, including the rinsing and sieving contributed to this finding. One free living species, the brittle star *Ophiothrix fragilis*, was prominently observed amongst the mussels by the divers during sampling and both species formed a typical association (see also Mavraki *et al.* 2020), which – to our knowledge – has not been observed elsewhere. The suspension feeding *O. fragilis* may take profit from the absence of fine sediments and strong currents as in our study, because high levels of sedimentation can prevent them from feeding and eventually inhibit respiration (Aronson 1989; Jackson 2008; de Kluijver & Ingalsuo 2012). Encrusting organisms, such as barnacles, encrusting bryozoans and calcareous tube forming polychaetes apparently flourish in this setting of strong currents hence their observed prevalence.

Mussels often outcompete barnacles attached to the primary substratum (e.g., Menge 1976), now the large mussels offer a secondary substratum for barnacle settlement. This is illustrated by the presence of relatively small individuals and juveniles of the barnacles *Verruca stroemia*, *Balanus perforatus* and *Balanus crenatus* indicate recent settlement.

On the concrete gravity base foundations at the nearby C-Power wind farm the plumose



anemone *M. senile* dominated the subtidal species assemblage resulting in a species poor community (Kerckhof *et al.* 2019). Several other studies demonstrated an association of low species richness when the community is dominated by *M. senile* (Zintzen *et al.* 2006; Coolen *et al.* 2015, 2018; van der Stap *et al.* 2016). *Metridium senile* is a superior spatial competitor, which has been attributed to its clonal reproduction, mobility and locomotion (Nelson & Craig 2011). Additionally, it actively predated on larvae of other species, preventing their settlement on adjacent substrata, and by actively killing new settlers by smothering them (Nelson & Craig 2011). In this study, we demonstrate that the shells of *M. edulis* provide a secondary substratum for settlement of encrusting species there where the primary substratum (i.e., the pile) has already been fully colonized and counteracting the effect of dominant *M. senile*. The results in a positive relationship between the abundance of *M. edulis* with species richness and diversity (Zupan & Rumes, in prep).

The near absence of encrusting species on the primary substratum is not only due to a lack of available suitable substratum but may in part be an artifact of the sampling technique. In samples collected by scraping the biota of the substratum, due to the used technique, one can imagine that small encrusting organisms are less efficiently collected, easily destroyed, or simply not collected which may blur the picture of the abundance and species diversity. However, this would not explain that in 2010 a total of 17 different sessile species, five of which are encrusting, were recovered from the primary substratum. It is possible that even more (mobile) species were associated with the mussels but that these were separated during the rinsing and sieving. The sessile and hemi-sessile species found on the mussels differ from those previously found on the piles and are more similar to that of the scour protection. This may be due to the fact that the secondary substratum provided by the mussels differs in physical properties (e.g., microhabitat complexity) from the primary (vertical) substratum of the pile.

## References

- Albrecht, T.A. & Reise, K. 1994. Effects of *Fucus vesiculosus* covering intertidal mussel beds in the Wadden Sea. *Helgoländer Meeresuntersuchungen* 48: 243-256. <https://doi.org/10.1007/BF02367039>
- Aronson, R. 1989. Brittlestar beds: low-predation anachronisms in the British Isles. *Ecology* 70 (4): 856-865. <https://doi.org/10.2307/1941354>
- Chao, A. 1987. Estimating the population size for capture-recapture data with unequal catchability. *Biometrics* 43: 783-791. <https://doi.org/10.2307/2531532>
- Connor, D.W. & Hiscock, K. 1996. Data collection methods (with Appendices 5-10). In: Hiscock, K. (ed.) *Marine Nature Conservation Review: Rationale and Methods*: 51-65, 126- 158. Peterborough, Joint Nature Conservation Committee. (Coasts and seas of the United Kingdom. MNCR series.)
- Coolen, J.W.P., Bos, O.G., Glorius, S., Lengkeek, W., Cuperus, J., Van der Weide, B.E. & Aguëra, A. 2015. Reefs, sand and reef-like sand: a comparison of the benthic biodiversity of habitats in the Dutch Borkum Reef Grounds. *Journal of Sea Research* 103: 84-92. <https://doi.org/10.1016/j.seares.2015.06.010>
- Coolen, J.W.P., van der Weide, B., Cuperus, J., Blomberg, M., Van Moorsel, G.W.N.M., Faasse, M.A., Bos, O.G., Degraer, S. & Lindeboom, H.J. 2018. Benthic biodiversity on old platforms, young wind farms and rocky reefs. *ICES Journal of Marine Science* 77 (3): 1250-1265. <https://doi.org/10.1093/icesjms/fsy092>

- de Kluijver, M. & Ingalsuo, S. 2012. Common Brittle Star (*Ophiothrix fragilis*). *Marine Species Identification Portal*. Available from [http://species-identification.org/species.php?species\\_group=echinodermata&id=100](http://species-identification.org/species.php?species_group=echinodermata&id=100) [accessed July 12, 2021].
- 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. <https://doi.org/10.1007/s10750-014-2157-1>
- Degraer, S., Carey, D.A., Coolen, J., Hutchison, Z., Kerckhof, F., Rumes, B. & Vanaverbeke, J. 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning: A synthesis. *Oceanography* 33 (4): 48-57. <https://doi.org/10.5670/oceanog.2020.405>
- Hutchison, Z.L., LaFrance Bartley, M., Degraer, S., English, P., Khan, A., Livermore, J., Rumes, B. & King, J.W. 2020. Offshore wind energy and benthic habitat changes: Lessons from Block Island Wind Farm. *Oceanography* 33 (4): 58-69. <https://doi.org/10.5670/oceanog.2020.406>
- Jackson, A. 2008. *Ophiothrix fragilis* Common brittlestar. In: Tyler-Walters, H. & Hiscock, K. (eds) *Marine Life Information Network: Biology and Sensitivity Key Information Reviews*. Marine Biological Association of the United Kingdom, Plymouth. Available from <https://www.marlin.ac.uk/species/detail/1198> [accessed 30 November 2021].
- Joschko, T., Buck, B., Gutow, L. & Schröder, A. 2008. Colonization of an Artificial Hard Substrate by *Mytilus edulis* in the German Bight in the German Bight. *Marine Biology Research* 4 (5): 350-360. <https://doi.org/10.1080/17451000801947043>
- Kaplan, S.W. 1984. The association between the sea anemone *Metridium senile* and the mussel *Mytilus edulis* reduces predation by the starfish *Asterias forbesii*. *Journal of Experimental Marine Biology and Ecology* 79: 155-157. [https://doi.org/10.1016/0022-0981\(84\)90216-8](https://doi.org/10.1016/0022-0981(84)90216-8)
- 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: Degraer, S. et al. (eds) *Offshore Wind Farms in the Belgian Part of the North Sea: Early Environmental Impact Assessment and Spatio-Temporal Variability*: 53-68.
- Kerckhof, F., Rumes, B. & Degraer, S. 2017. On the replicability of natural gravel beds by artificial hard substrata in Belgian waters. In: Degraer, S. et al. (eds) *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: A Continued Move Towards Integration and Quantification*: 73-83.
- Kerckhof, F., Rumes, B. & Degraer, S. 2019. About “Mytilisation” and “Slimeification”: a decade of succession of the fouling assemblages on wind turbines off the Belgian coast. In: Degraer, S. et al. (eds) *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Making a Decade of Monitoring, Research and Innovation*: 73-84. *Memoirs on the Marine Environment*.
- Krone, R., Gutow, L., Joschko, T.J. & Schröder, A. 2013. Epifauna dynamics at an offshore foundation – Implications of 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: 149-153. <https://doi.org/10.1016/j.seares.2004.01.003>

- Lintas, C. & Seed, R. 1994. Spatial variation in the fauna associated with *Mytilus edulis* on a wave-exposed rocky shore. *Journal of Molluscan Studies* 60: 165-174.  
<https://doi.org/10.1093/mollus/60.2.165>
- Mavraki, N., De Mesel, I., Degraer, S., Moens, T. & Vanaverbeke, J. 2020. Resource niches of co-occurring invertebrate species at an offshore wind turbine indicate a substantial degree of trophic plasticity. *Frontiers in Marine Science* 7: 1-17. <https://doi.org/10.3389/fmars.2020.00379>
- M'harzi, A., Tackx, M., Daro, M.H., Kesaulia, I., Caturao R. & Podoor, N. 1998. Winter distribution of phytoplankton and zooplankton around some sandbanks of the Belgian coastal zone. *Journal of Plankton Research* 20: 2031-2052. <https://doi.org/10.1093/plankt/20.11.2031>
- Menge, B.A. 1976. Organisation of the New England rocky intertidal community: role of predation, competition and environmental heterogeneity. *Ecological Monographs* 46: 355-393.  
<https://doi.org/10.2307/1942563>
- Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlenn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Szoecs, E. & Wagner, H. 2019. Vegan: Community Ecology Package R package version 2.5-6 (2019). Available from <https://CRAN.R-project.org/package=vegan>
- Nelson, M.L. & Craig, S.F. 2011. Role of the sea anemone *Metridium senile* in structuring a developing subtidal fouling community. *Marine Ecology Progress Series* 421: 139-149.  
<https://doi.org/10.3354/meps08838>
- 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.  
[https://doi.org/10.1579/0044-7447\(2006\)35\[75:OWFTTO\]2.0.CO;2](https://doi.org/10.1579/0044-7447(2006)35[75:OWFTTO]2.0.CO;2)
- R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available from <https://www.R-project.org/>.
- Suchanek, T.H. 1985. Mussels and their role in structuring rocky shore communities. In: Moore, P.G. & Seed, R. (eds) *The Ecology of Rocky Coasts*: 70-96. Hodder & Stoughton, London.
- Tsuchiya, M. & Nishihira, M. 1985. Islands of *Mytilus* as a habitat for small intertidal animals: effect of island size on community structure. *Marine Ecology Progress Series* 25: 71-81.  
<https://doi.org/10.3354/meps025071>
- van der Stap, T., Coolen, J.W.P. & Lindeboom, H.J. 2016. Marine fouling assemblages on offshore gas platforms in the southern North Sea: Effects of depth and distance from shore on biodiversity. *PLoS ONE* 11: 1-16. <https://doi.org/10.1371/journal.pone.0146324>
- Yager, P.L., Nowell, A.R.M. & Jumars, P. 1993. Enhanced deposition to pits: a local source for benthos. *Journal of Marine Research* 51: 209-236. <https://doi.org/10.1357/0022240933223819>
- Zintzen, V., Massin, C., Norro, A. & Mallefet, J. 2006. Epifaunal inventory of two shipwrecks from the Belgian Continental Shelf. *Hydrobiologia* 555 (1): 207-219.  
<https://doi.org/10.1007/s10750-005-1117-1>







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