EXECUTIVE SUMMARY

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 km². 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 km² realized and planned for OWFs in Belgium, 344 km² in the adjacent Dutch Borssele zone, and 122 km² 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 µPa (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^{-2}) 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^{-2}). 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^{-1} $hour^{-1}$ at rotor height. Such events occurred 14 times during autumn 2019 (maximum of 995 bird tracks km^{-1} $hour^{-1}$) and did not occur in spring 2021 (maximum of 261 bird tracks km^{-1} $hour^{-1}$) 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^{-1} $hour^{-1}$ 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 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^{-2}). 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.