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

LEARNING FROM THE PAST TO OPTIMISE FUTURE MONITORING PROGRAMMES

Edited by
Steven Degraer
Robin Brabant
Bob Rumes

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 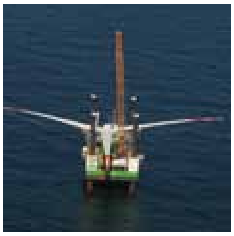    

INTRO

EXECUTIVE SUMMARY AND CONTEXT SETTING

CHAPTER 1

Executive summary

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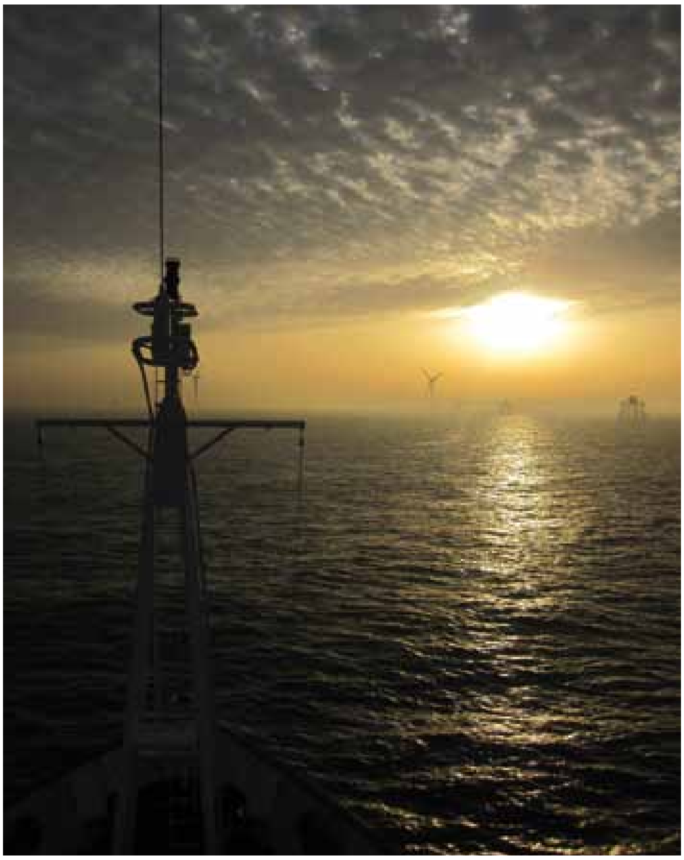
THE BELGIAN OFFSHORE WIND FARM MONITORING PROGRAMME

Belgium has allocated a 238 km² zone in the Belgian part of the North Sea (BPNS) to offshore renewable energy production, for example offshore wind farms (Chapter 2). The first wind turbines were built in 2008. At present (October 2013), 109 turbines are operational in the BPNS. The installed wind turbines differ in foundation type and generated power: while the first six wind turbines have gravity based foundations (GBF), the majority are monopiles (55) followed by jacket foundations (48). The power that can be generated ranges between 3 and 6.15 megawatt (MW) per wind turbine. In the next few years, several hundreds of turbines will be up and running. The offshore wind farms are expected to contribute for about 43% of the Belgian 2020 targets for renewable energy.

Prior to construction, a developer needs to obtain a domain concession and an environmental permit. The latter includes a number of terms and conditions to minimise or mitigate the environmental impact of the wind farm project. This imposes a monitoring programme to assess the potential impacts on the marine environment. These assessments enable the authorities to impose mitigation measures or even halt the activities in case of extreme damage to the marine ecosystem. The monitoring programme equally allows understanding and evaluating the underlying ecological processes in support of an environment-friendly offshore wind farm policy and management. The programme started in 2005 and targets physical (hydro-geomorphology and underwater noise), biological (epifouling community on the hard substratum, macro- and epibenthos of the soft substratum, fish, seabirds and marine mammals), as well as socio-economic (seascape perception and offshore renewables appreciation) aspects of the marine environment. 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 (RBINS) coordinates the monitoring programme. To cover all necessary scientific expertise MUMM collaborates with several institutes: the Research Institute for Nature and Forest (INBO), the Institute for Agricultural and Fisheries Research (ILVO-Bio-Environmental research group), Ghent University (Marine Biology Research Group and INTEC), International Marine and Dredging Consultants (IMDC) and Grontmij Belgium NV.

This report presents an integrated overview of all scientific findings of the Belgian offshore wind farm monitoring programme, with the specific aim of drawing lessons from these findings to optimise future monitoring programmes. A series of anticipated negative and positive impacts are covered, but the report also targets an insight in the underlying ecological processes. The report further elaborates on context setting and nuancing the results, and ends with some reflections to optimise the future monitoring programme.



ANTICIPATED NEGATIVE IMPACTS

Anticipated negative impacts on the marine environment also affect social acceptance of offshore wind farm developments (Chapter 3). The lack of social acceptance is actually considered one of the most important challenges of energy project developers worldwide. The social acceptance of offshore wind farms in Belgian waters was investigated through questionnaires in 2002 and 2009, i.e. prior to and after the first wind turbines had been constructed in 2008. The research demonstrated an increasing positive attitude towards offshore wind farms with 68% in support of the initiatives in 2009 versus 53% in 2002, and only 8% opponents in 2009 versus 21% in 2002. More than 90% of the 2009 respondents considered wind energy to be a good alternative to non-renewable energy sources. In Belgium, offshore wind farm siting is socially and environmentally more acceptable than onshore wind farms, even when seascape is taken into account. Interestingly, getting informed on environmental impacts of offshore wind farms was valued highest by the public. A follow up study on social acceptance is proposed when the wind farms closest to the coast are constructed.

Anticipated negative ecological impacts cover the risks of increased turbidity, increased sediment erosion and surfacing of the electricity export cable (Chapter 4). Detailed morphological investigations found that increases in turbidity are mainly due to meteorological events rather than to the construction and operation of the wind farms. Sediment erosion stayed within acceptable limits: the erosion protection around GBFs wind turbines functioned without any secondary erosion, while the monopile erosion pits ranging from 2 to 6.5 m were adequately confined by an erosion protection layer. However, there were substantial sediment losses (30 to 35 %) during the dredging and dumping activities to install the GBFs, leaving a series of dredging pits that have been refilled by using sand from the second phase of wind farm development. Electricity export cables further proved susceptible to exposure because of the dynamic sand dune migration. A continued monitoring of turbidity using satellite images is advised. The follow-up with multibeam of erosion near the foundations, wind turbine stability and cable burial, should be continued...

Negative impacts on seabirds through habitat change, habitat loss, barrier-effects and collision are major environmental concerns (Chapter 5). While some species avoided the wind farms (i.e. northern gannet *Morus bassanus*, common guillemot *Uria aalge* and razorbill *Alca torda* at the most offshore Bligh Bank, and common gull *Larus canus* at the most onshore Thorntonbank), other species seemed to be attracted (i.e. lesser black-backed gull *Larus fuscus* and herring gull *Larus argentatus* at the Bligh Bank, and little gull *Hydrocoloeus minutus*, great black-backed gull *Larus marinus*, Sandwich tern *Sterna sandvicensis* and common tern *Sterna hirundo* at the Thorntonbank). Large gulls were often seen flying at rotor height (15-22%). Based on daytime observations, each year up to about 1300 birds, mainly gulls, are expected to collide with the turbines once all wind farms will be operational in the BPNS. During strong migration periods, thrush *Turdus* spp. collisions can reach 200 victims during a single night. Visual census combined with radar observations will aid a future accurate bird mortality assessment. Future monitoring of the local seabird distribution will further increase the likelihood of displacement effect detection and will allow discerning possible habituation effects.

Increased noise levels generated by wind farms, may harm the marine environment (Chapter 6). For example, the maximum detected above water sound pressure level during pin piling activities for the installation of jacket foundations, reached 145 dB(A). The operational sound pressure level mainly generated by the blades passing through the air, amounted to 105-115 dB(A) at wind speeds higher than 12 m/s and could hence be detected up to a distance of 10 km. Underwater noise generated during the installation of gravity based foundations (about 115 dB re 1 µPa root mean square) was close to ambient noise levels. In contrast, monopile piling produced excessive underwater noise levels of 179-194 dB re 1 µPa (zero to peak level at 750 m), attenuating to ambient noise levels at a distance of up to 70 km. For pin piling (jacket foundations) lower noise levels of 172-189 dB re 1 µPa were measured, but the total number of blows per megawatt installed is 57% higher than for a monopile. When in operation, steel monopile sound pressure is double of that emitted by a jacket foundation turbine, in its turn twice the sound pressure of the background or GBF foundation turbine. Future monitoring will mainly target continuous underwater noise measurements, which can be compared with other types of human-induced noise in the marine environment.

Piling noise in fact is a major concern to marine mammals and fish (Chapter 7). For the harbour porpoise *Phocoena phocoena* occurring in Belgian waters with densities of up to 2.7 ind./ km², aerial surveys during a piling event showed a distance of disturbance of porpoises of up to at least 20 km from the piling location. A model allowed reproducing the porpoise displacement in a wide area around the piling zone, but outside this area larger differences between the observations and the model were detected. The latter difficulties may be caused by the spatial variability in food availability or seasonal movements. Further fine tuning and testing of the model in different piling conditions and based on aerial surveys and passive acoustic monitoring data, is therefore advised. The impact of construction and operational noise on fish eggs and larval development in Belgian waters only started recently, and needs more attention in the future monitoring programme. These 'passive drifters' cannot actively escape from the exposure to human-induced noise. Especially fish with a swim bladder, for which the European sea bass *Dicentrarchus labrax* will be used as a model species, will be targeted through an experimental study.

ANTICIPATED POSITIVE IMPACTS

The protection against fishing activities inside the wind farms is undoubtedly the main anticipated positive impact of offshore wind farms on the marine environment (Chapter 8). Based on VMS data (Vessel Monitoring System), it can be concluded that fishing vessels - mainly trawlers - are virtually everywhere in Belgian waters, except in the wind farms. A moderate increase in fishing activities, mostly from Dutch fishing vessels, is noted in the zone surrounding the wind farm concessions. Recreational anglers, mostly targeting pelagic and bentho-pelagic fish, first concentrated close to the gravity-based foundations at the Thorntonbank, but recently seem to have almost left the area.

Combined with a possible reef effect, the exclusion of fisheries was expected to have a significant positive impact on the soft sediment benthos. A macrobenthic *Nephtys cirrosa* community was found at the Thorntonbank and Gootebank, corresponding to a typical sedimentology with a median grain size between 331 µm and 410 µm (Chapter 9). The community is dominated by a few species, like the polychaetes *N. cirrosa* and *Spiophanes bombyx*, the mysid shrimp *Gastrosaccus spinifer* and the amphipod *Urothoe brevicornis*. A natural inter-annual variability in densities between about 200 and 800 ind./m², was detected. While the macrobenthic community structure was similar in the control and concession sites before construction, significant differences were found in 2008. In this year, i.e. shortly after major construction works, high densities (dominated by *S. bombyx*) were detected. However, no large-scale effects could be detected, as the differences between control and impact sites disappeared again after two years. The Benthic Ecosystem Quality Index (BEQI) confirmed the recovery of the community after the construction works. Long-term and larger-scale effects could hence not be detected. Future monitoring will focus on the fisheries exclusion and smaller-scale enrichment effects (Chapters 8 and 13), and aim at detecting these effects at the scale of a complete wind farm.

Demersal fish, benthopelagic fish and epibenthos from soft sediments may be positively impacted as well (Chapter 10). For example, epibenthos biomass and length of whiting *Merlangius merlangus* slightly increased at the edge of the Thorntonbank, while (temporarily) increased abundances of sole *Solea solea* and dab *Limanda limanda* were observed at the edge of the Bligh Bank. Inside the wind farms, several local and temporal impacts were detected. At the Thorntonbank, increases in dab mean length (2012), epibenthos biomass (2009) and number of demersal fish species (2009) were observed. At the Bligh Bank, densities of the common starfish *Asterias rubens* and sole increased over the monitoring period, and several 'larger' plaice *Pleuronectes platessa* and turbot *Psetta maxima* were noted. Some short time construction effects were seen shortly after the start of the piling activities, like increased sandeel *Ammodytes tobianus* densities and decreased densities in dab, ophiuroids *Ophiura ophiura*, squid *Allotheutis subulata* and dragonet *Callionymus lyra*. A continued monitoring, taking into account the high natural spatio-temporal variability, will ensure an increased power of impact detectability.

Some fish may be directly attracted to the artificial hard substrata, in search for food or shelter (Chapter 11). The offshore wind turbine fish community (near the gravity-based foundations) was dominated by pouting *Trisopterus luscus* and cod *Gadus morhua*, while also other species such as poor cod *Trisopterus minutus*, saithe *Pollachius virens* and black seabream *Spondyliosoma cantharus* were exclusively detected close to the turbines. Cod and pouting catches were up to 12 and 30 times higher, respectively, compared to the wrecks, and up to > 100 times higher compared to the nearby sandy areas. The density peaks of both species (May-November for cod and September-December for pouting), probably reflect a seasonal spawning migration. Young individuals dominated the local cod and pouting populations. Future monitoring will focus on the representativeness of GBF wind turbines compared to steel monopile turbines, the latter having a smaller erosion protection layer and are positioned in more offshore waters.

Fouling organisms colonising artificial hard substrata, increase the local species richness (Chapter 12). Different communities can be detected along the depth gradient: the marine splash midge *Telmatogeton japonicus* dominated the splash zone; the intertidal fringe was characterised by barnacles and the blue mussel *Mytilus edulis*; a *Jassa*-*Tubularia*-Actiniaria community in the subtidal zone was dominated by the amphipod *Jassa herdmani* (up to 3 10^5 ind./m²) and the hydroids *Tubularia indivisa* and *T. larynx* (up to 90% coverage). The patterns in species richness, density and coverage were best illustrated at the Thorntonbank, where they showed an increase mainly during the first two to three years, after which they stabilised. These long-term dynamics are superimposed by seasonal dynamics with highest densities (generally ranging between 1-1.5 10^5 ind./m²) and coverage (on average 60-70%) in spring and summer. In addition to the settling of new species, competition and predation are important biological processes shaping hard substrata communities. Future monitoring will focus on a better understanding of the spatial heterogeneity, the dynamics along the onshore-offshore gradient, and the use of the artificial reefs by larger invertebrates, such as crabs and lobsters.

UNDERSTANDING ECOLOGICAL PROCESSES BEHIND THE OBSERVED PATTERNS

A proper understanding of the ecological processes underlying the observed impacts is indispensable to deliver science-based advice for an environment-friendly design of future wind farms. For example, understanding the effects of organic enrichment on soft sediment macrobenthos at a small scale, allows extrapolating these small-scale effects to large-scale and long-term impacts (Chapter 13). Lower median grain sizes of the sediment and increased organic matter levels were found close to the gravity based foundations at the Thorntonbank. These phenomena could be linked to a macrobenthic community evolving away from the typical *N. cirrosa* community in this area. Close to the turbines, elevated macrofaunal densities (up to 11500 ind/m^2), biomasses (up to 9540 mg/m^2) and number of species (up to 32 spp.) were found, especially along the Northwest and Southwest transects. Juvenile common starfish *A. rubens*, the sand mason *Lanice conchilega*, the bee spionid *S. bombyx*, and the typical hard substrate species *Monocorophium acherusicum* and *J. herdmani* tend to dominate in this enriched environment. The local enrichment was detectable to a distance of 50 m from the turbines. Future monitoring will target the spatial extension of this effect through time and at other types of wind turbine foundations.

Zooming into fish habitat use in Belgian offshore wind farms, mainly young individuals of Atlantic cod and pouting were clearly attracted nearby the wind turbines as was observed by divers and by line fishing. Demersal fish species were however not found to be consistently attracted at larger distances (minimum 180 m) from the turbines (Chapter 14). So far, no clues of increased recruitment or growth in demersal species were detected at larger distance. However a number of larger individuals of plaice *Pleuronectes platessa* were caught at the Bligh Bank. Dab on the other hand occurred in lower numbers, but remarkably had a fuller stomach inside (mean Fullness Index, FI: 0.15) than outside (FI: 0.05) the area. Similarly to cod, pouting showed feeding mainly upon epifouling species, such as *J. herdmani* and *Pisidia longicornis*. Cod indeed showed an attraction to the artificial hard substrata with about 90 % of the individuals staying within a 40 m range from the wind turbines. Future monitoring will focus on attraction and production mechanisms other than food availability, but will also aim at including a wider set of fish species and an energy profiling of their prey species.

Recent sightings of European shag *Phalacrocorax aristotelis*, a seabird species favouring cliffs and rocky shores, in Belgian wind farms and black-legged kittiwakes *Rissa tridactyla* starting to breed on North Sea gas platforms, all point towards the attraction-production potential of offshore wind farms for seabirds (Chapter 15). Whether birds are attracted to wind farms from a sheer physical point of view, with the wind farm functioning as a stepping stone or a resting place (attraction), or whether they already learned to exploit the possibly increased food availability (production), remains to be investigated. Black-legged kittiwakes were already regularly observed foraging inside the Bligh Bank wind farm, with the percentage of kittiwakes actively foraging inside the wind farm being much higher than in the control area (5.9% versus 0.3%). Also high numbers of lesser black-backed gulls were foraging close to the Thorntonbank jacket foundations. Future monitoring will pay attention to the behaviour and foraging-related activities of seabirds, and to pelagic fish as the most important prey species for seabirds.

Within the attraction-production debate of offshore wind farms we also investigated whether marine mammals were attracted to the increased fish abundance close to wind turbines or rather repulsed by the increased noise levels (Chapter 16). Harbour porpoises showed an uneven spatio-temporal distribution in Belgian waters, with a shift from the northern and north-eastern part of the Belgian waters towards the south-west and west between February and April. As the offshore wind farms are relatively small compared to the area that can be covered in a short time period by this highly mobile species, differences in distribution of harbour porpoise within and outside wind farms are probably inferior to seasonal variations within the southern North Sea caused by movements to find suitable prey resources. In addition to continued aerial surveys, future monitoring will target small-scale passive acoustic monitoring (PAM) to investigate the potential use of offshore wind farms by harbour porpoises. Attention will also be paid to disentangle the complex link between PAM data and species densities.

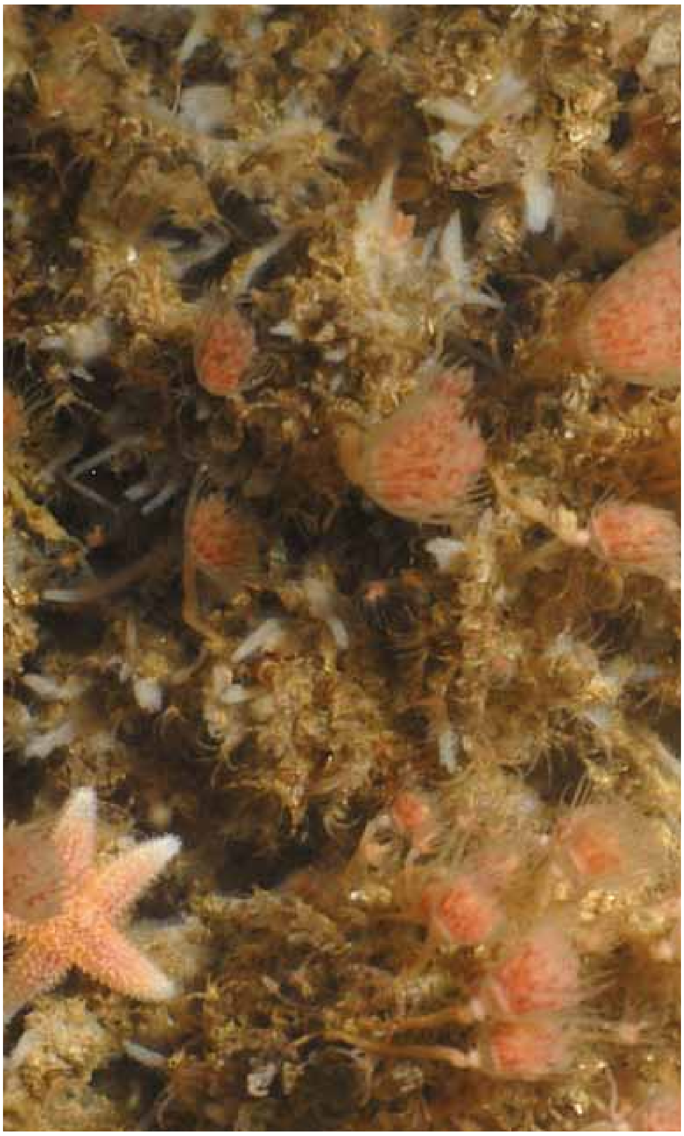
NUANCING EFFECT INTERPRETATION

Several impacts have been identified in the Belgian offshore wind farms, varying from seemingly negative to seemingly positive impacts (Chapter 17). Species richness increased because hard substrata (wind turbine foundations and erosion protection layers) were introduced. However, offshore wind farms may also increase the risk of invasions in the North Sea, as non-indigenous species (NIS) may now find more suitable place to survive and hence strengthen their competitive position in the North Sea. More than half of the hard substratum intertidal species (e.g. the invasive Pacific oyster *Crassostrea gigas*) in the wind farms can be categorised as NIS. Pouting is attracted to wind farms, but we do not know yet whether these offshore wind farms act as an ecological trap. However, pouting is significantly larger inside than outside the wind farms, their stomach is filled more and their condition is similar, so no evidence was obtained to assume that the habitat quality of offshore wind farms does not fulfil the functional needs of pouting. Preliminary extrapolation of bird collisions (at North Sea population scale) to future expansions of offshore wind farms showed that the existing adult mortality for instance of lesser and great black-backed gull might exceed the accepted threshold of 5%. Future monitoring will take account of the need for up scaling to species population levels and the expansion of offshore wind farms in the North Sea.

Increased species richness, densities and biomass further can be evaluated in different spatial settings, for instance at turbine level or at the level of a wind farm or even the Belgian part of the North Sea (Chapter 18). The species pool of soft sediment fish and squid did not change drastically, but the number of hard substrate associated fish species increased from 2 to 8 inside the wind farm concession area. The number of benthic species in the concession area more than doubled, from 91 to 264 species, since the installation of the first turbine foundations, mainly because of the increase of hard substratum species from 10 to 100. Autumn benthic biomass increased ~4000 times at the scale of a single gravity based foundation from 0.6 kg ash-free dry weight (AFDW) before construction to ~2500 kg after construction, with the major part of the biomass at the scour protection (89%) and the intertidal *M. edulis* zone (10%). For the entire Thorntonbank wind farm, the autumn biomass increased about 14 times from about 5 to 70 ton AFDW. The offshore wind farms may contribute about 3% of the total biomass in the BPNS. Future monitoring will focus on a validation of the fouling biomass estimates for jacket and monopile foundations.

REFLECTIONS FOR AN OPTIMISATION OF FUTURE MONITORING PROGRAMMES

Six years of monitoring triggered a reflection on how to best continue the monitoring programme, building on both basic and targeted monitoring contexts (Chapter 19). The basic monitoring should be rationalised at the level of the likelihood of impact detection, related to research effort and impact size. The meaningfulness of impact size deserves our attention and should be aligned with the current implementation of European Directives, such as the Marine Strategy Framework Directive. Future basic monitoring finally needs to consider the representativeness of the current findings, so far largely focused on GBFs. Within a targeted monitoring context, the artificial reef effect will undoubtedly play a key role in the future monitoring programme. It already received a lot of attention in the monitoring so far, but various cause-effect relationships, mainly linked to the attraction-production hypothesis, remain yet to be tackled, preferably through international scientific collaboration. A major challenge however is to achieve a reliable assessment of cumulative impacts and to upscale locally observed impacts to the larger scale at which ecological processes take place. This will require a close collaboration between scientists, industry stakeholders and administrators, preferably across countries bordering the North Sea.



CHAPTER 2

Monitoring offshore wind farms in the Belgian part of the North Sea: Setting the scene

Robin Brabant*, Steven Degraer* and Bob Rumes

*shared first authorship

Offshore wind farms are expected to contribute for about 43% of the Belgian 2020 targets for renewable energy. Today, 109 turbines are operational in the Belgian part of the North Sea. In the next few years, several hundred of turbines will be up and running. With 238 km² reserved for offshore wind farms, major ecological impacts may however be expected. These impacts both positive and negative, triggered an environmental monitoring programme focusing on various aspects of the marine ecosystem components, but also on the human appreciation of offshore wind farms. This report targeting marine scientists, policy makers and managers, provides an overview of the major scientific achievements of six years of monitoring.

OFFSHORE WIND FARMS IN BELGIUM

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 2020. Offshore wind farms in the Belgian part of the North Sea (BPNS) are expected to make an important contribution (ca. 43%, assuming 2000 MW installed capacity by 2020) to achieve that goal.

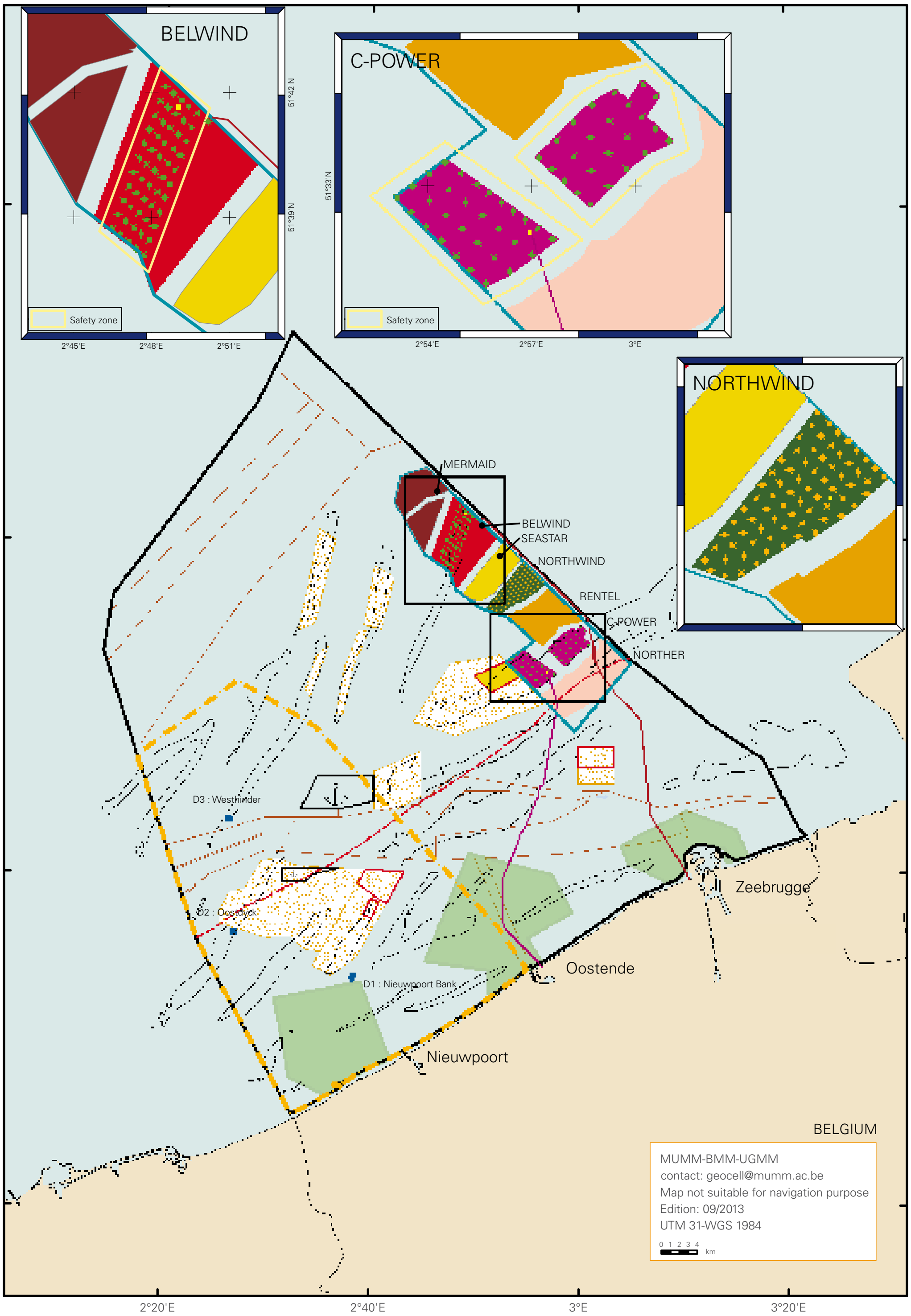
With the Royal Decree of 17 May 2004, a 264 km² area within the BPNS is reserved for the production of electricity from water, currents or wind. It is located between two major shipping routes: the north and south traffic separation schemes. In 2011, the zone was adjusted on its Northern and Southern 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 km².

Prior to installing a wind farm, 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 (EIA), based on the EIS. The Minister then grants or denies the environmental permit in a duly motivated Decree.

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 on the marine environment.

At present, five projects were granted a domain concession and an environmental permit (from South to North: Norther, C-Power, Rentel, Northwind & Belwind). Two additional projects were granted a domain concession, one of which has submitted its application to obtain an environmental permit in summer 2013 (Table 1).



Map of the Belgian part of the North Sea with an indication of the human activities. A 238 km² area (blue polygon) is reserved for the production of renewable energy by the Royal Decree of 17 May 2004, as adjusted by the Royal Decree of 3 February 2011 (http://www.mumm.ac.be/EN/Management/Atlas).

Human activities in the Belgian marine area

- Belgian continental shelf
- Territorial sea limit
- Anchorage area
- Navigation route
- Area reserved for electricity production
- Operational wind turbine
- Turbine under construction
- Offshore transformer station
- Export cable Belwind
- Export cable C-Power
- Reference zone for Wind farm monitoring
- Mineral resources extraction zone
- Zone closed for mineral resources extraction
- Mariculture area
- Site of Community Importance (Habitat Directive) "Vlaamse banken". New Special Area of Conservation
- Special Protection Area (Birds Directive)

Table 1. Overview of wind farms in the Belgian part of the North Sea (situation on 30th of September 2013)

*number of turbines and/or total capacity still to be decided

**20 MW wave energy

Project		Number of turbines	Capacity (MW)	Total capacity (MW)	Concession obtained	Environmental permit obtained	Status
C-Power	phase 1	6	5	325	YES	YES	Phase 1 completed in 2009
	phase 2&3	48	6.15		YES	YES	Entire wind farm completed in 2013
Belwind	phase 1	55	3	330	YES	YES	Phase 1 completed in 2011
	phase 2	55	3		YES	YES	Phase 2 construction foreseen to start in 2014
	demo	1	6		YES	YES	Alstom Haliade demo turbine installed in 2013
Northwind		72	3	216	YES	YES	Construction ongoing
Norther		47 – 100*	3-10	258 – 470*	YES	YES	Construction foreseen to start in 2014
Rentel		47 – 78*	4-10	289 – 468*	YES	YES	Construction foreseen to start in 2016-2017
Seastar		41*	4-10	252 – 540*	YES	NO	Construction foreseen to start in 2016-2017
Mermaid		75*	6*	450*+ 20**	YES	NO	No information

C-Power's onshore construction site of the gravity based foundations in Ostend.

TIMELINE WIND FARMS DEVELOPMENT

The C-Power project is located on the Thorntonbank sandbank, located at 27 km off the Belgian coast. In 2008, C-Power started with the construction of the first phase of its project, i.e. six turbines on gravity based foundations (GBF). A GBF is a hollow, concrete structure that is filled with sand once it is placed on the seabed. Due to its weight, it remains stable. Before the GBF can be placed, the seabed needs to be prepared to create a flat surface on dense sand.

2008

Transport of a gravity based foundation from the port of Ostend to the C-Power site at the Thorntonbank.

Assembly of a C-Power phase 1 turbine on the Thorntonbank.

2009

The six turbines of C-Power's first phase were commissioned and producing electricity by May 10th, 2009.

Phase 1 turbines on the Thorntonbank.

Pile driving of monopiles (MP) for the Belwind project on the Bligh Bank started on September 8th 2009. The 56th and last monopile of the first phase was installed on February 5th 2010.

2010

Piling vessel (with red and white hammer) at the Belwind site on the Bligh Bank.

A transition piece (TP) was installed on every Belwind monopile. The TP makes the connection between the MP and the wind turbine. In 2010, Belwind installed 55 wind turbines and one offshore high voltage station. The entire phase 1 of Belwind was fully operational from December 31st 2010 onwards.

Belwind Phase 1 wind turbines on the Bligh Bank.

The construction of phase 2 and 3 of the C-Power project (i.e. 48 turbines and one offshore transformer station) started in spring 2011. The foundation type for the phase 2 and 3 turbines is different from the pilot phase since jacket foundations, instead of the GBFs, were installed. These foundations consist of a steel jacket with four legs. The foundations were installed using the pre-piling concept: four pin-piles were driven into the seabed and the legs of the foundation were grouted on the pre-piles.

2011

Phase 3 jacket installation at the C-Power site.

The C-Power offshore transformer station was installed on March 17th, 2012. On the background the six phase 1 turbines and ongoing jacket installation.

The construction of the Northwind project on the Lodewijkbank started in spring 2013. The wind farm is expected to be fully operational by spring 2014.

2012

Vessel on its way to the Nortwind site on the Lodewijkbank with two monopiles and two transition pieces.

In the summer of 2013 the entire C-Power wind farm was finalised and producing energy. The wind farm was officially inaugurated on September 17th, 2013.

2013

Partial view of the C-Power wind farm.

OFFSHORE WIND FARM MONITORING AND RESEARCH STRATEGY

The monitoring programme started in 2005 with the investigation of the pre-impact condition of the ecosystem and the search for appropriate reference sites, but it was continued only from 2008 onwards when the first six wind turbines were installed onto the Thorntonbank. The monitoring programme targets physical (i.e. hydro-geomorphology and underwater noise), biological (i.e. hard substratum epifauna, hard substratum fish, soft substratum macrobenthos, soft substratum epibenthos and fish, seabirds and marine mammals), as well as socio-economic (i.e. seascape perception and offshore renewables appreciation) aspects of the marine environment. MUMM coordinates the monitoring and covers the socio-economic aspects of the monitoring. OD Nature further adds its expertise in hydro-geomorphology, underwater noise, hard substratum and non-indigenous epifauna, marine mammals and radar detection of seabirds. Further collaborations complete the necessary expertise in the following domains: seabirds (Research Institute for Nature and Forest), soft substratum epibenthos and fish (Institute for Agricultural and Fisheries Research), soft substratum macrobenthos, hard substratum fish (Marine Biology Research Group, Ghent University), above water noise (INTEC, Ghent University), seabed morphology (IMDC) and seascape (Grontmij).

With the monitoring programme, MUMM and its partners (1) assess the extent of the anticipated impacts on the different aspects of the marine ecosystem and (2) aim at revealing the processes behind these impacts. The first objective is basically tackled through the 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. As such, the basic monitoring deals with observing rather than understanding impacts and hence leads to area-specific results, which might form a basis for halting activities. In this study, basic monitoring generally follows a before-after, control-impact or BACI design, in which ecological changes at the impact site are compared with the ecological condition before the impact and in non-impacted reference or control sites. Targeted monitoring on the other hand deals with the understanding of the processes behind the impacts of a selected set of hypothesised cause-effect relationships highly relevant to the wind energy sector. This step is not only a prerequisite for an effective regulatory application, but also permits (1) current and future impact mitigation, (2) better prediction of future impacts, as well as (3) moving away from site-specific observations to more generic knowledge. More details on this topic can be found in Degraer and Brabant (2009).

SIX YEARS OF MONITORING AND RESEARCH

In addition to a set of early scientific reports presenting the baseline condition at future impact and reference sites (De Maersschalck et al., 2006; Henriet et al., 2006; Vanermen et al., 2006), an overview of the major achievements of the monitoring programme has been presented in a series of yearly published, integrated reports.

In 2009 (Degraer and Brabant, 2009), we reported on the lessons learnt and recommendations from the first two years of environmental monitoring. This report more specifically evaluated the appropriateness of the selected reference sites and reference conditions for both the C-Power and the Belwind projects. It further introduced the various environmental data under surveillance, including a preliminary evaluation of the impacts linked to the construction of the first six turbines at the Thorntonbank. Its main importance however is found in its advices for future monitoring at the level of technicalities, scientific design, as well as research focus and strategies.

Degraer et al. (2010) then focused on the early and or localised environmental impacts of the GBF wind turbines (C-Power) and or monopiles (Belwind), as well as on the natural spatio-temporal variability (i.e. dynamic equilibrium). Early impacts were detected for the geophysical environment of both the GBF wind turbines at the Thorntonbank and the monopile wind turbines at the Bligh Bank, the establishment of hard substratum biota on and close to the GBF wind turbines at the Thorntonbank, and the social attitude towards offshore renewables. The natural spatio-temporal variability was investigated for the soft substratum macrobenthos, soft substratum epibenthos, soft substratum fish and marine mammals.

In 2011 (Degraer et al., 2011), a selection of targeted monitoring results was presented for the first time, from which we attempted to construct a hypothesis-driven impact scenario, including presumed cause-effect relationships between the various ecosystem components. The integration of the monitoring findings obtained so far, already allowed for some preliminary speculation on the long-term impact processes within the Belgian wind farm zone. Those were a prolonged organic enrichment of a naturally relatively poor environment, an increased food availability for epibenthic and fish predators and the improved seabird and marine mammal habitat quality. The Benthic Ecosystem Quality Index (BEQI) was further applied to evaluate the deviation in macrobenthic density, number of species, species composition and biomass between the benthic data collected in the impact area and the reference area, both from the period before and after the construction of the first wind turbines.

The 2012 report (Degraer et al., 2012) continued building on a common understanding of the environmental impacts of offshore wind farms. This included the cause-effect relationships of observed impacts within the benthos, a strengthening of the visual detection of impacts on seabirds and getting prepared for going offshore with the bird radar, and a quantification of harbour porpoise *Phocoena phocoena* disturbance by piling activities.

THIS REPORT

This report finally presents an integrated overview of all scientific findings of the Belgian offshore wind farm monitoring programme, with the specific aim of drawing lessons from these findings to optimise future monitoring programmes. The report as such covers a series of anticipated negative (Part I) and positive impacts (Part II), but also targets an understanding of the ecological processes behind observed impacts (Part III). Further considerations on context setting, nuancing and reflections on future monitoring are further presented in Parts IV and V, respectively.

Part I reports on the anticipated negative impacts, with:

- the disruption of a previously unspoiled seascape by offshore wind farms visible from the coast (Chapter 3); altered sediment characteristics and increased erosion of the natural sandy sediments around wind turbine foundations because of accelerating currents next to the foundations (Chapter 4);
- a major disturbance of seabirds because of avoidance and collision by seabirds (Chapter 5);
- increased construction and exploitation noise levels and the associated impact on marine mammals and fish (Chapters 6 and 7).

Part II targets a set of anticipated positive impacts, with:

- an enrichment of the soft-substratum macro-, epibenthos and fish as a result of e.g. the exclusion of fisheries from the wind farms (Chapters 8, 9 and 10);
- an attraction of fish by the introduced hard substrata (Chapter 11);
- an increased species richness because of the introduction of hard substrata (i.e. wind turbine foundations) and a consequent fouling by hard substrata invertebrates (Chapter 12).

Part III focuses on the results from the targeted monitoring, hence shedding a light onto cause-effect relationships behind the observed changes in the ecosystem (e.g. artificial reef, refugium and ecological trap effects; see Box), with:

- a local enrichment in soft sediment macrobenthos close to wind turbines (Chapter 13);
- a (possible) attraction of fish, seabirds and marine mammals as a consequence of habitat alterations (Chapters 14, 15 and 16).

Part IV aims at putting all findings into a wider context, as such nuancing anticipated positive and negative effects, with:

- an introduction to ecological pitfalls and unintended consequences in non-indigenous biofouling organisms, attracted fish and colliding seabirds (Chapter 17);
- a context setting of the locally observed increase in biodiversity and biomass (Chapter 18)

Part V finally reflects on the optimisation of the future offshore wind farm monitoring (Chapter 19).

While providing an overview of all major scientific findings, this report also serves as a feedback moment after six years of monitoring and research. Such feedback moment necessitates the attention not only of scientists, but also of the offshore wind energy sector as well as marine policy makers and managers, and the public at large. As its target audience hence is very wide we have chosen to restrict the scientific details to that level needed to comprehend our major findings. The report may and should hence be read as a non-specialist document. We fully understand some readers would however be interested in getting more detail, for which we refer to the integrated scientific reports introduced above (Degraer and Brabant, 2009; Degraer et al., 2010, 2011, 2012), all downloadable from www.mumm.ac.be. Alternatively, those readers may directly want to get in touch with the authors of the chapters, whose contact details may be found at page 239.

BOX:

The ecological hypothesis-derived terms artificial reef effect, refugium effect and ecological trap effect are commonly used throughout this report. The following definitions ascertain the reader to be clear on what is meant by these terms.

- Artificial reef / reef effect (Langhamer, 2012)

  When introduced into the marine environment, wind turbines together with their associated scour protection, constitute an artificial reef which means that the surfaces are readily colonised by a typical and broadly predictable assemblage of organisms, reflecting zonation patterns observed in adjacent rocky shore communities. Although the scientific literature mostly agreed that there is likely to be a positive effect on fish and crabs, the extent and nature of the effect is heavily dependent on the nature of the reef created, the location, and the characteristics of the native populations at the time of introducing the artificial reef.

- Refugium effect / no trawling zone (Langhamer, 2012)

  Establishing offshore wind farms facilitates the creation of no-trawling zones, covering hundreds to thousands square kilometres. As such, wind farms may prevent fisheries-induced stirring up of bottom sediments and loading suspended solids into the water column, as well as a direct reduction in vulnerable species, biodiversity, production and biomass in general. These no-trawling zones as such mitigate habitat losses and degradation. In these areas juvenile fish will have a higher chance to survive. Even older, larger fish will have increased survival rates and in this way offshore wind farms may contribute to a spill over effect. A consequent higher fishing pressure at the edge of the wind farms may counteract this anticipated positive effect.

- Ecological trap (Robertson and Hutto, 2006)

  In suddenly altered ecosystems as is the case for the construction of offshore wind farms, ecological traps may arise. When an organism is attracted to, and preferably settles in a habitat with suboptimal conditions relative to other available habitats, it is caught in a so-called ecological trap. Ecological traps are thought to occur when the attractiveness of a habitat increases disproportionately relative to its value for survival and reproduction. Habitat choices are a consequence of natural selection and are based upon a number of ecological cues which indicate the quality status of a habitat. An ecological trap may occur when changes in the environment act to uncouple the cues used to assess habitat quality from the true quality of the environment.






PART I

EVALUATING ANTICIPATED « NEGATIVE » ENVIRONMENTAL EFFECTS

CHAPTER 3

Seascape: final results of a socio-economic study

Marisa Di Marcantonio, An Vanhulle, Rik Houthaeve and Bob Rumes

In 2002 and 2009 two sociological seascape surveys took place in Belgium. These surveys focused on both the visual and overall experience. People's general opinion on wind energy and on the local planned wind farms were asked. Results show that in 2002 there was already a majority in favor of wind farms and this number still increased by 10% in 2009. A future survey is proposed to take place in the summer after the first wind turbines of the wind farms closest to the land have been installed. At that time at least three other wind farms will also be operational.

INTRODUCTION

Feenstra (2013) mentions that the lack of social acceptance also called NIMBY (Not In My Backyard) has become the third most important challenge of energy project developers worldwide, in addition to financial and regulatory issues. The NIMBY label is heavily discussed in research: where in the early years of wind farm development the NIMBY attitude – preferring technical siting elsewhere- was frequently used to explain opposition to new developments, more recent research has focused on looking for the reasons underlying opposition or support (Devine-Wright, 2008; Firestone et al. 2009; Haggett, 2011 and Wolsink, 2000 and many more). As part of the licensing conditions for the first offshore wind farms in the Belgian part of the North sea, a socio-economic study was conducted. This research focuses on people's opinion on renewable energy in general and opinions on specific projects in the Belgian part of the North sea. It tries to get an insight on underlying reasons for people's attitudes towards renewables and offshore wind energy in particular.

RESEARCH STRATEGY

When did we survey?

Since Belgium has little experience with sociological land(sea)scape studies, a research methodology was used that is very well known in other countries (Krohn and Damborg, 1999 and Wolsink, 1996) where a long experience exists of measuring perceptive effects of infrastructural works within a certain landscape.
This particular sociological survey focuses on both the visual experience and "total experience" of the perception of the surroundings and landscape. This kind of survey usually has a wide scope and will investigate the (changes in) quality of the life of the respondents and will attempt to relate this to several effects simultaneously.

In 2002 a first sociological seascape survey (WES, 2002; WES, 2003) took place in Belgium to study acceptance and assessment of renewable energy and more specifically of offshore wind farms in Belgium. For this purpose 405 persons (137 coastal residents, 67 second residents, 13 coastal workers and 188 tourists) were interviewed face to face at the coast. During the summer of 2009 a public inquiry (Houthaeve and Vanhulle, 2010) was held to check for comparable results since 2002. Similar to the study of 2002, the methodology of the 2009 study included a public inquiry of 1000 persons, particularly coastal inhabitants (235), tourists (257 daytrip tourists, 244 overnightstay tourists), second residents (222), sailors and coastal workers (42). Researchers wanted to know if eventually acceptance changes as wind farms are constructed (integration of perception/acceptance). Respondents were asked their opinion on the construction of offshore wind farms and the results were compared to the results of 2002 (Figure 1).

Six wind turbines were already built in 2008.To investigate the impact of these already built wind turbines at sea simulations of the offshore wind farms, as well as the actual view from the coastline, were used. Photomontages were used for calibration purposes.

For these montages a real view picture base layer was used, whereas for the photo simulation a base layer of a neutral sea picture was used. On this base layer a simulation of the wind turbines was added digitally to give an impression on what the situation would look like with real wind turbines. Using this technique a large number of viewpoints and angles can be simulated taking into account different wind farm configurations, turbine types,... The use of a neutral base layer is important because the simulations are used in the inquiries for the sociological landscape study and the evaluations made by the interviewed people may not be influenced by random distractions on the photo like e. g. ships, objects on the beach, etc. Sunny weather conditions were used on all simulations. Respondents were asked to evaluate four different simulations (presented on high quality paper photographs with a 20x30 cm format): a first one showing wind turbines of the three permitted projects, followed by a simulation of the Belgian wind farm area fully occupied with wind turbines (worst cases scenario) (Figure 7). Also a simulation of a night view and a simulated situation at sea (at a distance of 2 km from the wind farm) were shown.

What did we ask to the people?

To find out how people think about a certain subject the selection of the questions asked during the enquiry are of utmost importance and lot of effort is spent in selecting the questions to be asked during the survey. Questions used in the 2009 survey were based on the previous study of 2002. The questionnaire had six different parts, each linked to a specific objective:

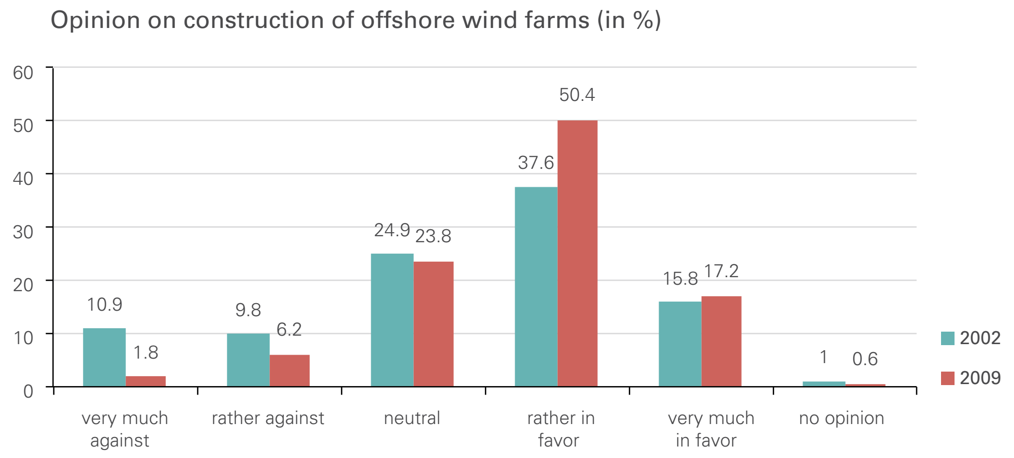
- the first part of the questionnaire focused on the relation of the respondent with the coast side in order to determine the frequency with which the respondent is in contact with the view of offshore wind farms e.g. "how many times do you visit the coast";
- the second part examined the social relevance of sustainable development by proposing a number of statements on wind farms and wind energy in general; this in order to gage the respondents opinion on this matter and see if the people's opinion had changed according to the previous survey in 2002;
- the third part sounded the experience of the actual wind farm, how the visual impact is appreciated from the dyke, what the impact was of the turning blades what the impact of lights in bad weather conditions or at night are;
- the fourth part of the questionnaire looked into the effects the wind farm has on the behavior of people (perception, acceptance,…) e.g. "will you still visit the coast if this wind farm is to be built?";
- the fifth part focused on the cumulative impact of the second and third wind farm planned in the wind farm area; photo simulations were used for this part;
- the last part focused on socio demographic information of the respondents (age, education level, etc.).

RESULTS

Did people's opinion change in time?

Figure 1 shows that, in 2009, more than half of the respondents (50%) said to be rather in favor of the construction of offshore wind farms and 17% is even very much in favor thereof. A small minority of 8% is (rather) against offshore wind farms. The number of persons with a positive attitude has risen by 10% in comparison with 2002. Generally, people still find the quality of the seascape very important: the wide sea view and the openness, naturalness and the tranquility of the sea. Kuehn et al. (2005) mentions that interviewers for the Horns Rev wind farm in Denmark revealed that many of the opponents modified their views after construction of the farm. Ladenburg et al. (2005) gives the figures for this statement: two years after the construction, 12 % of residents felt the wind turbines negatively impacted the view and 89% supported new offshore developments in Denmark. A survey conducted in 2005 in USA for the Cape Cod offshore wind farm showed that a majority of the Cape Cod residents (55%) were opposed to the project (and 44 % supporters). A more recent survey conducted in 2007 showed that the project has been gaining support amongst residents with 61% of residents supporting the development of the Cape Cod offshore wind farm and 36% opposing (2% unsure) (Firestone et al, 2009) .

Figure 1. Opinion on construction of offshore wind farms, survey 2009 compared to survey 2002 (in %).



Age doesn't matter, gender does

People living at the coast and sailors are less in favor of construction of offshore wind farms than people living further inland, but both groups still remain predominantly positive. Firestone (2009) mentions comparable conclusions for the Cape Cod and Delaware projects in USA. Age did not matter in the opinion on offshore wind farms but gender did, with men being slightly more positive than women. Also more people are in favor when they had a higher education. As the higher educated people are more represented in the respondents group this opinion on the construction of offshore wind farm is globally too positively presented. Nevertheless similar results were found for the Cape Cod wind farm where the supporters of wind farms had higher educational background attainment (Nordman, 2011).

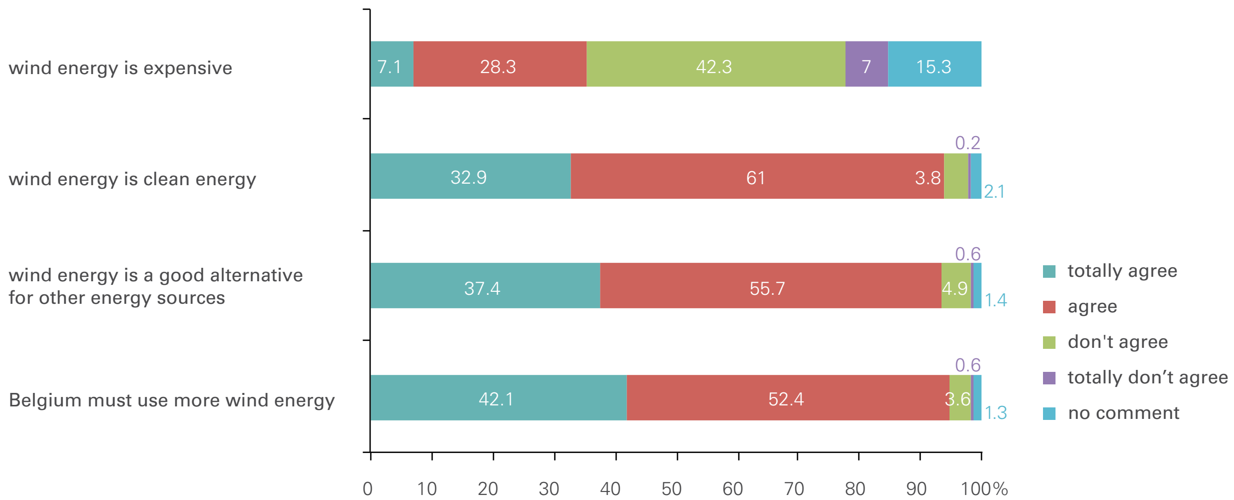
Opinion about wind energy

Here we look at people's opinion about wind energy in general and offshore wind energy in particular.

Wind energy in general and applicability of wind energy

Following statements on **general wind energy subjects** were proposed to the people.

Figure 2. Agreement / disagreement with the statements on wind energy in general, survey 2009 (in %).

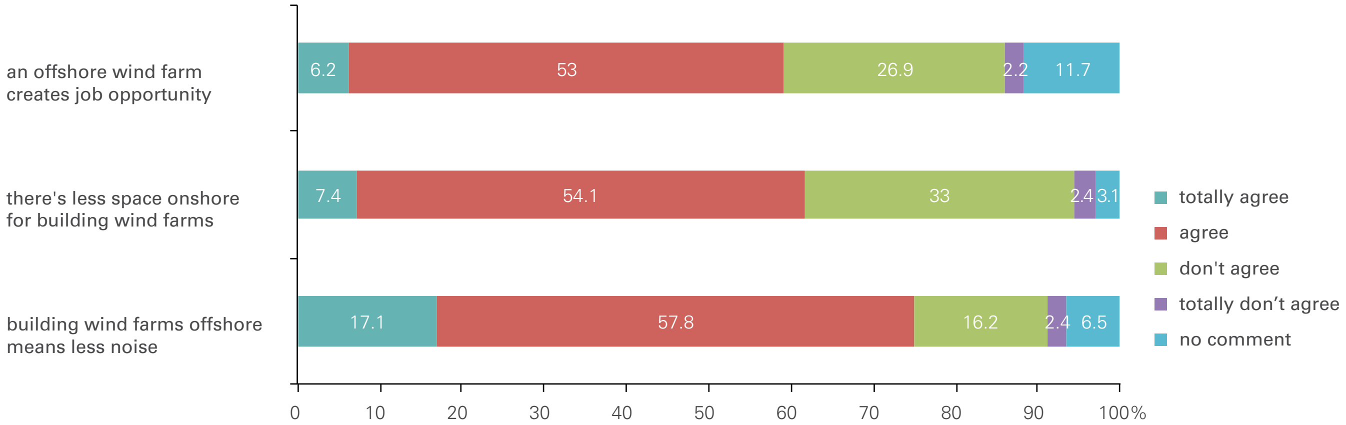


Almost everyone (95 % of the respondents) is strongly convinced that Belgium should use more wind energy, almost 94% agrees that wind energy is a clean energy. Almost everyone (93%) also agrees that wind energy is a good alternative for other classic energy sources; about 6% doesn't agree (totally), 1% has no opinion. It's striking how much people agree with these statements on wind energy in general.
The last statement gathers information on the financial implications of wind energy. It is notable that on this statement opinions are divided. More than one out of three agrees that wind energy is expensive. Quite a lot of people (15%) do not have an opinion on this subject; half of the respondents (49%) do not agree (totally) that wind energy is expensive.
The above results indicate that while the respondents in general considered wind energy to be a clean and sustainable energy source there is still uncertainty about the costs.

Offshore wind energy

Three statements sound people's opinion on the **advantages** of an offshore wind farm.

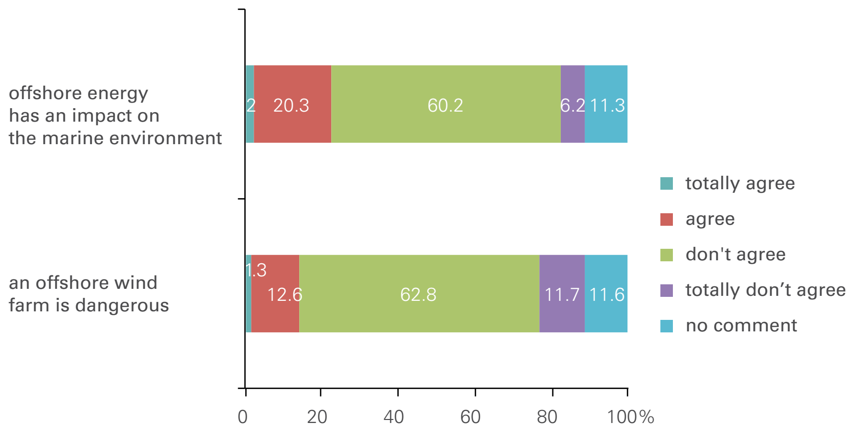
Figure 3. Agreement / disagreement with the statements about advantages of an offshore wind farm, survey 2009 (in %).



Globally a fairly positive perception of the siting on wind farm offshore rather than onshore is set forward. Almost ¾ of the respondents is convinced that at sea there's little or no burden of noise from a wind farm and more than 61% thinks moreover that more space is available for wind farms offshore than onshore. Still one out of three does not agree with this statement. Almost 60% of the respondents think that an offshore wind farm will bring more work to the region whereas less than 30% is in (total) disagreement with this statement. For this particular advantage respondents hesitated the most (almost 12% 'no opinion'). Nevertheless, since 2012, the harbour of Ostend (Belgium) which reoriented strategically to an energy port has experienced that a wind farm developer brings lots of side activities to a harbour (maintenance companies, electrical companies, boat transfer companies…). Due to the offshore industry in general 956 people were working in the front part of the harbour (where the wind farm industry is localized). This number is without counting for all temporally workers for the building of the wind farm, nor for the crew on the vessels in the building area. The wind farm industry doubled the number of ship transfers in/out the port to 4500 movements in 2012. A survey conducted one year after construction of the Nysted offshore wind farm (Denmark) indicated that 86% of respondents were supportive of new offshore wind farms in Denmark as a new turbine manufacturing plant brought jobs to the area, which had relatively high unemployment (Ladenburg et al., 2005).

Two statements sound people's opinion on the **disadvantages** of an offshore wind farm.

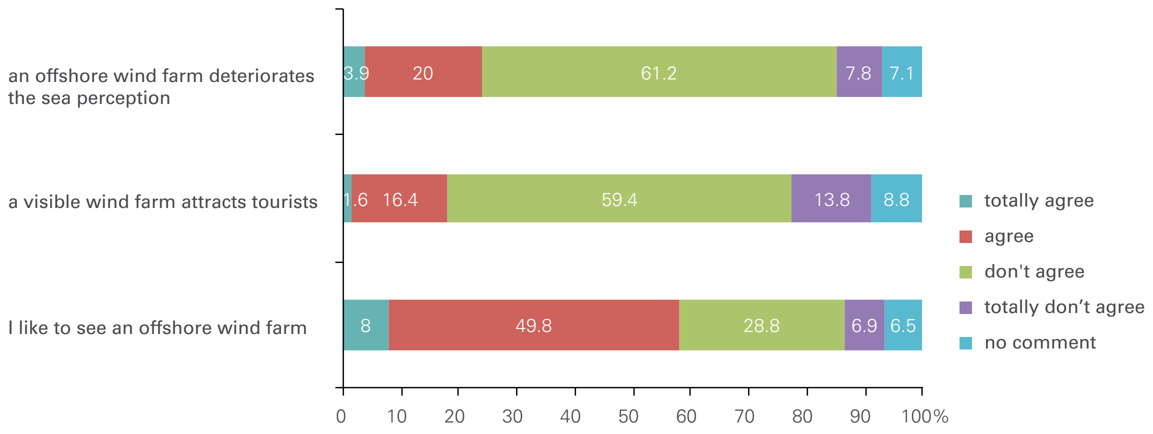
Figure 4. Agreement / disagreement with the statement about the disadvantages of an offshore wind farm, survey 2009 (in %).



Almost ¾th of the respondents do not believe (at all) that an offshore wind farm could be dangerous, although almost 12% has no opinion. The wording of this questions could have been better chosen: replacing 'dangerous' by 'risky' probably would give other responses. 2 out of 3 respondents expect that a wind farm does not affect the marine environment. Almost 25% of the respondents think that a wind farm affects nature although it is not specified if this effect would be positive or negative. Gee (2010) described in a similar German study that 15% of all arguments employed, were arguments on nature conservation and these were mostly exclusively used to object to offshore wind farms. In that study the nature conservation category was very diverse with arguments covering indistinct fears that offshore farms will harm the marine ecosystem and also fear of very specific negative impacts on bird and marine mammal species. The category also comprises indirect impacts, such as oil spills resulting from tanker collision with a wind farm.

Assessing people's **opinion on how the visibility** of an offshore wind farm **affects acceptance** was done by using following statements:

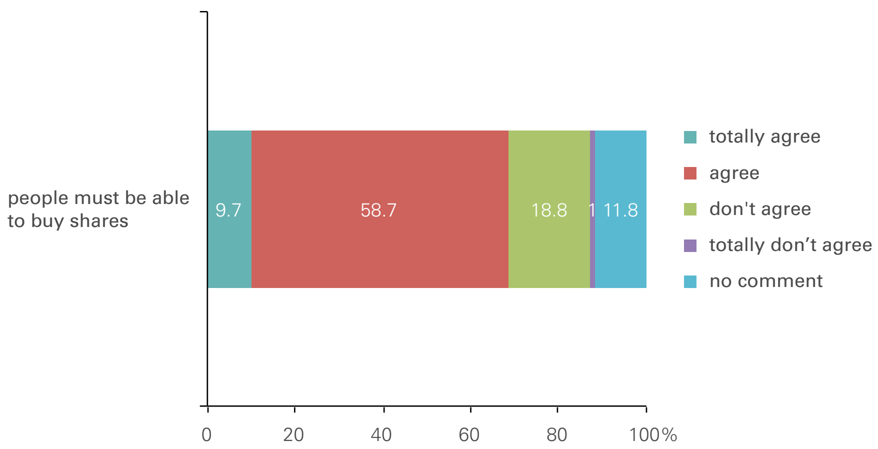
Figure 5. People's opinion on the view of an offshore wind farm, survey 2009 (in %).



More than half of the respondents (58%) (totally) would like to see an offshore wind farm. More than 1/3rd of the respondents (totally) would not like to look at a wind farm at sea.
A comparable, more generally formulated statement generates more positively results: almost 70% (totally) don't agree with the statement that a wind farm at sea will affect the 'sea perception', and only 24% agree. A majority of the respondents don't think that a visible offshore wind farm will attract more tourists, only 18% agrees (totally) with this statement.

Finally people's opinion on the **possibility of buying shares** of wind farms was surveyed.

Figure 6. People's opinion on the possibility of buying shares of an offshore wind farm, survey 2009 (in %).



More than 60% of the respondents (totally) agree that citizens should be able to buy shares of a wind farm. About 12% has no opinion about this and almost 1 out of 5 (totally) doesn't agree with this statement. Currently, at least one offshore wind farm in Belgium offers the possibility of participation by buying shares.

Photo simulations and photo montages

Worst case: Belgian wind farm area completely built[1]

After viewing a photo simulation in which the entire Belgian wind energy zone is operational (Figure 7), respondents were asked if the distance from the wind turbines to the beach is acceptable (i.e. large enough). More than 62% of respondents think this distance is acceptable with 13% finding it a rather acceptable. However 20% of respondents found the distance unacceptable, (in addition to 5% having no opinion). People indicating finding the distance unacceptable were asked under which conditions this fully built area would become acceptable. For 84% of those respondents it would become more acceptable if the wind farms were less visible, 69% wanted the wind farms to have another (less visible) orientation/set up, 56% would find it more acceptable if the wind farms would provide them with cheap energy, 53% if there's no harm for nature, 43% if the wind farms would provide economic growth and employment, 23% if people could buy shares and finally 20% if the park could be visited.

In general the results of the survey are similar to those published in the international literature regarding the perception of wind farms. Nordman et al. (2011) states that the researchers for the Cape Cod project (USA) found following patterns: residents expected positive impacts on job creation, electricity rates and air quality; many respondents would increase their support if Cape Cod received the electricity, if electricity rates decreased, if local fishing was helped and if air quality improved. The location of turbines and their visibility from the shore is clearly an important factor. In a coastal region of Germany, where 54% of coastal residents disagreed with a planned offshore project aesthetics was cited as the most common reason for opposition, while energy was the primary reason for support (Gee, 2010). Ladenburg et al. (2005), Firestone et al. (2009), Devine-Wright P. (2008) and Hübner and Pohl (2013) found that people consistently prefer wind farms located further from shore. However, the benefit that people perceived from moving a hypothetical wind farm an additional mile offshore diminishes with distance. That is, people are more sensitive to the difference between a wind farm at six versus seven miles from shore, than when comparing a wind farm at 12 versus 13 miles (Ladenburg et al., 2005).

From the before mentioned results it can be concluded that the perception value of the sea is influenced by the wind turbines at sea. In addition, the degree of visibility was found to influence acceptance. In our survey variations in the distance offshore, the orientation as seen from the coastal towns and the number of visible wind turbines were simulated. When the wind turbines were simulated at a sufficiently large distance and/or are limited in number, a fundamental change in this perception is prevented, which added to the acceptance. Aside from these visual factors, ecological and economic factors also play a rather important role in the degree of acceptance.

[1] **Other cases** are described in (Vanhulle, A. et al, 2010)

Figure 7. Simulation of the fully occupied wind farm area seen from the dyke in Blankenberge (Simulation and montage: Grontmij, 2010).

What do people want to be informed of?

As a last question respondents were asked on which aspects of offshore wind energy they would like to be informed. The most common answers given are shown in figure 8.

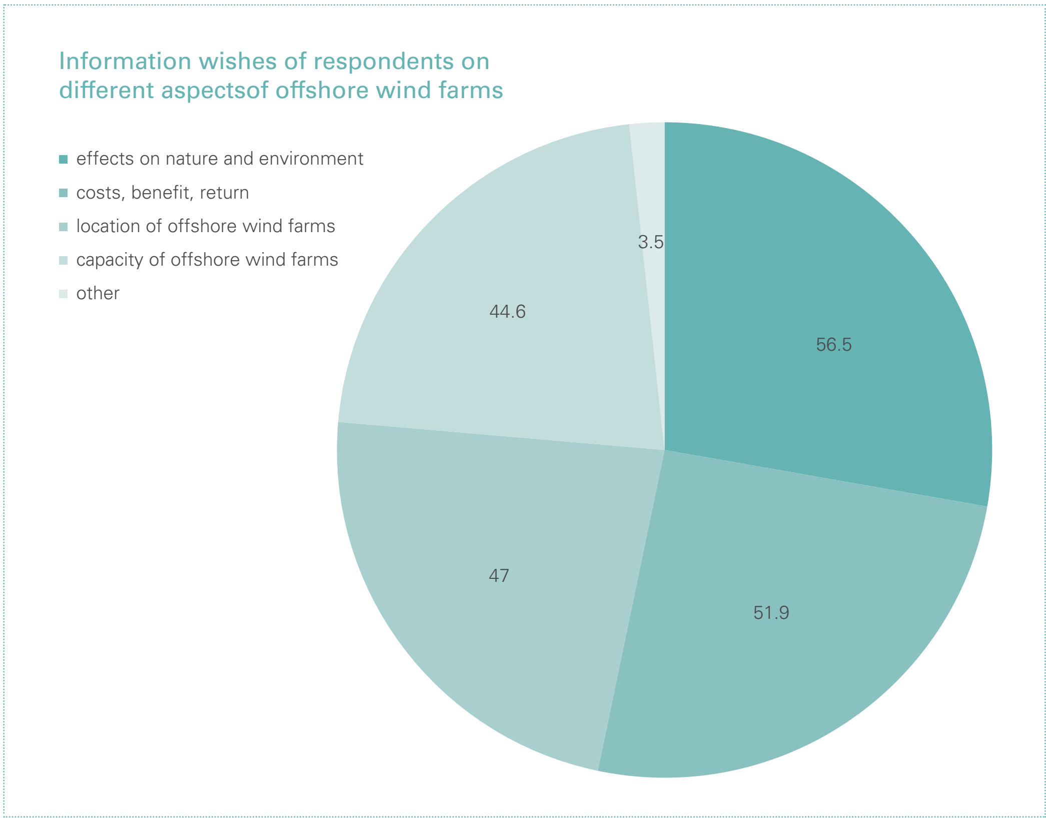


Figure 8. Information wishes of respondents on different aspects of offshore wind farms, survey 2009 (in %).

FUTURE MONITORING

Determining how peoples' perception has changed five years after the initial study could be the subject of a new socio-economical study in the (near) future. This study could focus on changes in people's opinion now that a number of parks are operational. The wind farms closest to the coast are visible and real time view on the offshore wind farms can now be used to validate photo simulations. The impact of the works on local lives (visual perception but also opportunities for local work) can be included and finally, as utility bills are rising, it would be interesting to see if and how people link this fact to local offshore wind projects. Such a follow up study is proposed to be done the summer after the first wind turbines of the wind farms closest to the land have been installed. At that time at least three other wind farms will also be operational.

With 53.2% of the people indicating that the worst-case scenario (fully occupied zone) would become acceptable if there is no damage to the marine environment and with results of the survey indicating (Figure 8) that the most important thing people want to be informed about is the effects on nature and environment one could say that the Belgian government was correct in implementing an extended monitoring programme when permitting the first wind farm. The following chapters describe the results of the different research programmes related to the environmental impacts of offshore wind in the past 5 years. These aim to provide the general public and the scientific community with a more robust knowledge on the possible impacts and allow the reader to develop his/her own opinion on the effects of offshore wind farms.

CHAPTER 4

All quiet on the sea bottom front? Lessons from the morphodynamic monitoring

Dries Van den Eynde, Matthias Baeye, Robin Brabant, Michael Fettweis, Frederic Francken, Piet Haerens, Mieke Mathys, Marc Sas and Vera Van Lancker

The impact of the construction of the offshore wind farms on the turbidity was local and temporary, with no significant difference between the before and after situation. Erosion pits were formed, both around gravity based foundations and monopiles, though erosion protection provided the necessary stability. Dredging/filling works were more complex than expected. Large volumes of sand were lost and sand pits did not refill naturally. In dune migrating areas the coverage of export cables could not be guaranteed. As a result they are now buried 1 m below the base of the dunes.

INTRODUCTION

Wind turbines may affect the marine environment in various ways (e.g., Petersen and Malm, 2006). For sediment- and morphodynamics this relates mainly to: (1) increases in turbidity; (2) scour around the foundations; and (3) erosion around the cables (e.g., Carroll et al., 2010).

For Belgian waters, the installation of wind farms was new, with large uncertainties in the estimations of environmental impact. The concession zones fall within offshore areas where natural turbidity is relatively low, hence, given the large-scale works, increases in turbidity needed quantification. Formation of scour or erosion pits was expected, because of the installation of gravity based foundations (GBF) for the first six wind turbines on the Thorntonbank. For the Belwind wind farm, consisting of monopiles, erosion pits around the monopiles were first allowed to develop, and were then filled with an erosion protection. The fact that the formation of erosion pits was accepted, required monitoring of both the erosion pits and turbidity levels.

On the Thorntonbank, dredging works were needed for seabed levelling in the areas of large sand dunes. Part of the dredged sand could be re-used to infill the GBF itself, as back-fill of the foundation pit or as backfill of the temporary trench that was dredged for the cable-crossing of the sea-lane. It was expected that, finally, a net amount of 385,000 m³ of sand would be disposed within the concession area. It could be expected that the transport of these sand piles would redistribute the sand towards the possible erosion pits, but monitoring was necessary to study this process.

Finally, the coverage (i.e. 1 m below the seabed) of the export cables to the shore was of concern. Sand dune migration was known to occur (e.g., Lanckneus et al., 2002); hence uncertainty arose on the longevity of coverage of the export cables.

ENVIRONMENTAL SETTING

The Thorntonbank, Lodewijkbank and Gootebank are coast-parallel sandbanks, belonging to the Zeeland Ridges, whilst the Bligh Bank is one of the Hinder Banks, lying more obliquely to the coastline (Figure 1). Minimum water depths are close to -6 m (below the lowest water level) for the Zeeland Ridges and -9 m for the Bligh Bank. In the gullies, -28 m up to -36 m is reached, respectively. Sandbank lengths are 15 to 30 km, while the width varies from 1 km for the Bligh Bank, to up to more than 4 km for the sandbanks of the Zeeland Ridges. Sandbanks are covered with large to very-large dunes with heights varying from 2 m to 6 m (Van Lancker et al., 2007). Median grain sizes of the sandbanks range between 300 µm and 350 µm (Verfaillie et al., 2006).

The hydrodynamics in the area are dominated by semi-diurnal tides with a spring tidal range of 4 to 5 m. Tidal current ellipses are elongated, with a southwest-northeast axis. Flood and ebb peak currents are oriented towards the northeast and the southwest, respectively. Surface peak currents reach up to 1 m/s; flood and ebb currents are competitive in strength, though the ebb period lasts longer. Flood currents are strongest along the southern slope of the Zeeland Ridges, whilst the ebb is strongest along the steep side of the Bligh Bank. An ebb oriented sand transport is observed along the gentle slope of the Zeeland Ridges, though preceding hydro-meteorological conditions may alter sand transport directions consistently (Lanckneus et al., 1993).

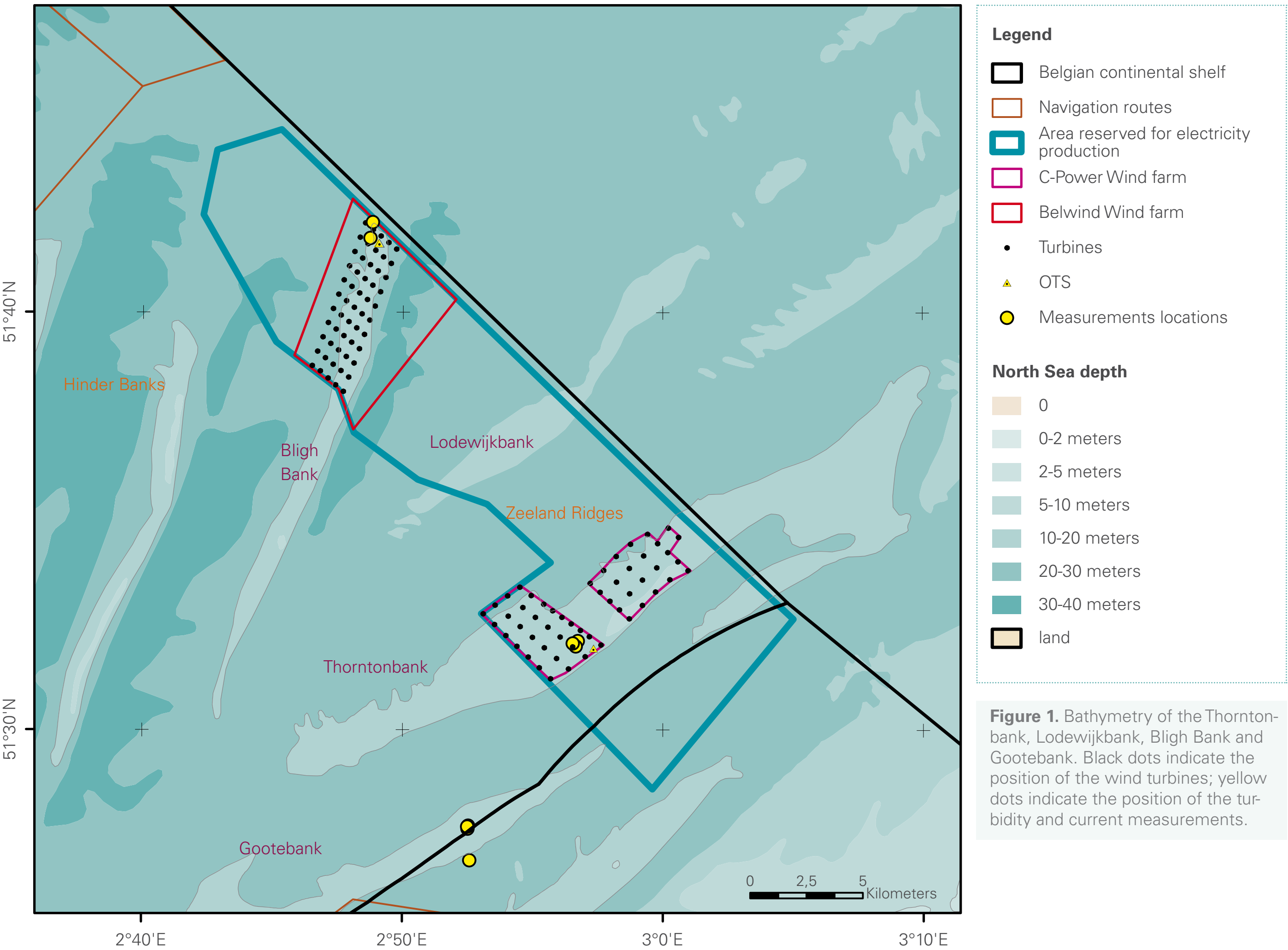


Figure 1. Bathymetry of the Thorntonbank, Lodewijkbank, Bligh Bank and Gootebank. Black dots indicate the position of the wind turbines; yellow dots indicate the position of the turbidity and current measurements.

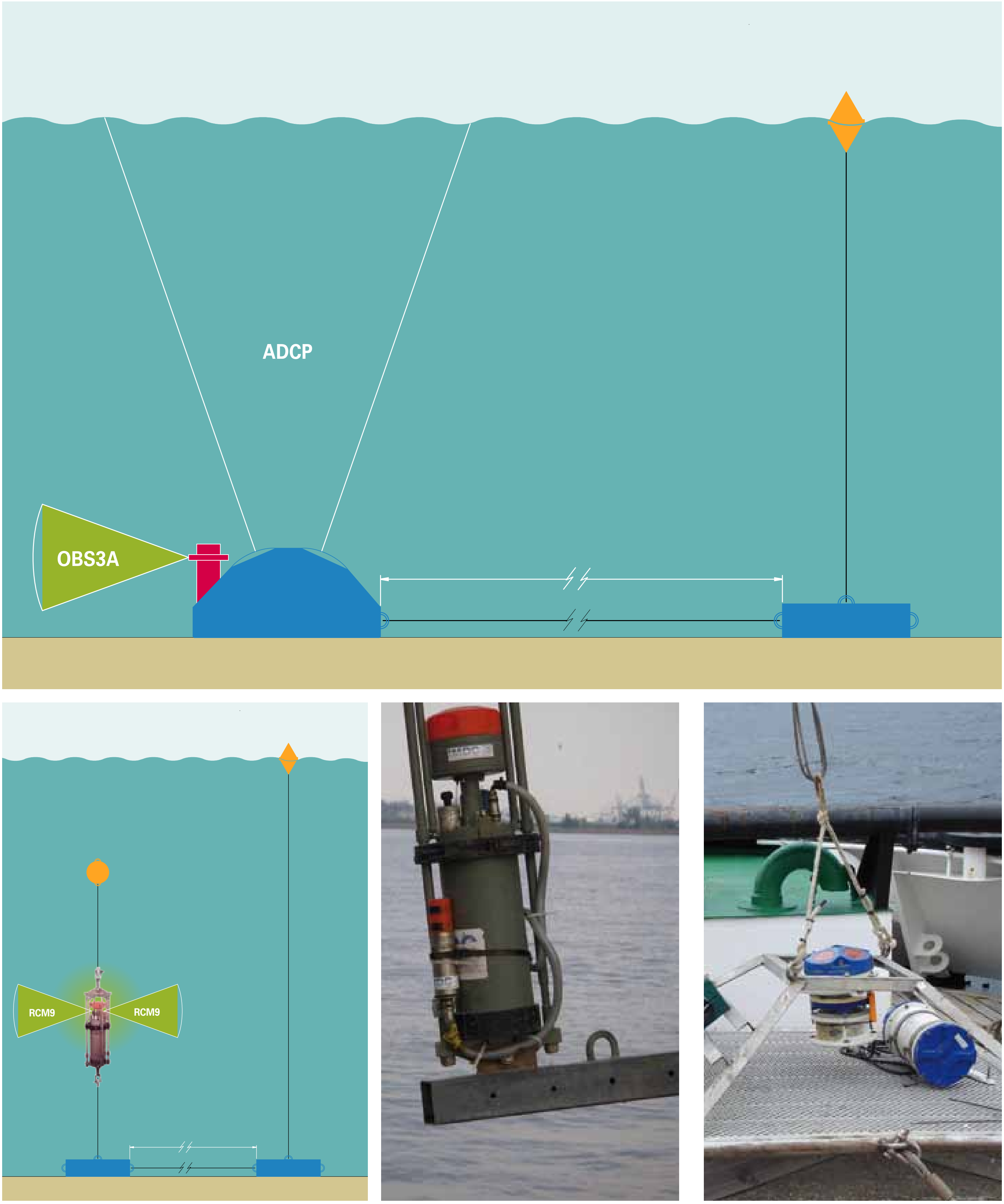
MONITORING TURBIDITY

The first part of the monitoring aimed at evaluating increases in turbidity, due to the installation works (e.g., of the GBFs on the Thorntonbank) or during the operation of the wind farms (e.g., as a result of the dynamic erosion protection in the Bligh Bank wind farm). From the monitoring specifications, measurements of currents, waves and turbidity were mandatory near the wind turbines before, during and after the works. Similar measurements were carried out at a nearby non-affected site, for which the Gootebank was chosen. A period of at least 15 days was chosen to cover a spring-neap tidal cycle. International Marine and Dredging Consultants (IMDC) executed the monitoring for the C-Power wind farm; RBINS-OD Natural Environment the one for Belwind.

On the Thorntonbank and on the Gootebank, measurements were performed using a bottom-mounted Acoustic Doppler Current Profiler (ADCP) (IMDC 2008a; 2008b; 2008c; 2009a) (Figure 2). This device measured current profiles over the entire water column, water level and wave heights. An optical back scatter sensor (OBS), measuring turbidity, was mounted on the ADCP at about 0.7 m above the bottom. Furthermore, an RCM9 current meter (Figure 2) was used as backup for current, turbidity and water level measurements. To convert the values from the OBS into material in suspension in mg/l, the instrument was calibrated in the laboratory using fine material from the harbour of Oostende. To estimate the effect of the construction works of the first phase on the suspended particulate matter (SPM) concentration, three measuring campaigns were executed: before (February-March 2008), during (June-July 2008) and after the works (June-July 2009). The positions of the measurements are indicated in Figure 1. The instruments were deployed along the gentle slope or on the top of the sandbanks in water depths of around -16 to -17 m.

Statistical analyses of wave, current and SPM concentration data was performed (IMDC, 2009b). Results showed that SPM concentration was low, both on the Thorntonbank and Gootebank. During the winter period, the median SPM concentration was 9 mg/l on the Gootebank and 4 mg/l on the Thorntonbank. High turbidity was generally correlated with higher wave conditions. During the summer periods, the median SPM concentration on the Thorntonbank and Gootebank was very low (1 to 2 mg/l). Overall, the range of SPM values was similar for both the Thorntonbank and Gootebank. No clear influence from the dredging works or from the installation of the GBF foundations was found in the data.

Figure 2. ADCP and RCM9 as deployed on the Gootebank in water depths of -17 m (IMDC, 2010).



On the Bligh Bank and on the Gootebank, two tripods (Figure 3) were used for measuring SPM concentration, suspended particle size distribution, salinity, temperature and current velocity. Water depths were around -26 m on the Bligh Bank, around -24m on the Gootebank. An Acoustic Doppler Profiler (ADP) measured the velocity profile from the top of the tripod to the bottom; an Acoustic Doppler Velocimeter (ADV) measured the velocity near the bottom with a high frequency; a CTD conductivity sensor system measured temperature, salinity and water depth; two OBS sensors measured turbidity at 0.2 m (SPM1) and 2 m (SPM2) above the bottom; finally a LISST 100C measured the particle size of the material in suspension. The ADP housed an altimeter, to measure the distance from the measuring point to the bottom, hence providing information on seabed evolution and thus indirectly on sediment transport. Furthermore, from the backscatter of the ADP, also SPM concentration profiles were derived. To measure current profiles from the bottom to the water surface, a bottom-mounted ADCP was deployed nearby the tripod. Water samples were taken and filtered to obtain SPM concentration, further used for the calibration of the OBS measurements.

Measurements were done before (June-July 2009), during (October-December 2009) and after the works (June-July 2010 and March-April 2012). Measurements before and during the works were executed simultaneously on the Bligh Bank and on the Gootebank. After the works, only measurements at the Bligh Bank were performed.

Figure 3. Two tripods and two ADCPs ready for deployment on the Bligh Bank and the Gootebank (RV Belgica).

Figure 4 shows SPM mass and volume concentrations, transmission, median particle size, temperature and salinity at the Bligh Bank, before the start of the construction works. Also the significant wave height at the Zuidwest Akkaert (Meetnet Vlaamse Banken, Flanders Hydrography) is shown. Figure 5 shows SPM concentration profiles (from the backscatter of the ADP) and seabed evolution (from the ADP altimeter), after the execution of the construction works at the Bligh Bank.

SPM concentrations were very low (< 5 mg/l) at both locations and during almost all campaigns (Van den Eynde et al., 2013). SPM concentrations showed a clear correlation with spring-neap tidal cycle variation, without a clear visible influence of wave activity. This is also shown in the scatter plot between significant wave height and SPM concentration on the Bligh Bank after the works (Figure 6). Remark that before and after the works, the significant wave heights were relatively low, with waves up to 2.2 m,before the works, and up to 2.0 m, after the works. Only during the works, wave heights were higher from November, 14th until December, 1st, 2009, with peaks higher than 3 m on December 1st.

Altimeter data showed a seabed variation of several tens of centimetres, probably due to migrating bed forms. During spring tide, the bottom is lower than during neap tide, possibly caused by higher erosion.

At the Bligh Bank and Gootebank variations in SPM concentrations were tidally-driven. The mean SPM concentration was higher at the Gootebank than at the Bligh Bank. At the Bligh Bank, the mean was somewhat higher after the works than before the works. However, no indication was found that the construction works resulted in a significant increase in turbidity.

Figure 4. Variation in SPM concentration (from the OBS sensors); SPM volume concentration, median particle size and transmission (from LISST); and temperature and salinity (from CTD sensor) at the Bligh Bank (-26 m water depth) from June, 24th, 2009 until July, 14th, 2009. Wave height at Zuidwest Akkaert (from Meetnet Vlaamse Banken, Flanders Hydrography). SPM1 at 29 cm above the bottom, SPM2 at 234 cm above the bottom.

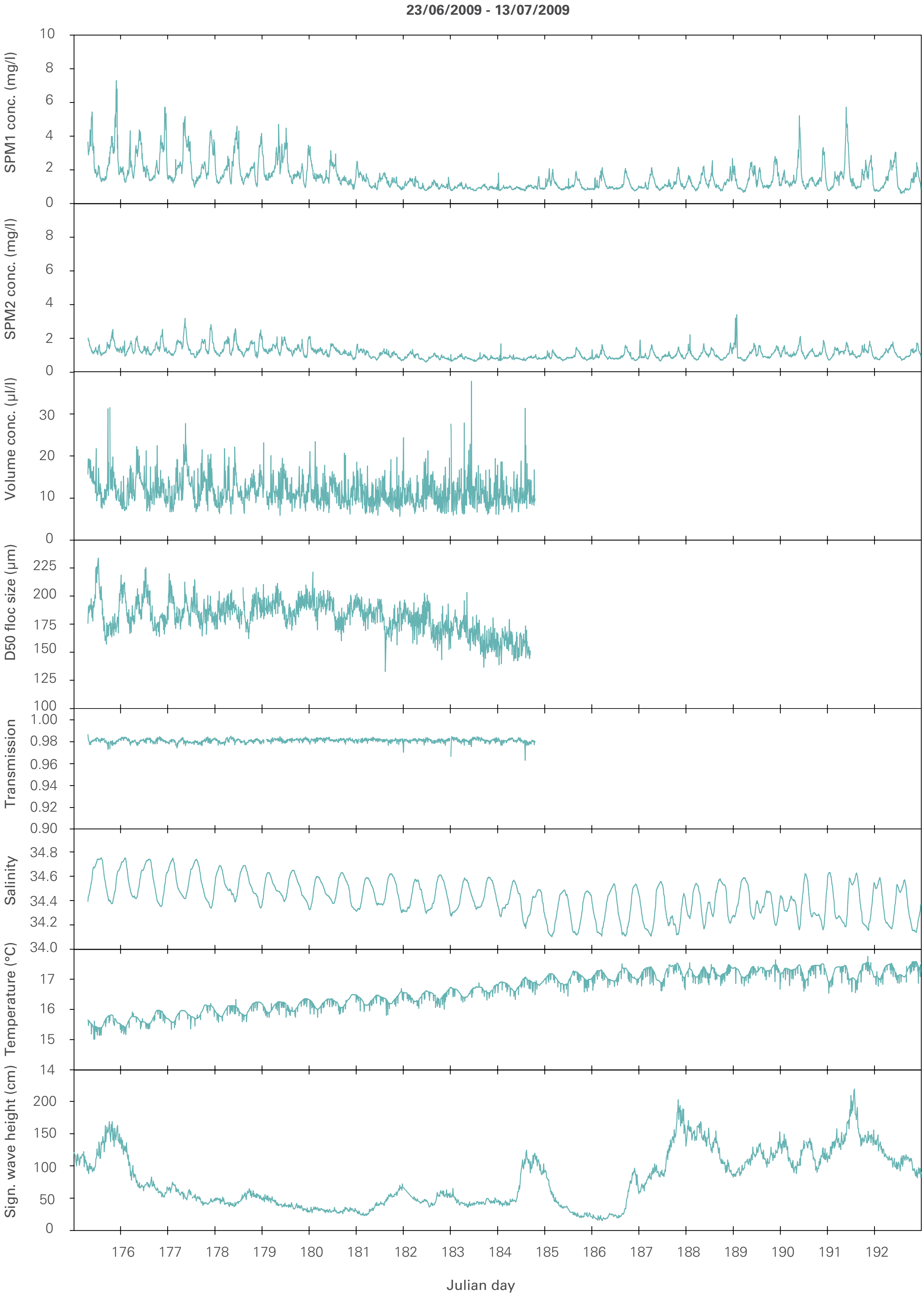
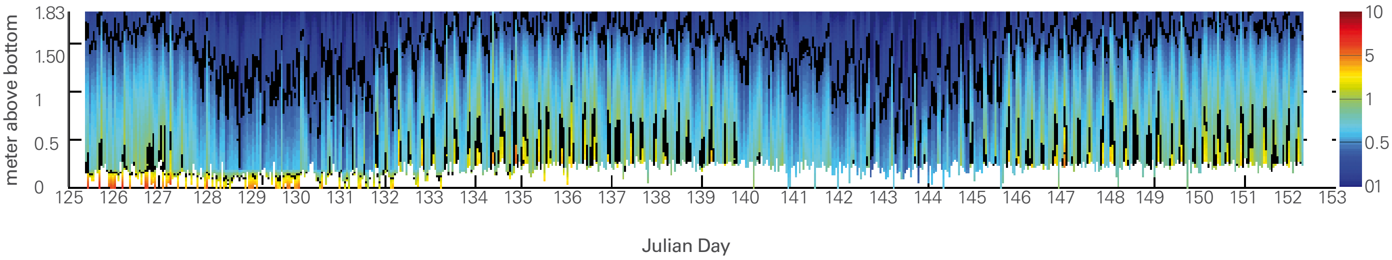


Figure 5. Measurements of SPM concentration in the lowest 1.5 m above the bottom, derived from the backscatter of the ADP, together with the seabed evolution from the ADP altimeter, at the Bligh Bank from May, 5th, 2010 till June, 3th, 2010.



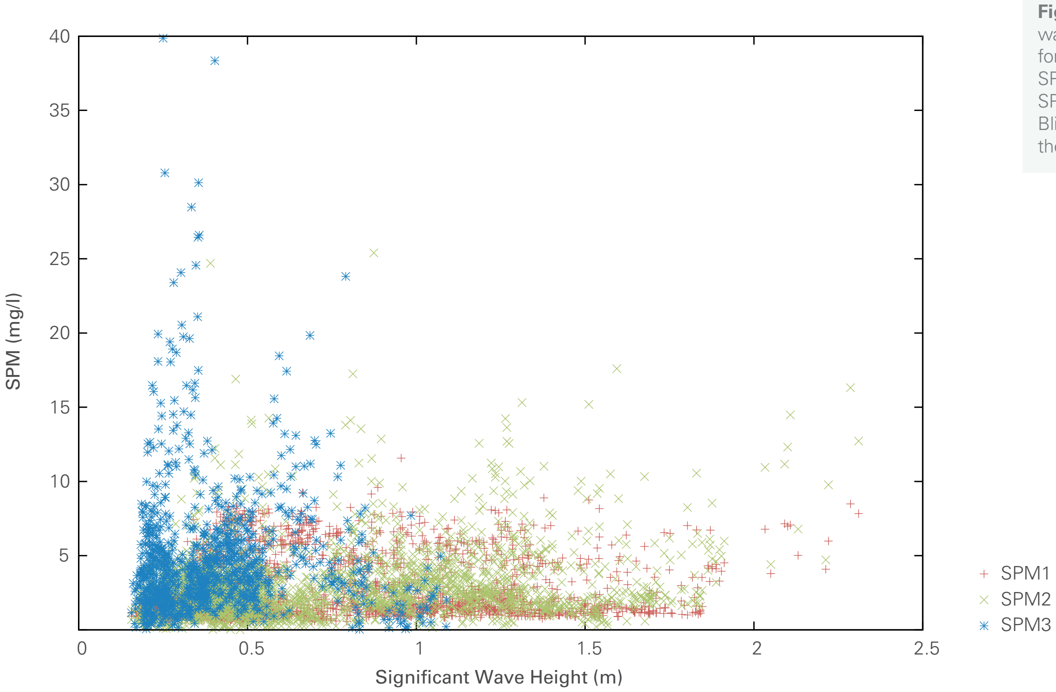
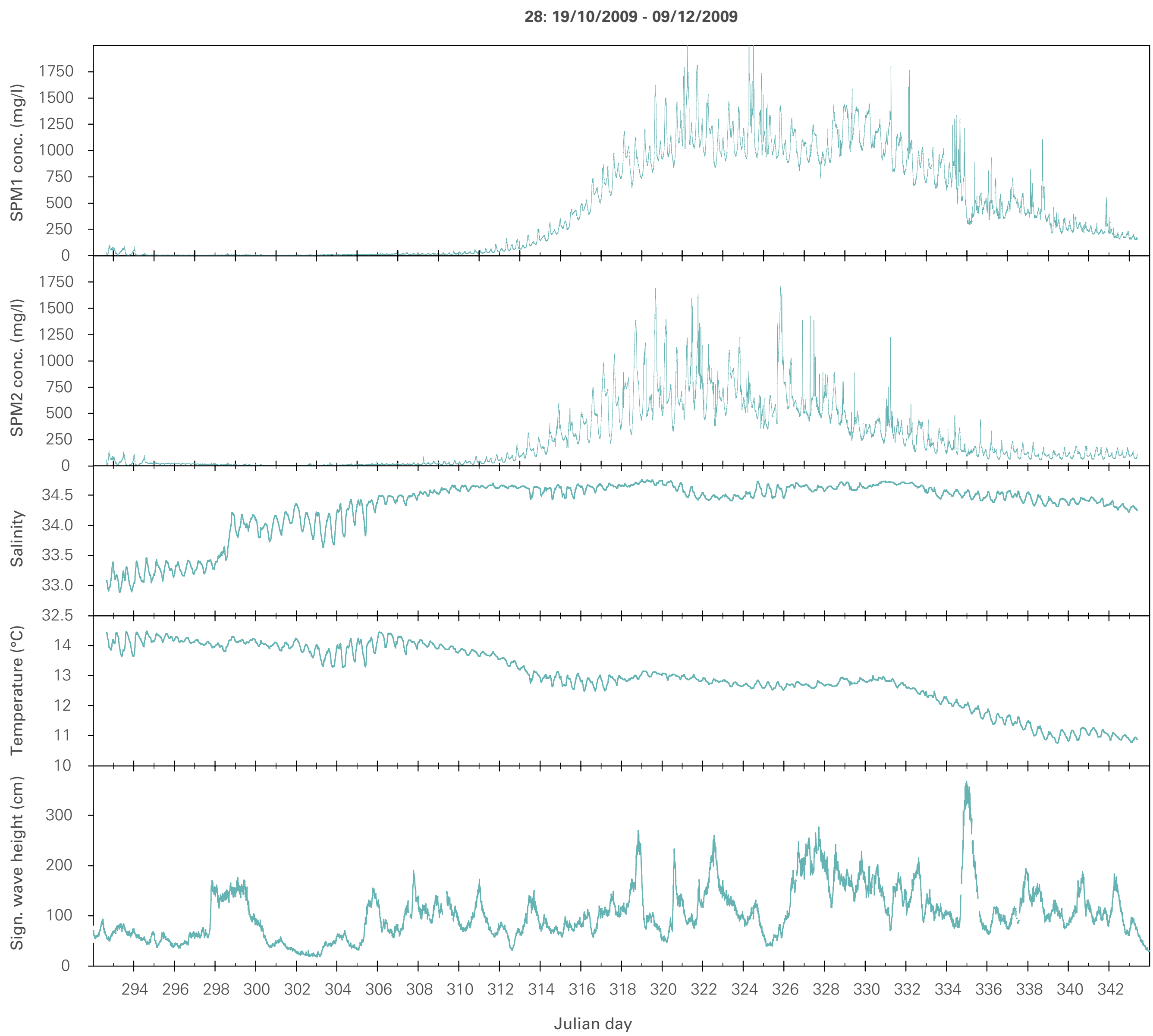


Figure 6. Scatter plot of significant wave height and SPM concentration for SPM1 (0.2 m above the bottom), SPM2 (2 m above the bottom) and SPM3 (1 m above the bottom) at the Bligh Bank (-26 m water depth), after the works.

While the SPM concentrations remained low during most of the measuring campaigns at the Bligh Bank and the Thorntonbank, this was clearly not the case at the Gootebank (Figure 7). At the Gootebank, from November 1st, 2009 onwards, the SPM concentrations increased considerably to high values up to 2000 mg/l close to the bottom, and 1700 mg/l at 2 m above the bottom. This was a result of a long period of prevailing southerly winds (Van den Eynde et al., 2013) that can cause an offshore shift of the coastal turbidity maximum (Baeye, 2012) and the introduction of associated high concentration mud suspension layers at the measuring location as observed in the ADV altimetry time series.

These findings indicate that the Gootebank is not a good reference station for the Bligh Bank and/or Thorntonbank. Under varying conditions or events, SPM dynamics might differ between these locations. Therefore longer time series should be used for the evaluation of effects of anthropogenic impacts on the turbidity. Such time series can be statistically analysed, and the significance in turbidity changes can then be determined before and after the construction works. Such an approach was successfully used for the assessment of turbidity changes due to disposal experiments of dredged material from the port of Zeebrugge (Fettweis et al., 2011).

Figure 7. SPM concentration (SPM1 at 29 cm above the bottom, SPM2 at 234 cm above the bottom), temperature, salinity at the Gootebank from October 19th, 2009 to December 9th, 2009. Significant wave height at Zuidwest Akkaert (Meetnet Vlaamse Banken, Flanders Hydrography).



In a first attempt to use longer time series to evaluate the effects of the wind farms on turbidity, satellite images were used from the MODIS and MERIS multi-spectral sensors on the EOS-PM and ENVISAT satellites (Van den Eynde et al., 2013). The spectral bands of these sensors can be used to estimate the SPM concentration at the water surface. Using the MUMM/GRIMAS tool (Vanhellemont et al., 2011) the SPM concentration time series was extracted at a point central on the Bligh Bank. These satellite data are available since 2002 and consist of one image per day, taken around noon. However, almost 86 % of the measurements are disturbed by clouds, resulting in 559 good values of surface SPM concentration at the Bligh Bank from the MODIS satellite and 397 good values from the MERIS satellite.
The surface SPM showed a very clear seasonal cycle, resulting in higher surface SPM concentration values in winter months (3-4 mg/l) and lower SPM concentration values in summer months (< 1 mg/l). Since the good values are not evenly distributed over the years and the months, the monthly values were calculated first, replacing the missing values by the climatological monthly means, before calculating the yearly mean values of the surface SPM concentrations. These monthly and yearly means from the MODIS sensor are presented in Figure 8. Student's T-test indicated that the yearly mean surface SPM concentration before the works (2002-2009) were not significantly different from the yearly mean surface SPM concentrations after the works (2010-2013). Also the monthly means did not differ significantly in most cases before and after the construction works. Only for a few months the differences were significant, but these results could be related to meteorological events, rather than to the construction and operation of the wind farms.

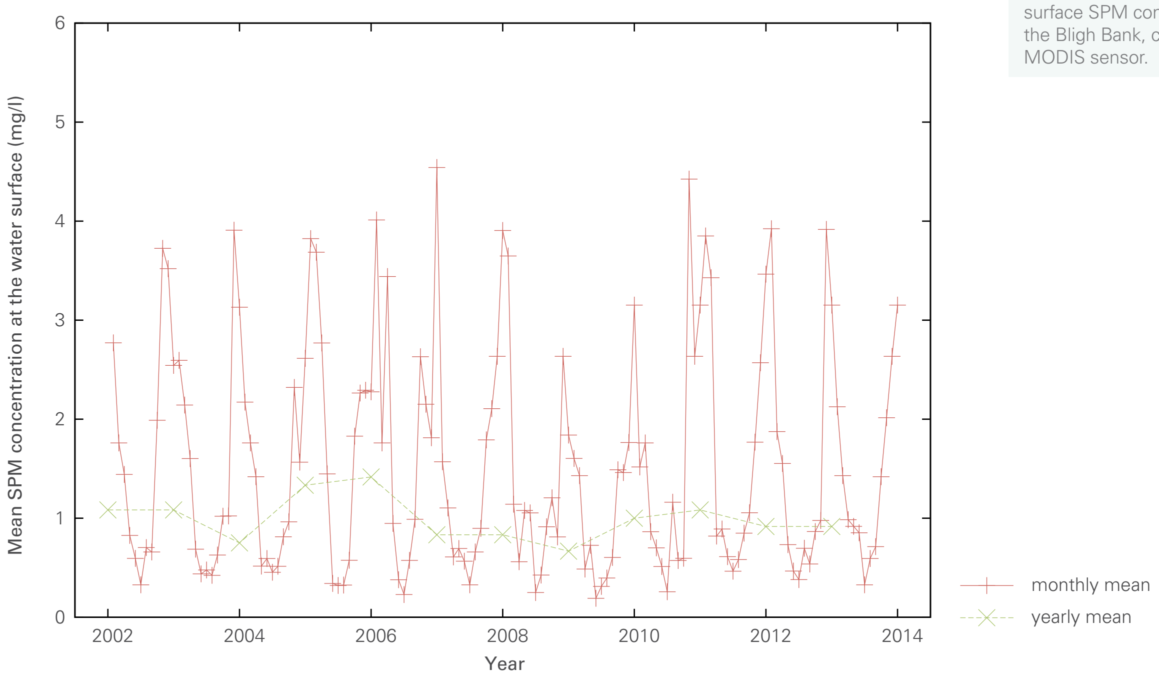


Figure 8. Monthly and yearly mean surface SPM concentration values at the Bligh Bank, calculated from the MODIS sensor.

Conclusion

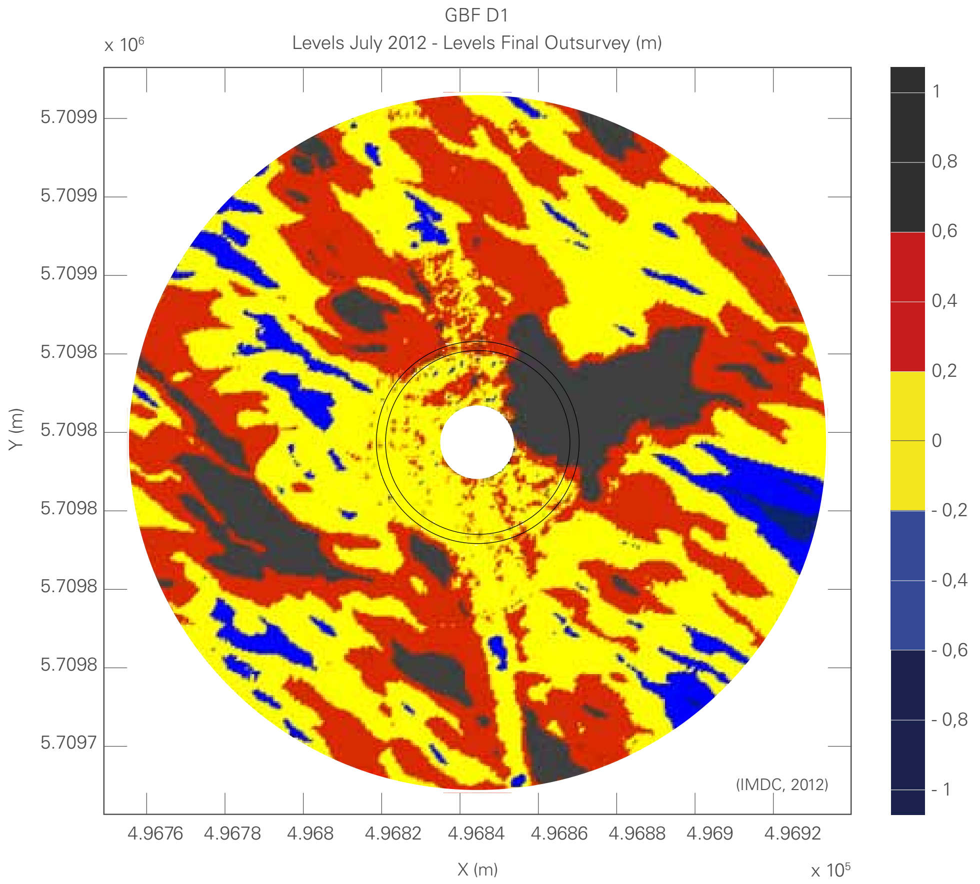
Both at the Thorntonbank and the Bligh Bank, no indication could be found of an increased turbidity due to the construction of the wind farms. Furthermore, it was shown that the Gootebank was clearly not a good reference site for these measurements. To investigate the effects of anthropogenic impacts on the marine environment, statistical analyses of long time series is more appropriate. Finally, also long time series of satellite-derived surface SPM concentrations were analysed to look at possible impacts of the wind farm on turbidity at the Bligh Bank. No significant differences of the yearly (and monthly) mean surface SPM concentrations before and after the installation of the wind farm could be demonstrated. Possible effects of the construction and operation of the wind farms on the turbidity are presumed to be local and temporary.

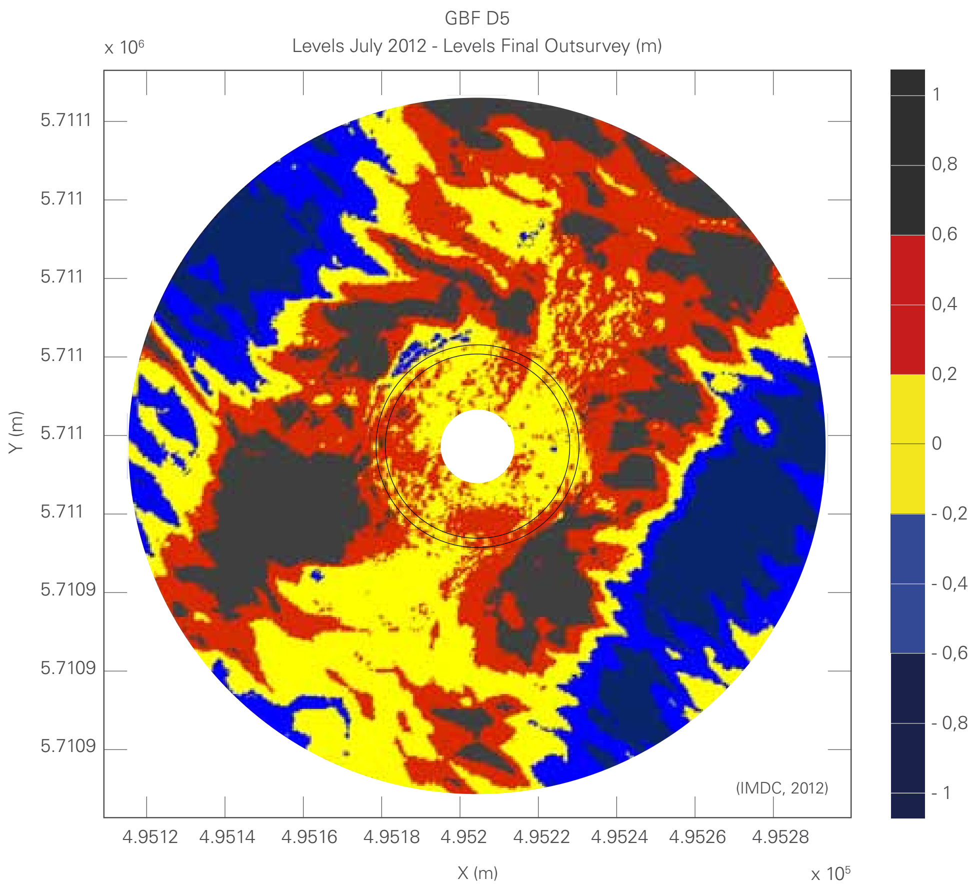
BATHYMETRICAL SURVEYS OF SCOUR AND DREDGED PITS

Multibeam-based bathymetry allowed studying the formation of scour or erosion pits around turbine foundations.
During the construction of six GBFs on the Thorntonbank, the morphological evolution of the construction site was intensively monitored (C-Power, 2009a). Surveys were done prior to the installation works, after the dredging of the foundation pits, after installation of the gravel bed, prior to the installation of the filter layer and after the installation of the GBFs. Since then, five surveys were conducted to monitor the condition of the scour protection. The results of these surveys were compared with the bathymetry after the installation of the GBFs (C-Power, 2012b).
In some cases, small areas were found where erosion exceeded a pre-set alarm level. This was mostly levelled out by natural sedimentation, apart from one location where rocks were deposited (northeast of GBF D1, see figure 9), preventing erosion at the foundation.
Overall, sedimentation occurred in the dredged pits (e.g., GBF D5, see figure 9). Around the erosion protection, similar seabed levels occurred, though important erosion or deposition was also observed. The erosion protection functioned without any secondary erosion.

To monitor scour around the foundations on the Bligh Bank, three bathymetric surveys were performed around 6 monopiles. Differential bathymetry maps were produced with the bathymetry before the installation as a reference (Belwind, 2010).
The results showed erosion pits ranging from 2 to 6.5 m, below the original seabed level. This was below the expected dimensions of erosion pits, as reported in den Boon et al. (2004). For monopiles with a diameter of about 5 m, their model predicted erosion pits of about 8.75 m.
Since 2010, 5 monopiles were monitored on a yearly basis: at the four corners of the wind farm, and at the monopile of the transformer station located in the centre of the wind farm where the seabed is most shallow. Results show that the scour protection was sufficient with erosion never below the alarm level. The rocks of the scour protection deposited in the erosion pits remained in place (Belwind, 2012).

Figure 9. Difference maps of the bathymetry around GBF D1 and GBF D5, comparing the bathymetry after installation against the situation in July 2012 (C-Power, 2012a).





BATHYMETRICAL SURVEYS OF THE SAND STOCK/DREDGING PITS

Before the GBF installation on the Thorntonbank, large sea bed preparation works were necessary, involving dredging of an important amount of sand. It was expected that an excess volume of 385,000 m³ sand had to be stored within the concession area. Three disposal sites were defined within the perspective that natural sand transport would replenish the construction pits. Given the large uncertainties on natural sand transport rates and on the behaviour of such sand stocks, the evolution of these sand piles was monitored.

However, first surveys revealed large losses during the dredging and dumping activities (IMDC, 2009c). From the dredging of 579,000 m³ sand to construct the foundation pits, only about 400,000 m³ was found back at the disposal sites. On the other hand, for backfill of the foundation pits, infill of the GBFs, correction disposals and backfilling of the fair channel, some 868,000 m³ was extracted again from these dumping sites, from which some 588,000 m³ was used effectively for the backfill and infill operations. IMDC (2009c) concluded that the sand was mostly lost during dredging (10 %) and disposal works (20-25 %). Due to these losses, no excess material was found at the disposal sites after the construction of the foundation pits and the backfill and infill operations, but instead 480,000 m³ sand was extracted. The bathymetry of one of these sand pits is shown in Figure 10.

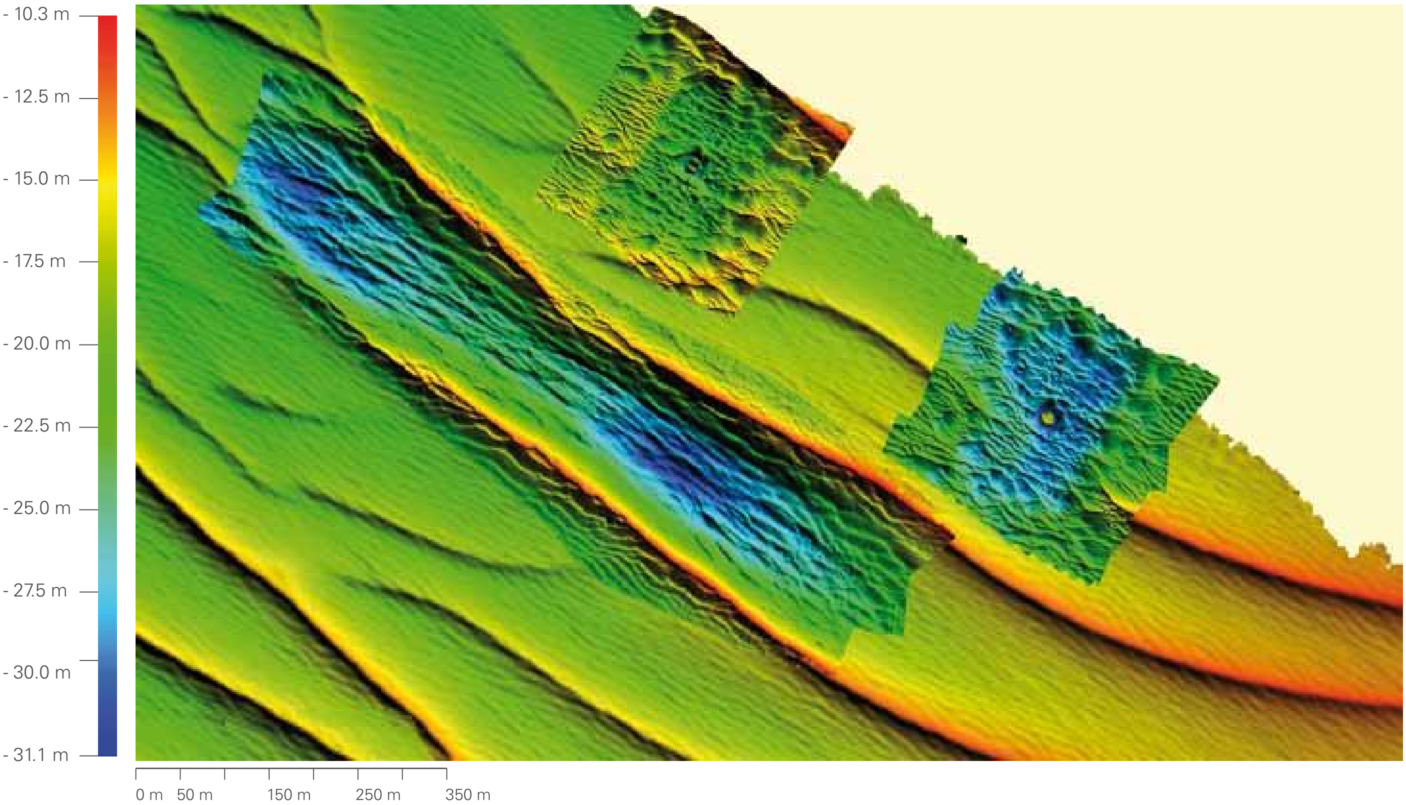


Figure 10. Depression generated in the C-Power concession area. Background bathymetry is from 2006 (FPS Economy).

Compared to October 2008, the continued monitoring of the depressions showed that in June 2009, 471,000 m³ was still missing, indicating that over a period of 8 months only 9,000 m³ were naturally deposited in the depressions (Figure 11). Between September 2009 and April 2010, some deposition resulted in a volume increase of 45,000 m³, but due to dune migration the material almost entirely disappeared again in February 2011. In February-March 2011, the sand pits were filled again, by using material from the foundation pits that were dredged for the installation of jacket foundations (second phase of the C-Power wind farm). The difference between the original sites and June 2011 amounted -18,000 m³. The last survey of July 2012 showed some additional deposition in the area, resulting in a total difference of +5,000 m³.

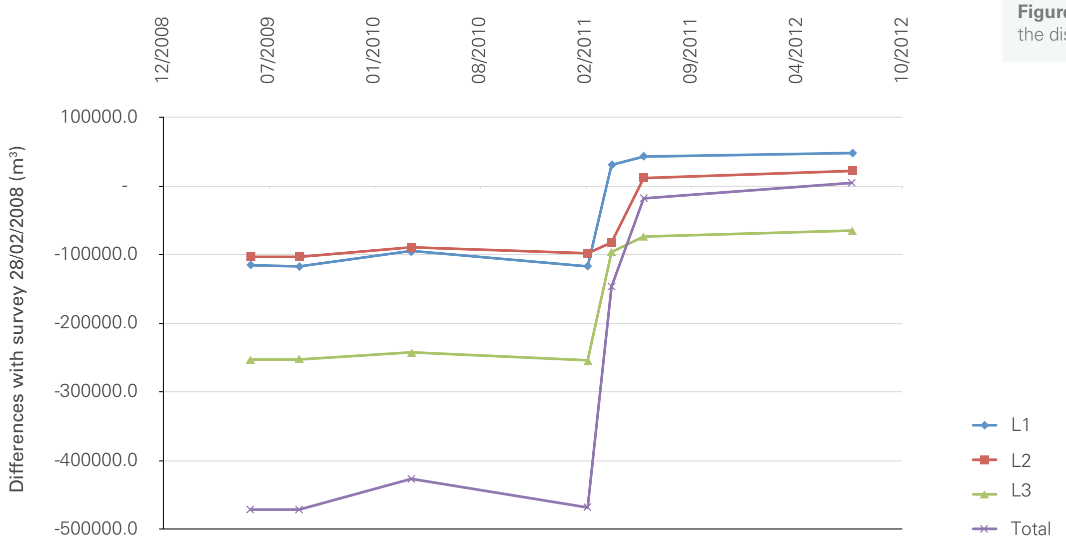


Figure 11. Evolution of the material in the disposal areas (C-Power, 2012a).

To conclude, substantial losses (30 to 35 %) of material during the dredging and dumping works were revealed. Furthermore, it appeared that the sand pits generated by the dredging works are quite stable over a longer period, despite the natural variation imposed by dune migration. Similar results, showing stability of sand pits, were found after severe aggregate extraction (Van Lancker et al., 2010).

BATHYMETRICAL SURVEYS OF THE EXPORT CABLES

To assure that the export cables remained buried, their coverage was verified on a regular basis. Along the entire length of the 150 kV (A) export cable from the C-Power wind farm to the cable landing at Oostende, a burial depth of 2 m was aimed for. In some areas, due to clay layers, only 1 m burial depth was reached (Figure 12) with a much deeper burial around km 14 where the cable crosses the navigation channel 'Scheur'. This was required in the environmental permit for safety reasons. At km 24, a surface communication cable was crossed and gravel was disposed to protect the cable. Verification of the depth of burial (DOB) of the cable showed that at some areas, especially near the GBF D1 and at the Scheur, the DOB was less than 1 m. At three locations, the cable was exposed at the seabed and needed re-burial. This was due to sand dune migration (Figure 13). Remediation works were executed to assure that the cable remains covered. From this, C-Power decided that the second export cable (B) would be buried 1 m below the base of those sand dunes. Similar difficulties were encountered with the export cables from the the Belwind wind farm to shore. Rocks were deposited on the locations where the cable was exposed.

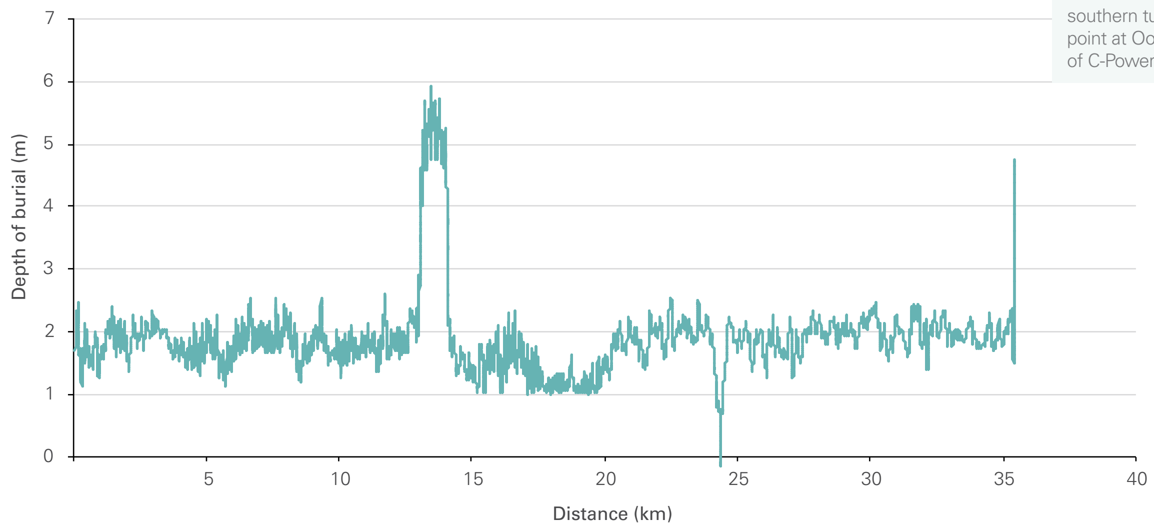
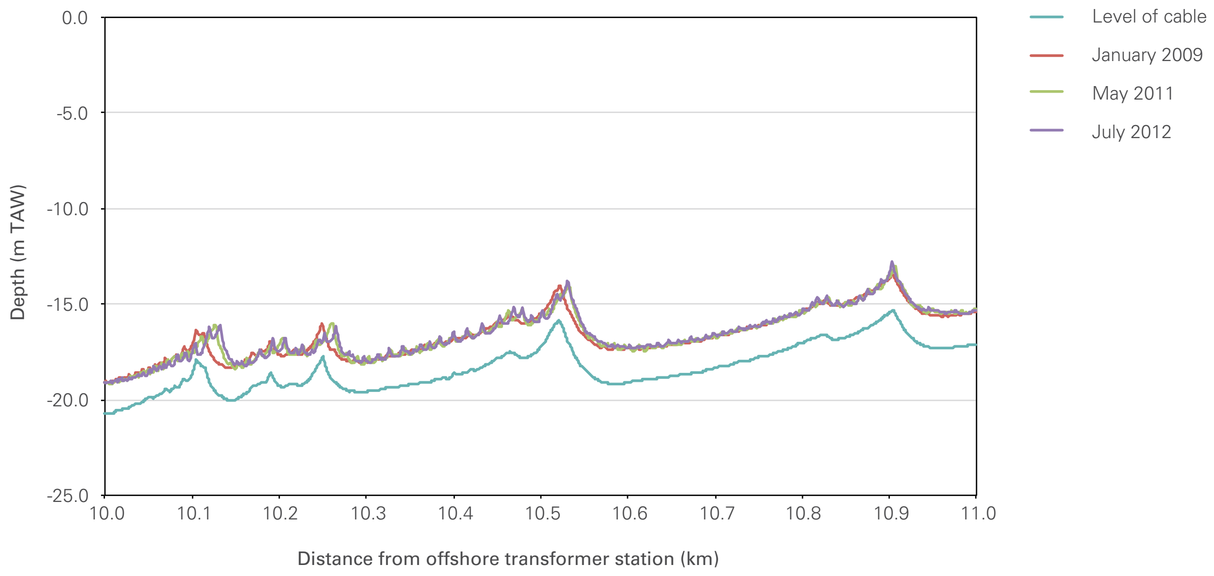


Figure 12. Original depth of burial (January 2009) of the export cable from the C-Power wind farm from the most southern turbine (km 0) to the landing point at Oostende (km 36) (From data of C-Power, 2009b).



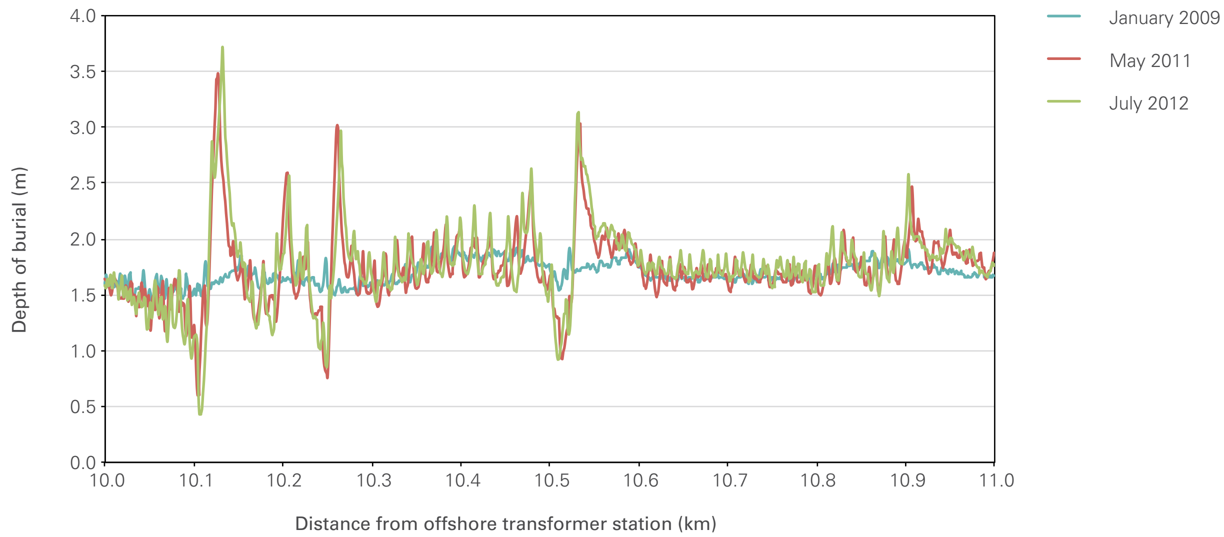


Figure 13. Bathymetry during different surveys and depth of burial of the 150 kV cable from the C-Power wind farm between km 10 and km 11 (From data of C-Power, 2012a).

In the North Sea, exposure of cables, due to moving sand dunes, could be expected based on experiences with pipelines (e.g., Morelissen et al., 2003). Model results and measurements showed that in the North Sea, sand wave migration occurs at a rate of 10 m per year (Van Dijck and Kleinhans, 2005). Within the wind farm areas, Bolle et al. (2013) quantified a dune migration of 1 to 7 m/year. Furthermore, Galagan et al. (2005) showed that cables could be uncovered after 6 to 18 years, using a migration velocity of only 1 to 3 m per year and a depth of burial of the cable of 1.8 m. For higher migration rates and smaller depths of burial, less time is expected. In areas of migrating sand dunes, the monitoring of the export cables remains important.

CONCLUSIONS

Related to the installation and exploitation of wind farms on the Belgian Continental Shelf, the monitoring of changes in sediment- and morphodynamics consisted of four parts:

1. Monitoring of the effect on the turbidity. No important effects were measured along the Thorntonbank, Bligh Bank and at a reference station at the Gootebank. Firstly, due to a higher variability in turbidity and different SPM dynamics, it was shown that the Gootebank was not a good reference site for the Bligh Bank and Thorntonbank. Nevertheless, measurements showed that the effects of the works at the wind farms and the wind turbines have a local and temporary effect on the turbidity. This was confirmed by the analysis of longer time series of satellite data for the Bligh Bank.

2. Monitoring of erosion pits. Surveys around the GBFs for the C-Power wind farm and the monopiles of the Belwind farm showed no secondary erosion and the erosion protection remained stable. Only at one GBF, an additional rock dumping was needed, when depths were below the alarm level. The monitoring of the dynamic erosion protection was executed around six monopiles. The depth of the erosion pits varied between 2.0 m and 6.5 m, in the north of the wind farm. The variation indicated that the erosion pit depth possibly depended on seabed sediments, geological substratum and prevailing hydrodynamics. A continuous monitoring of the foundations remains necessary.

3. Monitoring of sand piles and dredged pits. For the installation of the GBFs, it was shown that during the dredging and dumping works important sand losses of about 30 to 35 % occurred. Monitoring the sand pits, generated during these works during several years, showed that the sand pits were relatively stable and that no natural filling of the sand pits occurred.

4. Monitoring of the depth of burial of the export cables to the shore. Results showed that the cable can become exposed due to the migration of sand dunes. For both the Thorntonbank and Bligh Bank, some remedial rock dumpings were needed to ensure the burial of the cables. This led to the recommendation that in areas of migrating sand dunes, the cable should be buried 1 m below the base of the sand dunes. A regular control of the coverage of the cables remains necessary.

CHAPTER 5

Bird monitoring at the Belgian offshore wind farms: results after five years of impact assessment

Nicolas Vanermen, Robin Brabant, Eric Stienen, Wouter Courtens, Thierry Onkelinx, Marc Van de walle, Hilbran Verstraete, Laurence Vigin and Steven Degraer

To monitor the impact on birds following the construction of two offshore wind farms in the Belgian part of the North Sea, a twofold strategy was followed. Monthly ship-based seabird surveys allowed for a detailed displacement effect assessment, while radar research aimed at studying avoidance behaviour and barrier effects. Both methods provided input data for collision risk modelling in order to assess bird collision rates. Three years after the completion of the wind farm at the Bligh Bank, it showed that northern gannet, common guillemot and razorbill avoid the wind farm, while numbers of lesser black-backed and herring gull increased significantly. Collision risk modelling learned that gulls in particular are at risk of colliding with the turbine blades, with up to 2.4 bird strikes per turbine per year.

INTRODUCTION

Despite its limited surface, the Belgian part of the North Sea (BPNS) holds internationally important numbers of seabirds. Its specific importance to seabirds varies throughout the year. During winter, maximum numbers are present with over 46,000 seabirds, of which more than 20,000 auks. Offshore, the wintering community is dominated by common guillemots *Uria aalge*, razorbills *Alca torda* and black-legged kittiwakes *Rissa tridactyla*. Meanwhile, large numbers of grebes, scoters and divers reside inshore. In summer, fewer birds are present (on average 15,000), but high numbers of terns and gulls exploit the area in support of their breeding colony located in the port of Zeebrugge. During autumn and spring, the BPNS makes part of a very important seabird migration route through the Southern North Sea and an estimated number of no less than 1.0 to 1.3 million seabirds annually migrate through this 'migration bottleneck' (Stienen et al., 2007). For a number of species, the BPNS hosts more than 1% of the biogeographical populations involved, i.e. northern gannet *Morus bassanus* (autumn), little gull *Hydrocoloeus minutus* (spring), lesser black-backed gull *Larus fuscus* (summer), great black-backed gull *Larus marinus* (winter) and common tern *Sterna hirundo* (summer) (Vanermen et al., 2013).

Possible effects of offshore wind farms on seabirds range from indirect effects (habitat change, habitat loss and barrier-effects) to direct mortality through collision (Exo et al., 2003; Langston and Pullan, 2003; Fox et al., 2006; Drewitt and Langston, 2006). The installation of an offshore wind farm indeed changes the impacted area drastically, not only because of the impressive physical appearance in the wide open seascape, but also due to the underwater changes following the introduction of hard substrates in a soft-bottom marine ecosystem. On the one hand, some seabirds can be expected to avoid the huge vertical structures in much the same way as they avoid the coast or are scared off by ship traffic. As such, seabirds can be displaced out from an area which was used for foraging prior to the construction of the wind farm, resulting in habitat loss. In an offshore context, the impacted area is generally surrounded by a huge surface of turbine-free marine habitat, which however does not necessarily include equally suitable feeding grounds. Birds bound to shallow waters are thus the most at risk of losing large areas of valuable and irreplaceable habitat, since wind farms too are generally built on shallow sandbanks. On the other hand however, there are numerous examples of seabirds being attracted to offshore constructions, as for example gas platforms. Mostly, this attraction effect is hypothesised to result from increased food availability and roosting possibilities (Tasker et al., 1986; Wiese et al., 2001). The same of course can be expected to happen at offshore wind farms. But with wind farms acting as a magnet to seabirds, more birds face the risk of colliding with the turbine blades. Importantly, as seabirds are long-lived species with a delayed maturity and small clutch size, even the smallest change in adult survival may have a substantial impact at a population level (Stienen et al., 2007).

Wind farms may finally also act as barriers for local flight movements as well as for migration, resulting in longer flight paths and an increased energy expenditure. Petersen et al. (2006) and Krijgsveld et al. (2011) demonstrated birds to change their flight direction as they approach a wind farm (i.e. macro-avoidance). The extent of this effect is yet unknown but might be particularly important in case of wind farms oriented perpendicular to the main migration direction, as is the case in the BPNS.

Based on data collected during the first six years of offshore wind farm monitoring at the BPNS, this chapter addresses (1) the displacement effects of offshore wind farms, (2) the possible barrier-effect and (3) the expected number of birds colliding with the turbines.

RESEARCH STRATEGY

Two techniques were used in this investigation. Visual censuses from research vessels aimed at estimating local seabird densities, allowing to assess seabird displacement effects as well as to predict bird collision rates. This method provides a high taxonomic resolution and direct information on seabird behaviour, but is restricted to daylight and good weather conditions only. Radar research complemented the visual census data with continuous observations, and aimed to study barrier effects and – again – bird collision rates, yet with a significantly lower taxonomic resolution. While visual censuses are already at full maturity allowing for an in depth impact assessment, radar research first had to cope with various technical and analytical problems, some of which are addressed in this chapter.

Displacement

Since 2005, three years before the construction of the first offshore wind turbine, seabird displacement effects were investigated performing monthly BACI-designed seabird surveys across impact and control areas. Seabird surveys were conducted according to the internationally applied European Seabirds at Sea (ESAS) method (Tasker et al., 1984). The focus is on a 300 m wide transect along one side of the ship's track. While steaming, all birds in touch with the water (swimming, dipping, diving) located within this transect are counted ('transect counts'). In contrast, the density of flying birds was assessed through so-called 'snapshot counts': right at the start of each minute, the number of birds flying within a quadrant of 300 by 300 m inside the transect is counted. Taking account of the distance travelled, these count results can be transformed to seabird densities.

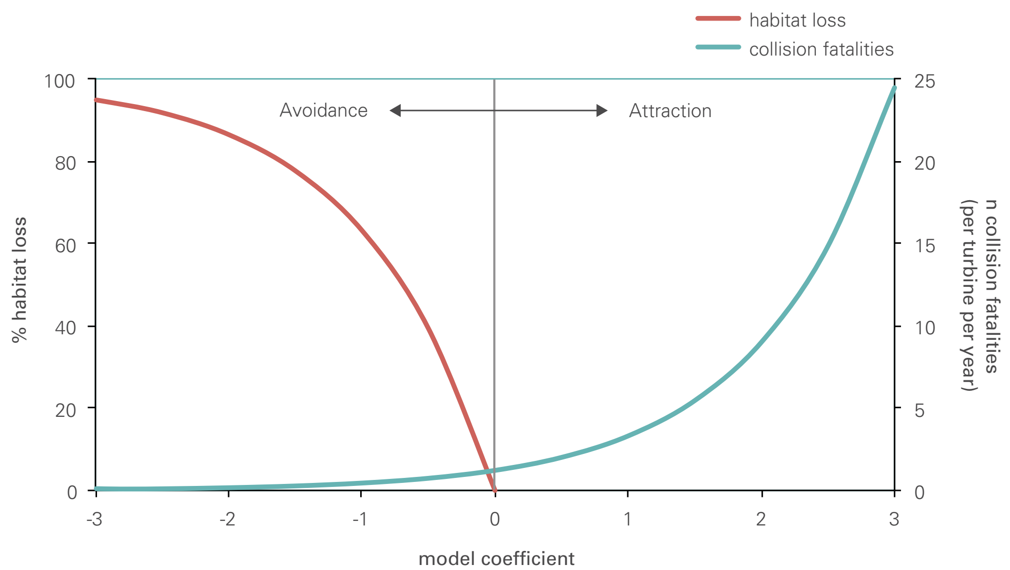
Based on the results gathered during the Danish pilot project on seabird displacement effects at offshore wind farms (Petersen et al., 2006), we surrounded the future wind farm areas by a buffer zone of 3 km to define the impact areas, being the zones where effects of turbine presence can be expected (Figure 1). Next, a more or less equally large control area was delineated, harbouring comparable numbers of seabirds, showing similar environmental conditions and enclosing a high number of historical count data (Vanermen et al., 2010). Considering the large day-to-day variation in observation conditions and seabird densities, the distance between the control and impact area was chosen to be small enough to be able to survey both areas on the same day by means of a research vessel. To minimise overall variance and in order to avoid pseudo-replication resulting from autocorrelation between subsequent ten-minute counts, the applied unit in our seabird database, count data were summed per area (control/impact) and per monitoring day (Stewart-Oaten et al., 1986). Only those days during which both areas were surveyed, were used in this study.

Seabird survey from the RV Belgica at the Thorntonbank.

Figure 1. Location of the impact and control areas for the Thorntonbank and Bligh Bank wind farms, with indication of the monitoring route sailed in the course of 2012.

Seabirds mostly occur strongly aggregated in (multi-species) flocks, inducing count results with a high proportion of zeros and relatively few but sometimes very high positive values. To correctly handle this inherent over-dispersion and excess in zero values, a zero-inflated negative binomial (ZINB) model was used (Zeileis et al., 2008). This type of model consists of two parts, (1) a 'zero component' modelling the chance of not encountering birds with a logistic regression, and (2) a 'count component' modelling the data according to a negative binomial (NB) distribution. Seasonality was added to the models as a covariate and was modelled as a cyclic sine curve, which can be described through a linear sum of a sine and a cosine term (Stewart-Oaten and Bence, 2001). Next, we included the two-level factor variable BA (before/after wind farm construction) and, depending on the outcome of the model selection process, CI (control/impact area) or T (turbines absent/present). The wind farm displacement effect is then estimated by the coefficient of the interaction between BA & CI or by the coefficient of the factor variable T. How the value of this coefficient relates to the impact of wind farm presence on seabirds is illustrated in Figure 2. A negative model coefficient value indicates that birds are avoiding the wind farm, resulting in habitat loss yet a decreasing number of collision fatalities, while a positive value suggests attraction of seabirds and increased bird mortality. The exponential relation between the model coefficient and the number of collision fatalities is explained by the logarithmic link between the response and the linear regression equation incorporated in the NB model structure.

Figure 2. Relation between the displacement-related model coefficient and the anticipated negative impact on seabirds (estimation of collision fatalities being based on the characteristics of lesser black-backed gull and a hypothetical density of 0.02 birds/km² at rotor height).



BOX:

Radar systems as a tool to study large scale effects of offshore wind farms on birds

The Merlin radar system (DeTect Inc., Florida, USA) consists of two identical solid state S-band radar antennas, one scanning in the horizontal pane and one in the vertical. The horizontal scanning radar (HSR) is rotating 360° in the horizontal pane and provides information on flight tracks and therefore on the possible avoidance behaviour of birds around the wind farm. By rotating in the vertical pane, the vertical radar (VSR) creates a 'radar screen' that registers all targets moving through that screen. As this 'radar screen' is fairly narrow, every registration can be seen as one (or a group of) target(s) passing through that area. This way of data collection allows deriving the flux of birds through the area. It also provides data on the flight altitudes.
The range of the radars can be specified in the system's settings. The radars are usually operated at a range between two and four nautical miles for the HSR and 0.75 – 1 nautical mile for the VSR. This type of system records birds continuously year-round and is remotely manageable. The Merlin software of the radar is designed to record and track moving objects. The objects of interest are in this case obviously birds. When the radar energy reflects on a bird and this is received by the radar antenna, an echo appears on the raw radar screen. If the echo meets certain (plotting) criteria (e.g. minimum size, intensity of the echo, etc.) it will be plotted on the processed Merlin screen. If the radar detects the same echo in four consecutive scans, it is considered as a confirmed 'track' and will be written to the database, together with its own, unique track identification code. The radar further registers over 40 variables (e.g. time, location, speed, heading, size) for every record.

Figure 3. Unprocessed data during the fall migration of 2012. Upper panel: 15 minutes of horizontal radar data from October 22nd (8:45 – 9:00 pm). The horizontal radar range is set at 4 NM (7408 m); lower panel: one hour of vertical radar data from October 6th (11 to 12 am). The vertical radar range is set at 1 NM (1852 m). On both figures some bird tracks are notable, but also wind turbines, rain, etc. Certain areas have few or no detections at all, due to some issues with the detectability of the radar signal, which have been improved now. The direction in which an object is moving is indicated by the color.

After a test-phase in the port of Zeebrugge, the radar system was moved to the transformer platform on the Thorntonbank, about 25 km from the coast. The radar antennas are installed on the top deck, about 36 m above the sea-surface, on the south-western side of the platform.

Merlin dual radar system installed on the top deck of the transformer platform of the C-Power wind farm at the Thorntonbank.

Obviously not only birds are recorded by the radar; this also happens for rain, waves, boats, wind turbines, etc. These unwanted echoes are being referred to as 'clutter'. For offshore studies the biggest source of clutter is the sea surface (further referred to as 'sea clutter'). The VSR is typically less vulnerable to sea clutter than the HSR. A first challenge in radar data analysis was to effectively remove this clutter from the radar database. Based on visually ground truthed radar observations during the test phase at Zeebrugge, we quantified the differences in echo characteristics between birds and other objects (e.g. vessels, sea clutter, etc.). A good example of a differentiating variable is the track length of a target. With a mean track length of about five records, the track length of sea clutter was found to be significantly shorter than the tracks for birds and vessels (Figure 4). Combining radar data variables and extensive ground truthing will hence allow us to further filter birds from the radar data for future seabird investigations.

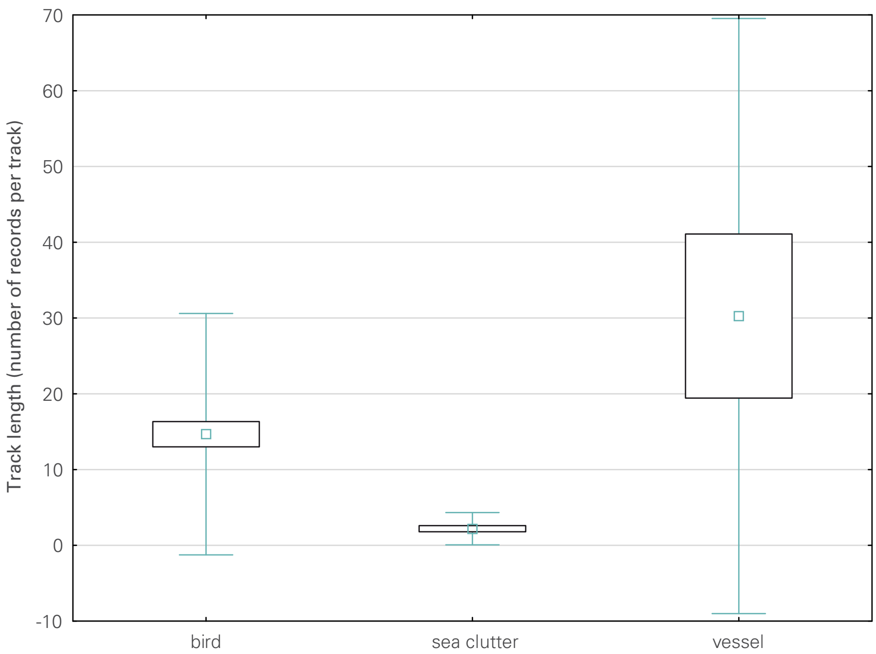


Figure 4. Track length of ground truthed tracks assigned to sea clutter, vessels and birds. Mean ± standard deviation (whiskers) and 95% confidence intervals (box).

Barrier-effect

Radar observations provide continuous data on flight movements over a wide area, allowing to assess barrier effects and avoidance behaviour on a large scale. Radars have been used for similar offshore research programs abroad, for instance in Denmark (Desholm, 2006) and the Netherlands (Krijgsveld et al., 2011). GIS processing of horizontal radar data allows to determine changes in seabird flight directions as they approach the wind farm (i.e. avoidance) and at what distance from the wind farm they show this avoidance behaviour. Although successfully applied in the tern breeding colony at the harbour of Zeebrugge (presented in Brabant et al., 2012a), we were not yet able to run such analysis for the offshore wind farm environment due to issues with the radar signal detectability.

Collision rate

Collisions of birds with fixed and rotating structures of wind turbines have been recorded in numerous wind farms on land (Everaert and Stienen, 2007; Barclay et al., 2007; etc.). For obvious reasons it is more difficult to assess the number of collision victims at an offshore wind farm, and at this point, actual data on offshore collision rates are lacking. Band (2012) however developed a (theoretical) collision risk model (CRM) to estimate the bird collision risk based on technical turbine specifications and wind farm configuration, combined with bird-related parameters. In this study, data on wingspan and flying speed were taken from Cramp (1977-1985) and Alerstam et al. (2007). The CRM also includes a micro-avoidance rate, accounting for last-minute avoidance actions. This factor is hard to assess, but is considered to be very high and is generally set to at least 95% (Chamberlain et al., 2006). Importantly, the number of estimated victims is proportional to the percentage of birds that *does not* perform avoidance actions (= 1 - % micro-avoidance). A seemingly small difference in avoidance rate between 95% and 99.5% therefore results in a factor 10 difference in terms of estimated collision victims. To estimate collision rate in this study, we applied the micro-avoidance value of 97.6% as found by Krijgsveld et al. (2011) based on their extensive radar research.

The 'snapshot counts' as performed during the seabird surveys allowed estimating densities of flying birds within the Bligh Bank wind farm, which were used as input for the CRM. Meanwhile, the flight height of all observed seabirds was categorised as 'in', 'under' or 'above' the rotor sweep zone (30-150 m). Radar observations too were used to determine bird densities, which were deducted from the flux of birds through the vertical radar beam. As the radar does not differentiate between individual and flocks of birds, the flux is expressed as the number of (groups of) birds/hr/km. The flux and estimated number of collisions were calculated for two days during the fall migration of 2012 (October 21st and 22nd 2012) and for two days in the winter of 2013 (January 22nd and 23rd 2013).

Lesser black-backed gull approaching the rotor sweep zone in the Bligh Bank wind farm.

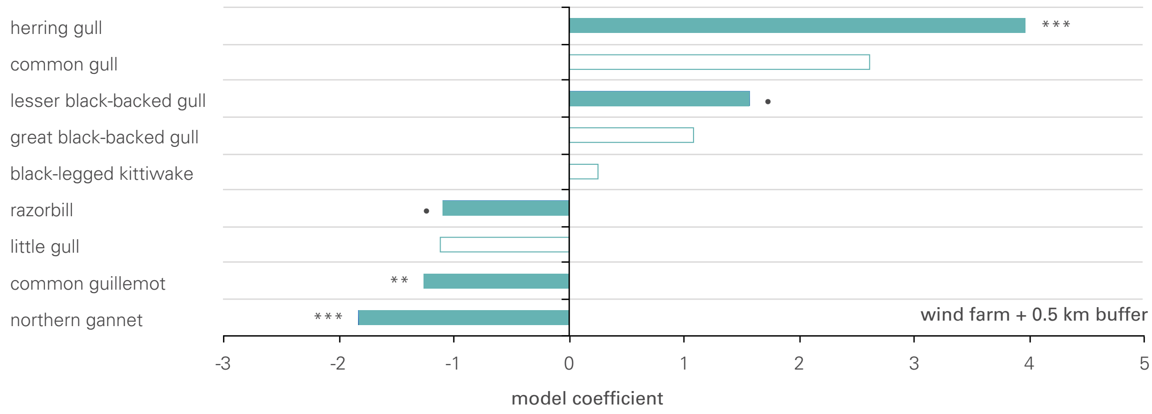
DISPLACEMENT EFFECTS REVEALED

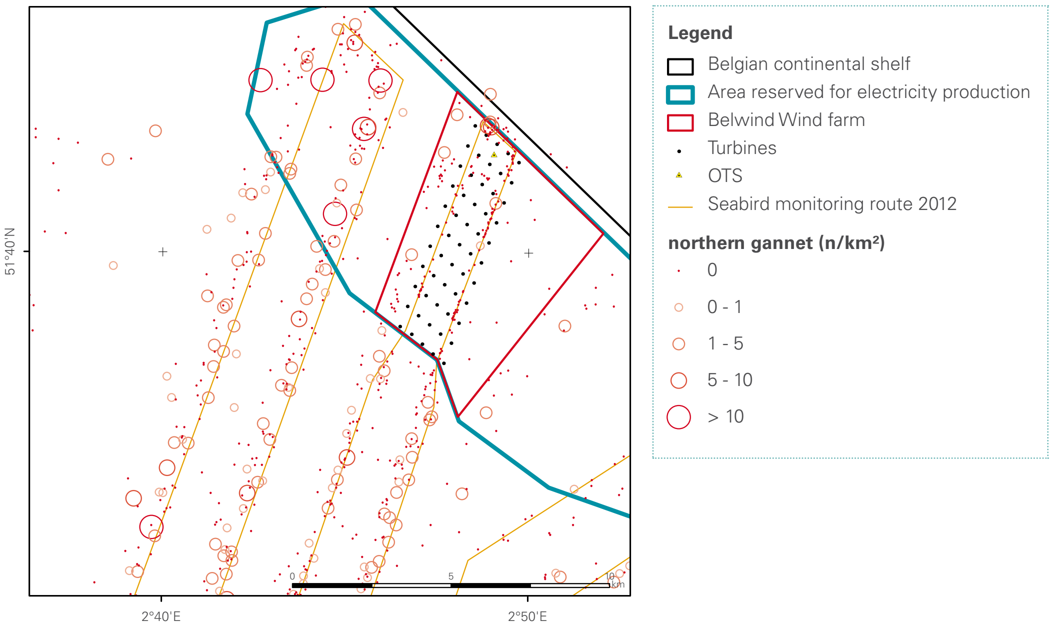
Because the large difference in configuration between the wind farms at the Bligh Bank (five rows of 11 turbines) and the Thorntonbank (a single row of six turbines at the time of the surveys) can be expected to trigger different displacement effects, we analysed both areas separately.

Bligh Bank

Three species significantly avoided the Bligh Bank wind farm, i.e. northern gannet and both auk species (Figure 5). For razorbill, this effect was limited to the wind farm area itself, but northern gannet and common guillemot also avoided the area up to at least 3 km from the nearest turbines. Little gull numbers decreased after the wind farm construction, but this change was not statistically significant. The distribution maps show that the avoidance by northern gannet (Figure 6, upper panel) was almost absolute while common guillemot (Figure 6, lower panel), despite its avoidance behaviour, was regularly observed inside the wind farm.

Figure 5. Seabird displacement effects at the Bligh Bank wind farm based on the results of 63 surveys before and 30 surveys after the turbines were built and indicated by the displacement-related model coefficient (blue bars indicate significance: . ~ p<0.1, * ~ p<0.05, ** ~ p<0.01, *** ~ p<0.001).





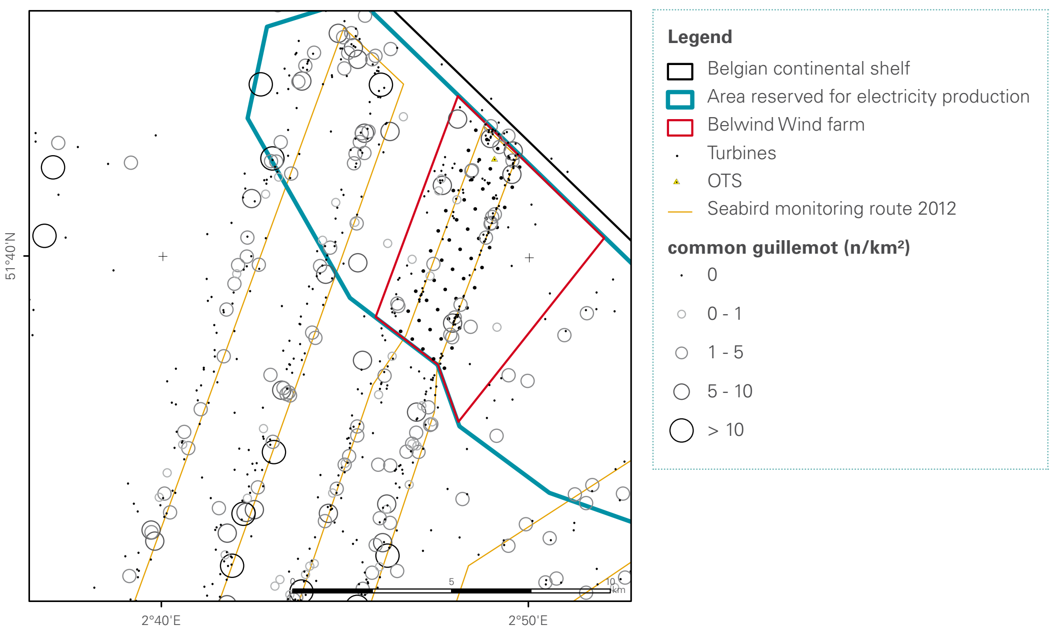
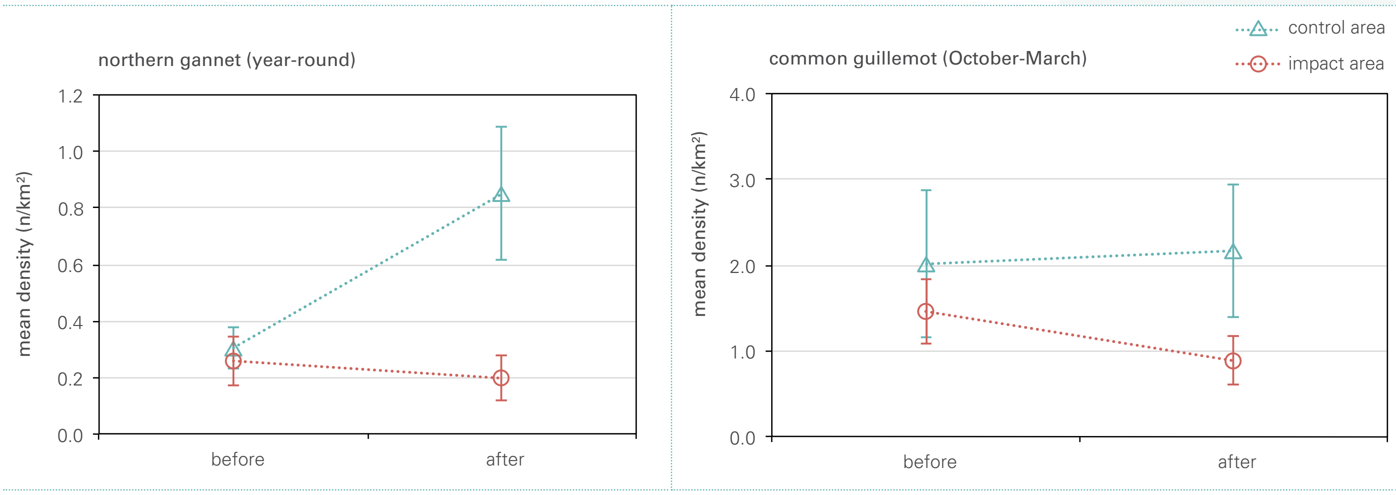


Figure 6. Observations of northern gannet and common guillemot during the seabird monitoring program at the Bligh Bank after wind farm construction.

Figure 7. Densities of northern gannet and common guillemot at the Bligh Bank study area before and after wind farm construction.



Lesser black-backed gulls and herring gulls *Larus argentatus* on the other hand showed a significant increase in numbers after the wind farm was constructed (Figure 5, see also Chapter 15 – Figure 1). For lesser black-backed gull the attraction effect was significant for up to at least 3 km from the wind farm, which was not the case for herring gull. The attraction of herring gulls is nicely illustrated by the distribution pattern in Figure 8 (lower panel), with high numbers being observed exclusively near or inside the wind farm. In contrast, the distribution pattern of lesser black-backed gull (Figure 8, upper panel) suggests indifference rather than attraction. Lastly, an increase in numbers was observed in three other gull species: common gull *Larus canus*, great black-backed gull and black-legged kittiwake, but these effects were not found to be statistically significant.

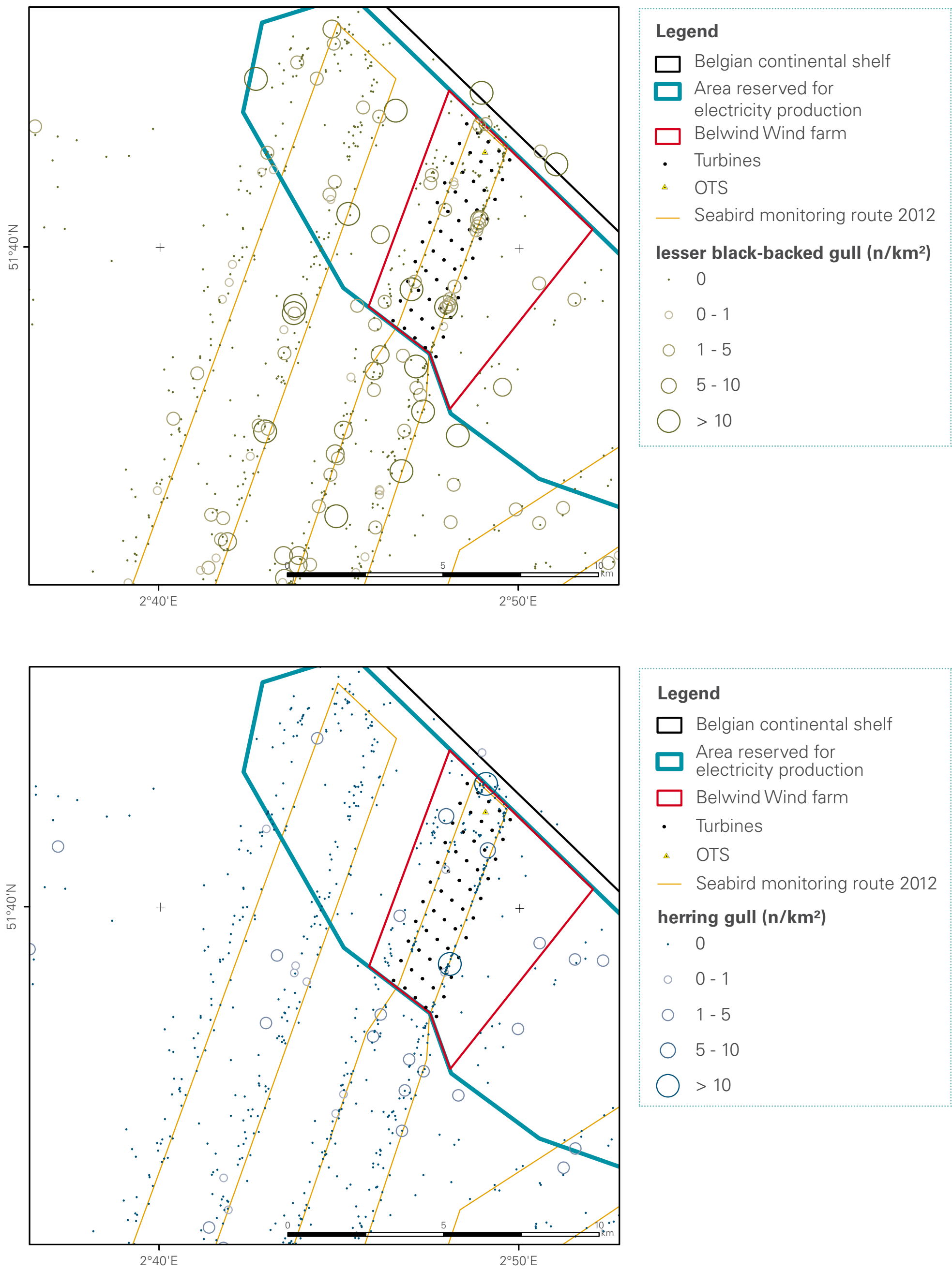
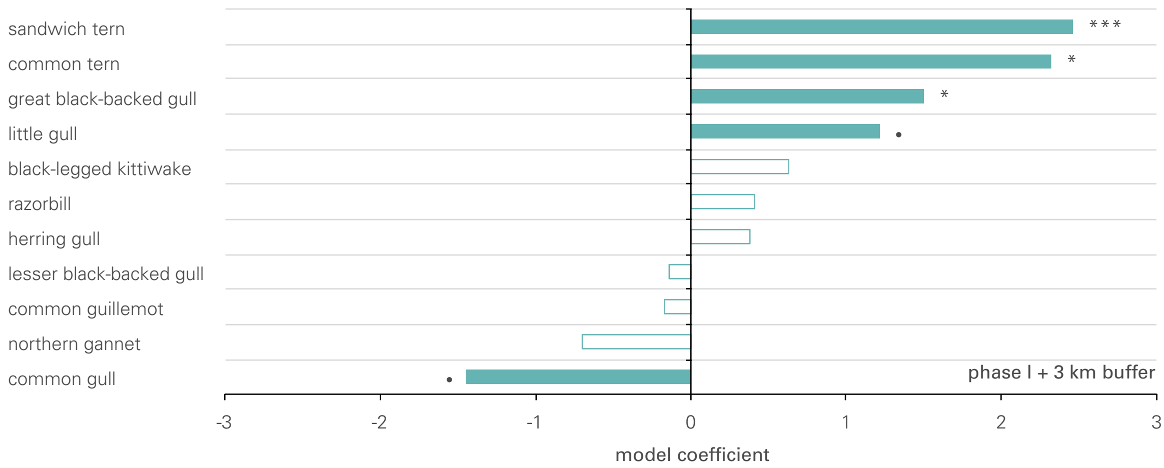


Figure 8. Observations of lesser black-backed and herring gull during the seabird monitoring program at the Bligh Bank after wind farm construction.

Thorntonbank

Four species occurred in significantly higher numbers after the construction of the first six turbines (phase I), i.e. little gull, great black-backed gull, sandwich tern *Sterna sandvicensis* and common tern (Figure 9). Common gull however avoided the area during the time of our research, opposite to what was found at the Bligh Bank. Data collected in 2012, i.e. during the construction period of phases II & III, showed significantly higher numbers of sandwich tern to occur in and around the wind farm under construction.

Figure 9. Seabird displacement effects at the Thorntonbank wind farm based on the results of 66 surveys before and 33 surveys after the turbines were built and indicated by the displacement-related model coefficient (blue bars indicate significance: . ~ p<0.1, * ~ p<0.05, ** ~ p<0.01, *** ~ p<0.001).



Razorbill

Seabird avoidance and attraction!

The wind farm monitoring programme revealed significant attraction of large gulls towards offshore wind farms at the BPNS. This was rather surprising since in contrast, no clear-cut attraction effects were found for large gulls during the Danish and Dutch monitoring programs (Petersen et al., 2006; Leopold et al., 2011). In general, at-sea gull distribution is strongly determined by the presence of fishing trawlers. The main anticipated effect of wind farms on gull distribution patterns was thus a decrease in densities resulting from the prohibition for trawlers to fish inside the farm boundaries. Yet, we found an increase in numbers, which can be caused by increased resting and feeding opportunities (see Chapter 15). For common gull and black-legged kittiwake results did not show unambiguous effects. Both species were however regularly observed between the turbines, suggesting indifference towards wind farm presence. On the other hand, three species displayed avoidance, being northern gannet, common guillemot and razorbill. Interestingly, strong avoidance by gannets and auks is reported by the Dutch researchers at the OWEZ wind farm (Leopold et al., 2011; Krijgsveld et al., 2011) and avoidance by auks was also found by Petersen et al. (2006) at the Horns Rev wind farm in Denmark.

Furthermore, we found significant attraction effects of three Annex I species (i.e. little gull, common tern and sandwich tern) to the operational phase I at the Thorntonbank. Importantly, high proportions of these species' biogeographical populations migrate through the Southern North Sea (Stienen et al., 2007).

Clearly it is impossible to count 'inside' a one-dimensional farm of six turbines, and the revealed attraction effects account for the wind farm *buffer* zone, rather than the wind farm area itself. This finding nevertheless agrees well with findings done by the Danish researchers Petersen et al. (2006), who observed a significant post-construction increase in numbers of little gull just outside the Horns Rev wind farm boundaries (up to 2 km), and a slight (non-significant) increase in numbers inside the wind farm. The same authors found a clear post-construction increase in numbers of common tern in the immediate vicinity of the farm (1 to 8 km), opposed to a total absence of the species inside the wind farm up to 1 km of its boundaries. Similarly, increased presence of sandwich terns foraging on the borders of the OWEZ wind farm was observed by our Dutch colleagues. Apart from this, Krijgsveld et al. (2011) report both tern species and little gull to regularly enter the wind farm, with little gull being observed in higher numbers inside compared to outside OWEZ. Unfortunately, densities of all three species were mostly too low to draw firm conclusions on displacement effects (Leopold et al., 2011).

Two common guillemots near the Bligh Bank wind farm

BIRD COLLISIONS

Visual census results

The species-specific flight height is of large influence on the expected collision risk, and forms a crucial input for the CRM. Table 1 shows our results of flight height estimations as performed during ship-based seabird surveys. While large gull species were seen flying at rotor height quite frequently (15-22%), common guillemots and razorbills were never observed flying above 30m.

Based on the densities of flying seabirds assessed during our ship-based surveys in the Bligh Bank wind farm and the corresponding CRM results, we expect one or more casualties per year for five seabird species (all gulls) at this specific location, up to more than one victim per turbine per year for lesser black-backed gull (see Table 2). For all other seabird species occurring in the study area, the density of individuals flying at rotor height was close to zero and the number of expected collision fatalities is regarded to be insignificantly low. In total, the number of gull victims is estimated at 134 per year (2.4 per turbine), which is almost half the number obtained by Poot et al. (2011), reporting an estimated 243 gull victims at the OWEZ wind farm (6.8 per turbine). This substantial difference in estimated collision rate can partly be explained by the far more offshore location of the Bligh Bank compared to the OWEZ wind farm, respectively 40 versus 10 km from the coast, which is inevitably reflected in lower gull densities.

Table 1. Species-specific percentages of birds flying at rotor height (30-150 m) as observed during seabird surveys at the BPNS.

	% at rotor height
northern gannet	5
little gull	2
common gull	15
lesser black-backed gull	22
herring gull	15
great black-backed gull	20
black-legged kittiwake	9
sandwich tern	2
common tern	1
common guillemot	0
razorbill	0

Table 2. Estimated collision victims based on observed densities of flying birds inside the Bligh Bank wind farm and an assumed micro-avoidance rate of 97.6%.

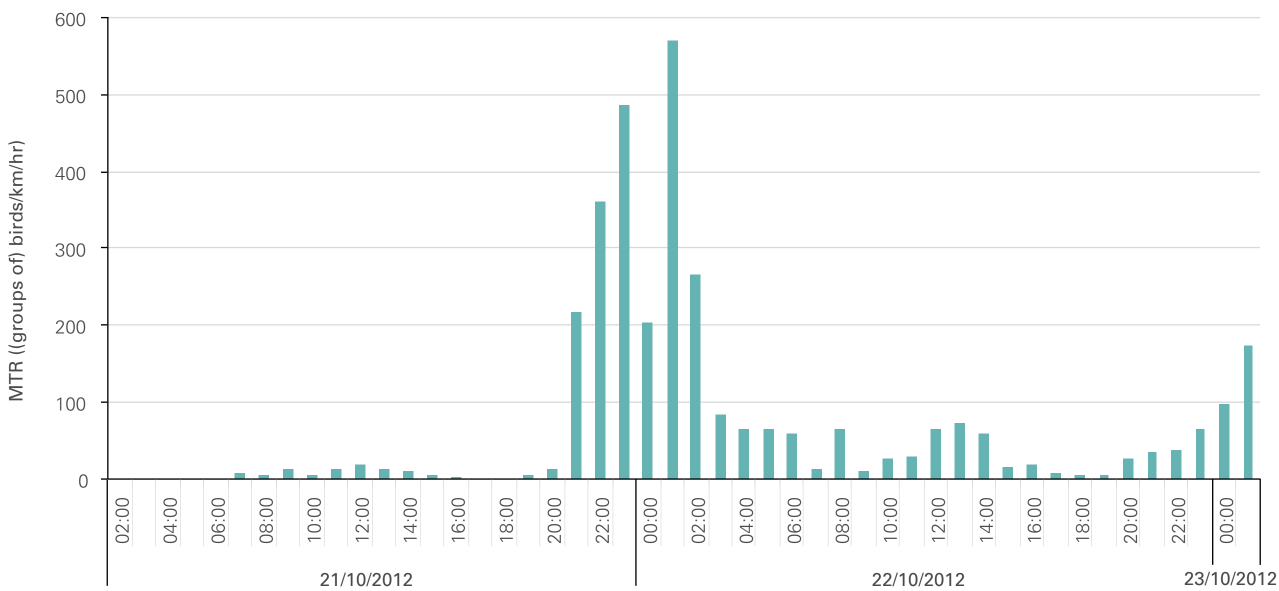
	common gull	lesser black-backed gull	herring gull	great black-backed gull	black-legged kittiwake
winter	3	0	3	3	19
spring	0	40	3	4	10
summer	0	22	0	0	0
autumn	0	3	0	21	3
number/year	3	65	6	28	32
number/(turbine*year)	0.05	1.18	0.11	0.51	0.58

Radar results

On October 21st, 1,176 (groups of) birds were recorded at rotor height in 17 hrs, with an average flux of 69.3 (groups of) birds/hr/km. The flux went up as high as 570 (groups of) birds/hr/km around midnight (Figure 10). On October 22nd, 1,864 (groups of) birds flew on rotor height in 24 hrs, with an average flux of 77.7 (groups of) birds/hr/km.

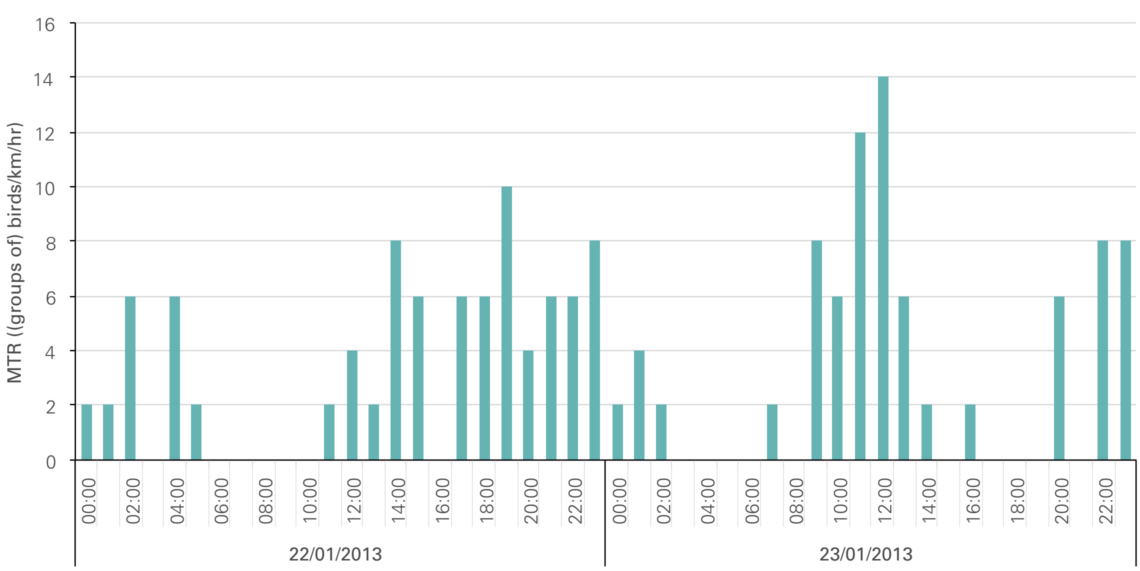
Isolating the radar results obtained during the night of October 21st and 22nd (sunset to sunrise), we observed an average flux at rotor height of no less than 204 (groups of) birds/km/hr. This massive night time bird movement can without doubt be assigned to thrush migration, the more considering the visual observation of large numbers of thrushes arriving at the port of Zeebrugge during the early morning of October 22nd. Wind conditions during that time were E-NE and thus favourable for southwest bound migration. Applying the CRM results in an estimated number of 21 collision victims during that specific night at the Thorntonbank (micro-avoidance rate set at 97.6%).

Figure 10. Bird flux (groups of birds/hr/km) at rotor height for October 21st and 22nd 2012.



Under normal circumstances however, less birds frequent the study area. For example, on January 22nd and 23rd, respectively 86 and 82 (groups of) birds/km were recorded at rotor height (Figure 11), resulting in an average flux of 3.5 (groups of) birds/km/hr. Applying the CRM results in an estimated 58 collision victims during the winter months December, January and February (micro-avoidance rate of 97.6%). Based on the known species-spectrum occurring at the Thorntonbank in winter, these collision victims are most likely to be common gulls, lesser black-backed gulls, herring gulls, great black-backed gulls and black-legged kittiwakes.

Figure 11. Bird flux (groups of birds/hr/km) at rotor height for January 22nd and 23rd 2013.



Extrapolating and nuancing bird collision estimates

Current plans are to construct seven wind farms at the BPNS, with a maximum number of turbines of 530. Extrapolating the earlier results leads to an estimated 209 thrushes to collide with offshore turbines at the BPNS during a single night with comparable migration (micro-avoidance rate 97.6%). Based on daytime observations, each year up to 1,291 birds are expected to collide with the turbines (micro-avoidance rate 97.6%), for the major part gulls. Such extrapolations should be handled with care as the results presented here are yet based on flux and density measurements collected during small time frames. While ship-based visual censuses were limited to a single daytime visit each month, it allows for a large spatial coverage. In contrast, radar observations are bound to one location but provide continuous measurements when fully operational. Applying both techniques is therefore invaluable for an integrated assessment of bird mortality at the Belgian concession zone for wind energy.

FUTURE MONITORING

With the wind farms at the BPNS being operational since the end of 2009 (Thorntonbank) and 2010 (Bligh Bank), the results presented here are still based on a relatively limited impact dataset. Power analyses showed that even for quite substantial changes in seabird densities (e.g. a decrease of 75%), up to ten years of monitoring may be needed to obtain sufficient statistical power (Vanermen et al., 2012). Indeed, at both wind farms we saw numbers of several seabird species to have changed, without the difference in density being statistically significant. With more years of monitoring ahead of us, our data will allow to better distinguish between true displacement and indifference. Long-term monitoring at the various wind farm sites is also needed to anticipate the possible habituation of seabirds to the presence of wind turbines (temporal variation) or the fact that displacement effects might differ between wind farm sites (spatial variation). The results from the Dutch and Danish research programs further show that the occurrence of increased numbers just outside an offshore wind farm (as was found near the single row of turbines at the Thorntonbank) cannot be extrapolated to the wind farm area itself. Continuing the monitoring of seabird presence in the now fully operational (and two-dimensional) Thorntonbank wind farm is therefore highly important. Clearly, if the attraction effects as found in this study persist during the coming years, the associated increased collision risk is of serious conservational concern considering the involved species' high protection status.

The main technical challenges currently being tackled in close collaboration with the radar developers are (1) the negative correlation between seabird detectability and distance and (2) the substantial shadow effects created by individual wind turbines. Once these issues are solved, the radar research will further focus on the barrier and collision effects, using a similar approach as was demonstrated above and taking account of radar data filtering. Also, Chamberlain et al. (2006) showed how small differences in estimated avoidance rates result in proportionally large changes in estimated mortality. To improve the outcome of the CRM, radar observations should be combined as much as possible with simultaneous visual observations at the spot, to assess species-specific flight heights and avoidance rates, taking account of differing bird behaviour under a range of conditions. The CRM however remains a theoretical model, and to know actual collision rates, devices that measure collisions of birds with turbines are still needed. Finally, the construction of a new wind farm in the area south of the radar location in the near future will provide an ideal opportunity for the comparison of pre- and post-impact patterns, which was not possible for earlier projects.

Northern gannet

CHAPTER 6

Qualifying and quantifying offshore wind farm-generated noise

Alain Norro, Dick Botteldooren, Luc Dekoninck, Jan Haelters, Bob Rumes, Timothy Van Renterghem and Steven Degraer

The construction, operation and dismantling of offshore wind farms generate noise both above and under water that may be of environmental concern. The maximum detected sound power level of the above water pin piling noise for example, reached 145 dB(A), while the operational sound power level amounted to 105-115 dB(A) at high wind speed. Underwater construction noise was close to ambient noise levels for gravity based foundations (about 115 dB re 1 µPa RMS), while pin piling and especially monopile piling produced excessive levels of underwater noise up to 194 dB re 1 µPa (zero to peak level at 750m), attenuating to ambient noise levels at a distance of up to 70 km. Whether or not such noise levels are to be considered acceptable will depend on the future implementation of proposed regulations into the Belgian legislation.

INTRODUCTION

In the past decade, the potential impact of underwater noise pollution has been increasingly recognised at the international level, with several intergovernmental bodies, including the UN General Assembly and the UN Convention on Migratory Species, calling for multilateral efforts to minimize the risk of adverse effects on the marine environment. (European Parliament, 2004) (Marine Mammal Commission, 2007) (International Fund for Animal Welfare, 2008), (International Maritime Organisation, 2009), At the European level, the new EU Marine Strategy Framework Directive has identified noise as one of the pressures that need to be controlled to achieve the 'good environmental status' of European marine waters (Anonymous, 2012a). The Belgian part of the North Sea (BPNS) hosts numerous human activities generating noise, including sand and gravel extraction, the installation of pipelines and cables, military exercises as well as intense shipping. As a recent activity, offshore wind farm construction and operation now contribute to the human-induced noise in the BPNS.

Four different phases, each with specific noise emitted, should be distinguished during a wind farm life cycle (Nedwell and Howell, 2004): (1) the reference situation before the start of the construction, (2) the construction phase, (3) the operational phase and (4) the dismantlement phase. Noise emissions associated with the construction phase include e.g. increased shipping traffic, dredging activities, cable trenching, the installation of the scour protection and pile driving. During the operational phase of a wind farm, various kinds of lower level, yet chronic (at least 20 years), noise is expected to propagate above and under water, among which machine noise, self noise generated by the blades passing through the air, noise due to inflow turbulence and noise generated by vibration of the turbine propagating into the water through the foundation. No information is available about the noise during the wind farm dismantling phase as this activity has yet to take place.

This chapter focuses on the qualification and the quantification of wind farm generated noise both above and under water during the construction and operational phase.

MONITORING STRATEGY

Above water noise

The above water or airborne noise level generated by the hammer during a pin pile piling event (jacket) was measured at a short distance (at about 284 m). The source power levels obtained from measurements during piling were used to estimate the impact distance of construction activities in the vicinity for different meteorological conditions using the parabolic equation numerical technique (Dekoninck and Van Renterghem, 2012).
Source power measurements of the operational phase of an offshore turbine are problematic due to the instrument unfriendly conditions. Two approaches were tested. At the one hand, measurements were made from a RHIB at various distances of the wind farm and at the other hand, continuous noise monitoring was set up on the platform of an operational turbine. Measurement conditions in a RHIB are highly limited due to safety issues for the persons on board (wave height) and due to the disturbing noise of waves breaking against the RHIB. Wind turbines at high production and hence high noise emission conditions cannot be monitored with this technique, but a good reference for the offshore background noise levels could be established. One of the remarkable findings was the presence of low frequency background noise related to engines of large ships at long distance. Long term measurements at the wind turbine platform of a 5 MW turbine of C-Power (at approximately 15 m above the water surface and at a minimum 30 m distance from the blade tip) proved to be a useful technique to evaluate the noise emission of a wind turbine in operational conditions.

Underwater noise

Before the construction the background or ambient noise, with both a natural and a human induced component (eg. shipping, rain, waves…), was measured at the Thorntonbank and the Bligh Bank respectively by Henriet et al. (2006) and by Haelters et al. (2009). Construction and operational noise were measured at both the Thorntonbank and the Bligh Bank. Real time noise recordings of maximum 20 minutes each were performed from a RHIB drifting in silent mode with a Brüel & Kjær hydrophone (type 8104) deployed at 10 m depth. A Brüel & Kjær amplifier (Nexus type 2692-0S4) allowed for an amplification of the signal, prior to its recording with an MARANTZ Solid State Recorder (type PMD671), operated at the highest possible sampling rate of 44.100 Hz. All signals recorded were post-treated for detecting maximum peak levels (zero to peak L_{z-p}), used to characterise impulsive noise events (Betke, 2008). Raw measurements were normalised to a distance of 750 m, taken as a standard distance for e.g. German and Belgian underwater noise measurements (Müller and Zerbs, 2011; Anonymous, 2012; see Ainslie et al., 2010). The third octave spectrum was used to identify the spectral window of the noise. Other parameters are also computed and more information on the standardized protocol could be found in Norro et al. (2013). We finally used the collected information on L_{z-p} to estimate offshore wind farm-generated noise propagation in the shallow water environment of the BPNS. A simple propagation model (regression) was fit through the data collected at different distances, which together with the addition of an attenuation term allowed for underwater noise propagation modelling (for details: see Norro et al. 2013).

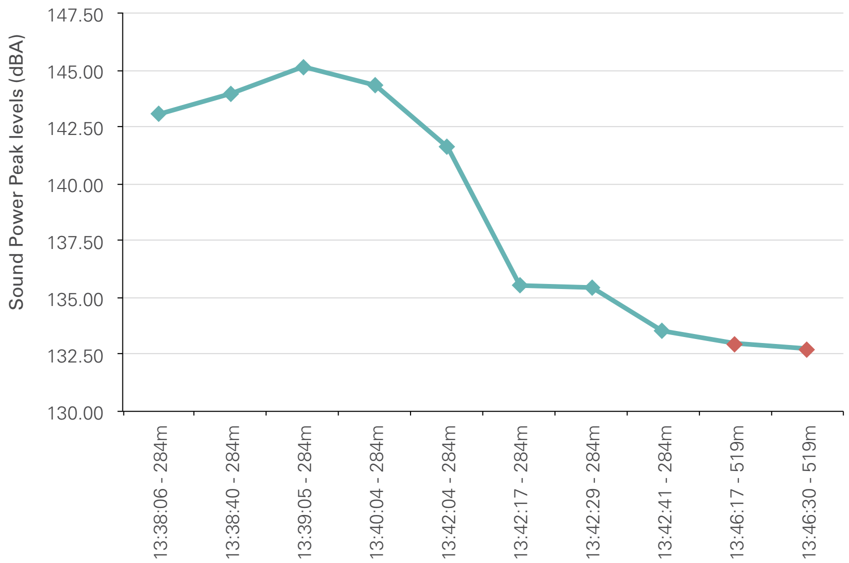
The three foundation types used in the Belgian waters.

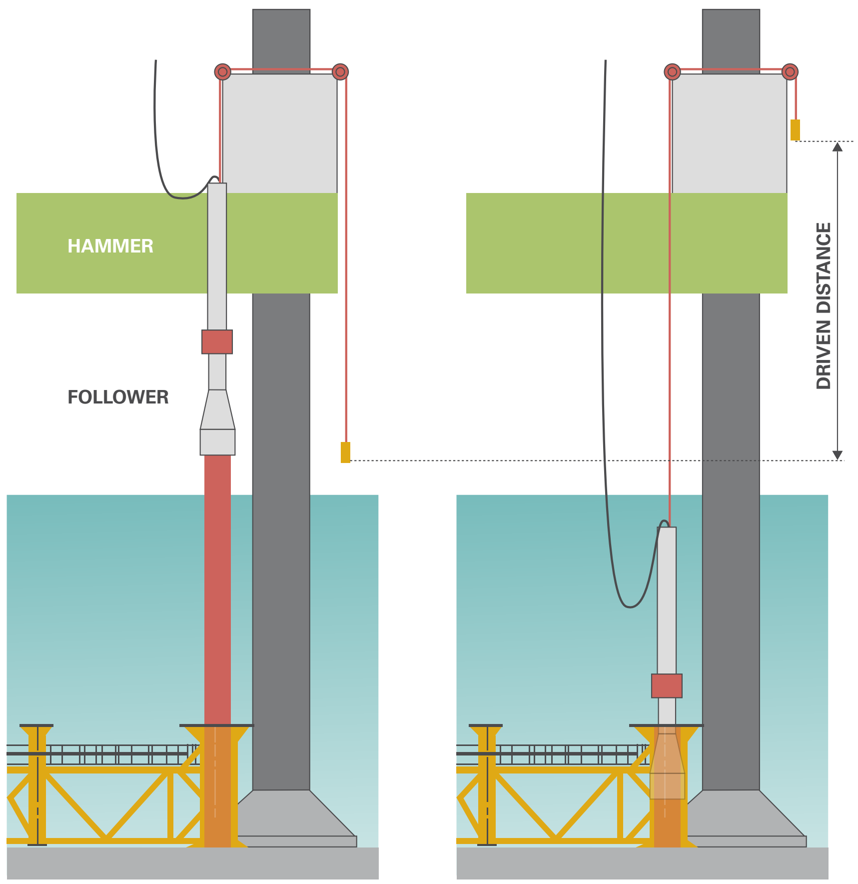
WIND FARM-GENERATED NOISE FEATURES

Above water noise characteristics

The maximum detected source power level of the above water noise during piling was 145 dB(A), but the source power level was highly dependent on the progress of the piling (Figure 1). Firstly, an increase is detected while the piling power is gradually reaching its maximum. While the pile is driven into the seabed, the noise emission drops when the largest section of the pile is below the water surface. Piling activities could be detected in low background noise conditions at a distance of up to 10 km from the source and hence cannot be heard from the coast.

Figure 1. Sound power of the peak levels of piling activity change during the piling progress. Blue points are based on measurements at 280 m distance from the pile, red points at 520 m.





Self noise generated by the blades passing through the air, was detected to be the most important source of sound during operation in modern horizontal axis wind turbines. It occurs when boundary layer turbulence passes the trailing edge of the blade and increases when the boundary layer separates or vortex shedding occurs. Atmospheric conditions could affect the generated sound power in different ways. Boundary layer wind gradients may result in non-optimal inflow conditions for some of the blade positions and inflow turbulence may differ depending on the weather. It can be expected that offshore conditions are more stable than onshore conditions. Noise measurements were evaluated against wind speed at hub height and production data (Figure 2). For very low wind speeds and correspondingly low production, noise levels increase with wind speed but as soon as production is above 2 MW or wind speed is over 9 m/s at hub height, a plateau is reached. Only when production reaches 4.5 MW, which roughly corresponds to wind speeds of 12 m/s at hub height, the noise level starts to rapidly increase again. This could be explained by the changing blade pitch that is used to limit the rotation speed at very high wind speeds, but it could also be caused by the interaction of the wind with the microphone or by secondary sources such as breaking waves. The overall A-weighted sound power level calculated backward from these measurements amount to 102-105 dB(A) for wind speeds between 8 and 12 m/s at hub height and to 105-115 dB(A) for wind speeds higher than 12 m/s. Meteorological effects on sound propagation are limited to a few hundred meters – typically of relevance for onshore operations – because of the height of the source. Long distance propagation over several kilometres over the sea surface depends on meteorological conditions.
Spectral data showed a faint tonal peak at low frequencies that increases with production (and rotation speed), which is expected to have a mechanical origin. This indicates that the mechanical noise generated by e.g. the gearbox and the generator may be less carefully encapsulated for these offshore wind turbines compared to onshore wind turbines, in which a significant effort is put into noise reduction. The main contribution is however broad band noise centred between 300 and 800 Hz for the most significant operational range. This spectrum corresponds to what can be expected for such large wind turbines (Møller et al., 2011).

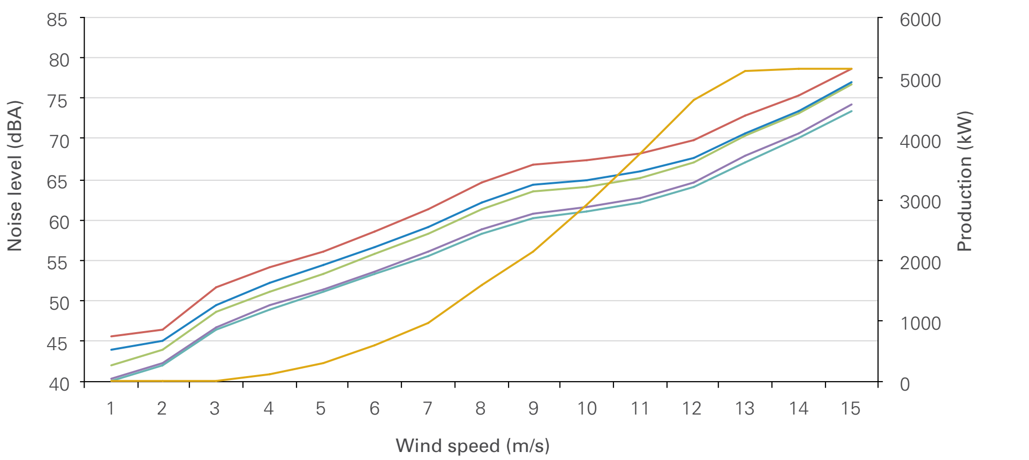


Figure 2. Noise level on the wind turbine platform as a function of wind speed and production.

Underwater noise characteristics

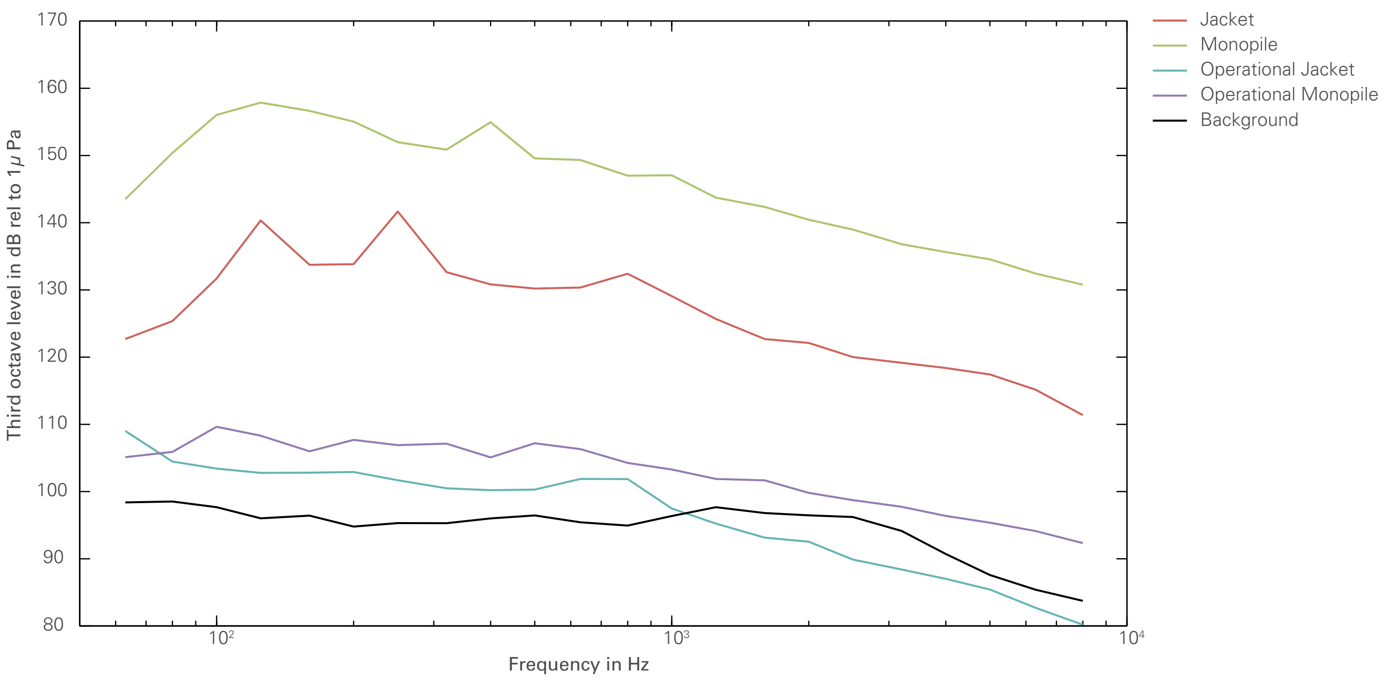
The ambient underwater noise amplitude ranged from 95 to 110 dB re 1 µPa in the 20 Hz to 3 kHz frequency window. The amplitude decreased to 80 dB re 1 µPa at 10 kHz. Slightly higher values were found at the Thorntonbank site (see Henriet et al., 2006), where also a peak at 100 Hz was detected. Both the increase in amplitude and the extra peak may be attributed to the location of the interconnector pipeline and/or the shipping route that are closer to the Thorntonbank than to the Bligh Bank.

Jacket pin pile (left) and monopile (right) driving preparation at the Thorntonbank and Bligh Bank.

As the installation of gravity based foundations (GBF) do not require piling, the construction of GBF wind turbines may be considered relatively silent as most of the noise is derived from an increase of shipping and dredging operations with RMS noise levels of about 115 dB re 1 µPa, i.e. little higher than the ambient noise level (Haelters et al., 2009). Piling events however are known to produce much higher peaks in noise levels. The piling of 5 m diameter monopiles at the Bligh Bank for example produced an L_{z-p} of 179 to 194 dB re 1 µPa as measured and normalized at a distance of 750 m from the piling location, while piling 1.8 m diameter pin piles for the jacket foundations at the Thorntonbank showed L_{z-p} levels ranging from 172 to 189 dB re 1 µPa at the same distance (Norro et al., 2013). Even if these emissions are limited in time, they have to be considered of the same order of magnitude as those produced by airguns (ESF. 2008). While piling pin piles seemed to generate less noise than piling larger monopiles, this could not be statistically underpinned. The total number of blows and hence the piling time required for the installation of one jacket, is however higher than for a monopile. When normalized to the installed power, 57% more blows/MW installed were needed for the construction of an average jacket foundation than for a monopile foundation. Most of the energy during piling is present in the 50 Hz to 1 kHz frequency window (computed for several strokes), where several foundation-specific peaks may be discerned (Figure 3).

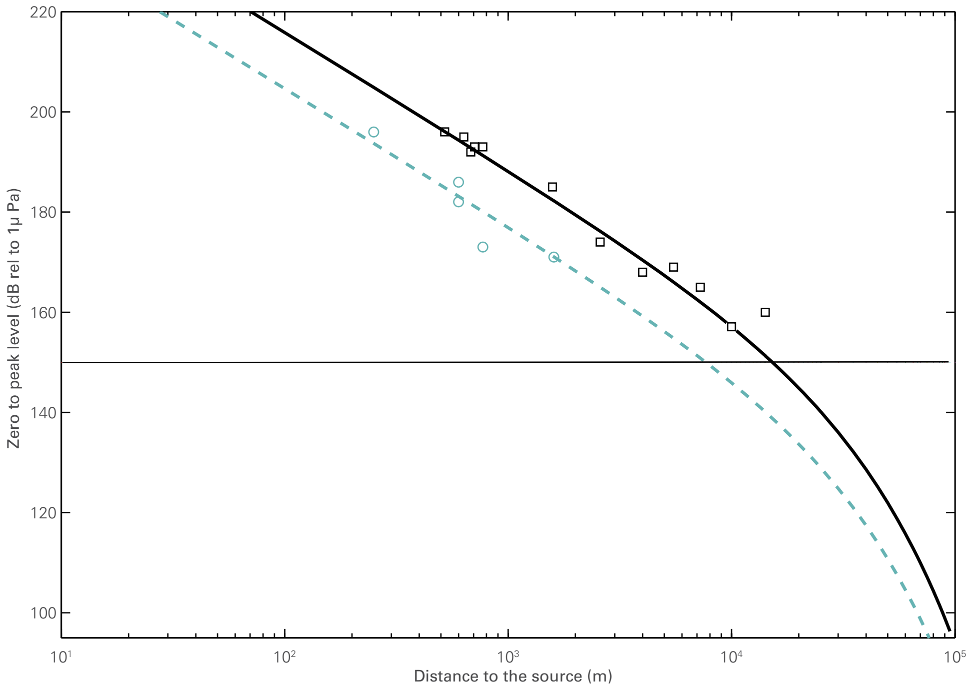
When normalised to 750 m for the source (Ainslie et al., 2010), the piling of a 5 m diameter monopile and a 1.8 m diameter pin pile generated a maximum L_{z-p} of 194 dB re 1 µPa, respectively 189 dB re 1 µPa. As comparison, same normalisation is applied to the literature data presented in Nehls et al. (2007), L_{z-p} ranged from 185 dB re 1 µPa for a 3.3m diameter pin piling event at FINO 2 (Germany) to 196 dB re 1 µPa for a 4.2 to 4.7 m diameter monopiling event at North Hoyle, Scroby Sands and Barrow (UK), and FINO 3 (Germany). A normalised 200 dB re 1 µPa at 750 m was finally obtained for the piling of a 4.7 m diameter monopile at the Q7 wind farm (de Jong and Ainslie. 2008).
Parvin et al. (2006) cited by Nehls et al (2008) derived a relation between L_{z-p} and the diameter of the pile. When applied for pile of 5m and 1.8 m diameter the L_{z-p} values obtained at 750 m are respectively 197 dB re 1 µPa and 190 dB re 1 µPa. Good agreement is obtained even if energy produced by the hammer as well as the nature of the sediment are not taken into account explicitly.

Figure 3. 1/3 octave spectra of ambient noise at the Bligh Bank (black), as well as noise emitted during the construction and operation of offshore wind farms. Jacket for a 6,15 MW turbine: construction (red) and operation (blue); monopile for a 3 MW turbine: construction (green) and operation (pink).



The propagation model indicates that noise generated by monopiling attenuated to ambient noise levels at 70 km from the source, while this distance is shorter for pin piling noise (i.e. 50 km; Figure 4). When considering the noise level of major disturbance for harbour porpoises *Phocoena phocoena* of L_{z-p} 149 dB re 1 µPa (Bailey et al., 2010), according to this model this species would suffer major disturbance up to a distance of 8 km for pin piling and 16 km for monopiling.

Figure 4. Propagation model derived from pin piling (dashed line) and monopiling (plain line). Squares and circles are the measured L_{z-p} for monopiles (squares) and jackets (circles) respectively, while the horizontal line at 149 dB re 1 µPa indicates the level (L_{z-p}) for major harbour porpoise disturbance (Bailey et al., 2010).



Because of the expectation of a more limited impact of relatively low level operational noise compared to construction noise, less data exist on the operational noise emitted by operational wind turbines, especially large ones (5 MW or more). Tougaard et al. (2009) based on measurements taken close to the foundation (14 and 20 m) demonstrated an increase above the ambient noise of 10 to 20 dB re 1 µPa at 125 Hz for 2 MW wind turbines, while no increase was detected at other frequencies. Betke (2006) however reported an additional peak in the 1/3 octave spectrum at 150 Hz. In our study, operational noise was measured both for the GBF and jacket foundation wind turbines at the Thorntonbank and the monopile foundation turbines at the Bligh Bank. A 3 MW monopile wind turbine typically generated a sound pressure twice as high as that of a 6.15 MW jacket foundation turbine (i.e. 6 dB re 1 µPa (RMS) higher throughout the 1/3 octave spectrum; Figure 3), in its turn emitting higher noise levels than a 5 MW GBF wind turbine (by 6 dB RMS). Note that during the measurements sea states ranged from 2 to 3, and/or a wind force of 4-5 Beaufort.

LEGISLATION AND NOISE LEVEL LIMITS

With regards to operational above water noise, environmental noise limits for onshore wind turbines are given in VLAREM, in which noise limits depend on the time of the day (i.e. day, evening, night) and the type of area. In the most restrictive conditions (i.e. residential area) the noise should not exceed 39 dB(A) at night. A decision on how to measure onshore wind turbine-generated noise is under construction by the Flemish government. However, detailed calculation guidelines are available. These are based on ISO9613, adverse meteorological conditions, and equivalent levels. If these regulations would be applied to the offshore wind turbines studied, the minimal distance for siting a residence to a single wind turbine would need to be higher than 500 m (at wind speeds below 12 m/s). For a park of 100 wind turbines, this distance would need to be increased to at least 3-4 km. We should however mention that the residential areas nearest to the offshore wind farms are located at a distance of 30 km at present and 21 km when the whole Belgian wind farm zone will be developed. Residents along the Belgian coast will hence never experience noise pollution from the offshore wind farms.

For underwater generated noise, limits are not yet fully implemented in Belgian legislation, but a maximum L_{z-p} of 185 dB re 1 µPa at 750m from the noise source has been recommended in the framework of the implementation of the Marine Strategy Framework Directive (MSFD) (Anonymous, 2012). These underwater noise level limits are of course not directly related to human welfare, but rather to its disturbance of marine life, with currently special attention to marine mammals. Given the seasonally high density of harbour porpoises in Belgian waters (up to more than 2 ind./km² on average), the possible impact of excessive noise on this species is explored in Chapter 7.

FUTURE MONITORING

Next to the weather limitations to perform *ad hoc* noise measurements from an RHIB at sea, the most critical issue to monitor construction noise is the ability to be on site when work is undertaken. At several occasions during the first years of monitoring the piling work was cancelled at short notice, forcing the monitoring team to return to the harbour without performing any measurements. To overcome the above-mentioned difficulties, the future construction noise monitoring will also be performed using moored instruments. These instruments record long time series of underwater noise covering one or more complete sequences of piling. The instruments will also be used for operational noise recordings throughout a wide range of weather conditions, currently problematic given the limitation of a sea-state of 2-3 and/or a 4-5 Beaufort wind force.

Also some questions regarding above water noise produced by large offshore wind turbines remain unsolved. The influence of inflow turbulence on (low frequency) noise emission could be worth studying. For offshore wind turbines, it is expected that it is mostly relevant in the presence of upwind turbines. Slow fluctuations in noise levels may be an issue when it comes to estimating the perception of wind turbine noise. The directivity of this component of the noise is not known very well. Piling noise propagation was calculated using linear propagation models. However, levels are high and propagation distance is long so mild non-linear effects may occur. Measurements at larger distance could validate this influence.

Finally, to comply with the newly proposed guidance document for monitoring underwater noise in European seas (Dekeling et al. 2013), a register of sources and levels of noise should be compiled. The future offshore wind farm noise monitoring programme will therefore start developing a register for underwater noise sources and levels in the BPNS, which will facilitate setting a context for underwater noise interpretation and evaluation.

CHAPTER 7

The effects of pile driving on marine mammals and fish in Belgian waters

Jan Haelters, Elisabeth Debusschere, Dick Botteldooren, Valérie Dulière, Kris Hostens, Alain Norro, Sofie Vandendriessche, Laurence Vigin, Magda Vincx, Steven Degraer

Pile driving generates very high levels of low frequency impulsive underwater noise, with possible consequences for marine mammals and fish. To describe the effects of pile driving on harbour porpoises we developed a model based on the results of aerial surveys, which clearly pointed at disturbance effects. Especially fish with a swim bladder can be affected by piling operations, but the investigation of sub-lethal effects and the sensitivity of different fish species and life stages is complex. A multidisciplinary study is proposed to investigate these effects in the field and under controlled laboratory conditions.

INTRODUCTION

The installation of numerous offshore wind farms across the North Sea has triggered a range of questions regarding its impact on the marine ecosystem. In most cases, wind turbine foundations are hammered into the seafloor. This activity is known to produce low frequency impulsive underwater noise (see chapter 6; ICES, 2010). Underwater sound travels at a speed of 1500 m/s, and can travel up to considerable distances. For pile driving, sound pressure levels (peak to peak, SPL_{p-p}) of up to 200 dB re 1 µPa at a distance of 750 m from the noise source have been measured or estimated (Madsen et al., 2006; Norro et al., 2010; 2012). Such noise levels can have consequences on living organisms ranging from masking, behavioural disturbance, physiological stress, hearing loss (temporary or permanent), and even to injury or death (Popper et al., 2004; Hastings and Popper, 2005; Wahlberg and Westerberg, 2005). Given such consequences, noise is increasingly considered as an important form of pollution. One of the aims of the European Marine Strategy Framework Directive (MSFD; 2008/56/EC) is to establish a framework for community action in the field of marine environmental policy, with anthropogenic underwater noise at levels that do not adversely affect the marine environment. To implement the MSFD, Belgium adopted an interim criterion of a maximum zero to peak noise level (L_{z-p}) of less than 185 dB re 1 µPa at 750 m from the source for anthropogenic impulsive sounds (Anonymous, 2012a).

The impact of noise is of particular concern for marine mammals and fish, which utilise sound in their everyday lives. To assess the effects of pile driving on marine mammals, the research has focused on the harbour porpoise *Phocoena phocoena*, as this is by far the most common cetacean in European, including Belgian, waters (Haelters et al., 2011). Harbour porpoises use sound production and reception for foraging, spatial orientation and social interactions. Sound has essentially taken over many of the roles normally requiring vision. Therefore, this species may be heavily impacted by excessive underwater noise, an impact not yet fully understood. Around a pile driving site, areas can be defined where exposure to the noise can lead to injury, permanent and temporal hearing threshold shifts (PTS; TTS), masking of the animal's sonar system, behavioural reactions (possibly leading to stress) and audibility of the noise to the harbour porpoise (Lucke et al., 2009).

At the very start of bio-acoustic research, marine mammals were the main target group. Later, researchers took an interest in fish, as sound enables them to communicate, forage, find a mate, orientate, avoid predators, defend their territory and express aggression (Hastings and Popper, 2005; Kikuchi et al., 2010).

Underwater sound consists of two components: particle motion, indicating the movement of the molecules in the medium due to the sound waves, and sound pressure. Particle motion moves through a fish's body and is detected by the inner ear, which acts as a biological accelerometer and enables fish to hear (Popper and Fay, 1999; Wysocki et al., 2009). Fish rely especially on particle motion in their response to sounds from different directions. In contrast to fish without swim bladders, those with gas-filled swim bladders will respond to sound pressure waves because of the higher compressibility of gas compared to seawater (Thomsen et al., 2006). These compressions may be transmitted to the inner ear whereby sound pressure is transformed into particle motion and will give them an auditory advantage, with information on sound characteristics such as distance and location.

Only for a limited number of fish species the hearing range is known, and although it varies greatly between species, frequencies from below 50 Hz up to 500-1500 Hz are detectable by the majority of them (Thomsen et al., 2006; Popper and Hastings, 2009; Andersson, 2011). A few species, including the Atlantic herring *Clupea harengus*, can perceive sound above 1500 Hz (Wysocki et al., 2009). The hearing range of the harbour porpoise stretches from 250 Hz to 160 kHz, while it is most sensitive between 100 and 140 kHz (Kastelein et al., 2002).

RESEARCH STRATEGY

One of the aims of the Belgian wind farm monitoring programme is to investigate the ecological impact of noise on marine mammals and fish. While the research on marine mammals already made some major achievements, the investigation of the effect of underwater noise on fish only recently started and its description here is limited to a scientific justification of what is and will be done.

Harbour porpoise *Phocoena phocoena*

Harbour porpoises are notoriously difficult to study in the wild because of their elusive nature and the technical difficulties related to the environment they live in. Our knowledge of the impact of piling on harbour porpoises is limited to exposure studies of individual animals in captivity with extrapolations to the marine environment, simple predictions of disturbance distance such as made in environmental impact assessments and a few studies at construction sites (ICES, 2010; Murphy et al., 2012). To describe and predict the impact of pile driving, we developed a model based on anticipated harbour porpoise behaviour. We compared the model results with changes in the in situ distribution patterns of harbour porpoises due to pile driving.

Before and during the piling of jacket foundations at the Thorntonbank in 2011, we performed a number of standardised aerial line transect surveys (Buckland et al, 2001), making observations in a predefined pattern consisting of parallel tracks 5 km apart and approximately covering the Belgian marine waters (Haelters, 2009). To assess possible effects of piling on the distribution and abundance of harbour porpoises, observations were transferred to a fine-scale density map, in which the density in unvisited areas was extrapolated from observations using inverse distance weighting.

As it is difficult to objectively qualify and quantify the impact of piling based on maps from aerial surveillance data, a model was developed describing the fundamental phenomena at the basis of the harbour porpoises' redistribution. We presumed that the speed of a harbour porpoise may be described as a combination of a directional movement and random dispersal. Close to the impact area and during piling, we presumed that a porpoise would exclusively head away from the piling location at a speed which would decrease as a function of disturbance, i.e. the noise level the animal is exposed to. In the absence of piling or at a distance where the piling noise is tolerated, harbour porpoises would – at least over the short time frame as applicable in this study – move more slowly and in random directions (i.e. random dispersal).

The model was first applied to hypothetical data, described by an even distribution of harbour porpoises throughout the area (1 animal/km²). The resulting density pattern after a first period of disturbance (piling), without taking account of random motion, can be described as an area near the impact location where the density is lower than average (due to animals moving away), surrounded by an area with a higher density (due to movement of individuals away from the piling zone), and an area with no change in density (i.e. the area beyond the influence of the pile driving activity). In the case of short, consecutive pile driving periods, the areas described above would systematically shift further away from the impact location (Figure 1).

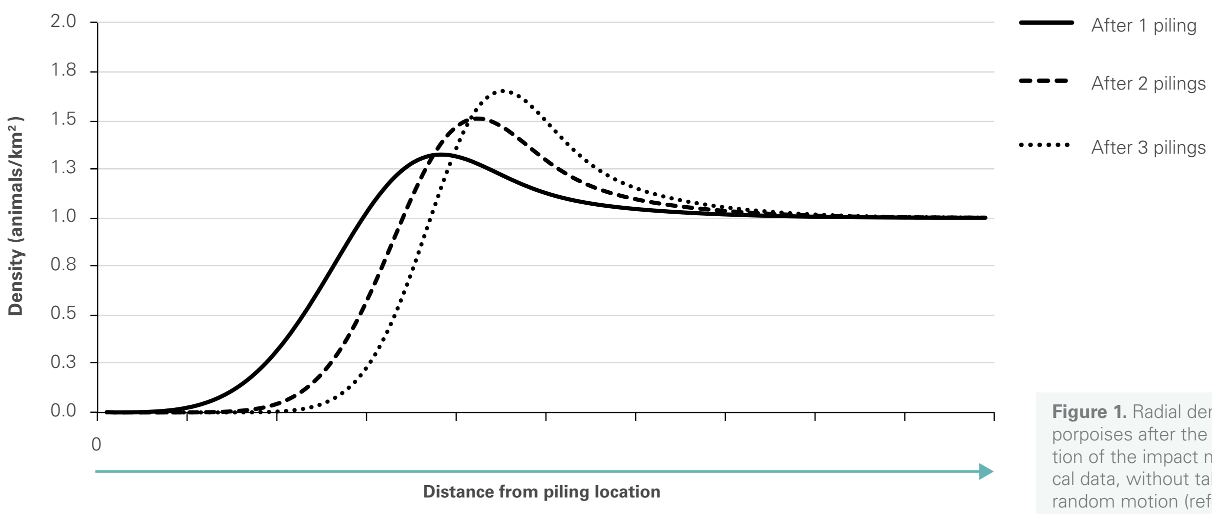


Figure 1. Radial density of harbour porpoises after the repeated application of the impact model to hypothetical data, without taking account of random motion (reference density = 1 animal/km²).

To apply the model to real data, we made several assumptions. The density distribution on 29 March 2011 was used as a reference situation. We used a particle tracking approach to simulate the displacement of harbour porpoises. As an average and maximum swimming speed we used respectively 0.9 and 4.3 m/s (after Otani et al., 2001). For the random dispersal during periods or in areas without disturbance, we ignored water currents. We modelled one impact phase that lasted for two hours and was followed by a quiet period of two hours. In the model, we used 19 km as the distance from the noise source where a noise level (L_{p-p}) of 140 dB re 1µPa is reached (Norro et al., 2013). Tougaard et al. (2011) consider 140 dB re 1µPa as the discomfort noise level for harbour porpoises. We did not take account of a different reaction of individual harbour porpoises to noise: e.g. some animals may be tolerant to higher noise levels than others and some may remain in a noisy area because of good feeding opportunities, less competition with other porpoises or fewer predators.

Fish

Most of the energy emitted by the construction and operational noise of offshore wind farms is at frequencies below 1 kHz, which is well within the hearing range of fish (Figure 2). The actual effects of noise depend on the physical characteristics of the sound and the environment, and on the characteristics of the fish itself, such as size, life stage and species-specific hearing capabilities. All these factors make bio-acoustic research a complex matter.

The variables used to describe impulsive sounds generated through piling are the sound exposure level to a single strike (SEL_{ss}), the cumulative sound exposure level (SEL_{cum}) and the number of strikes (Slabbekoorn et al., 2010). The first results on the effects of low and mid frequency impulsive noise on fish showed that SEL_{ss} >176 dB re 1 µPa^{2}s and SEL_{cum} >207 dB re 1µPa^{2}s are needed to induce significant tissue damage in juvenile and adult roundfish (Halvorsen et al., 2012; Casper et al., 2012). Something more difficult to assess is the disturbance of the natural behaviour of fish or the masking of the communication and orientation signals due to exposure to lower noise levels (Hastings and Popper, 2005; Thomsen et al., 2006; Walhberg and Westerberg, 2005; Mueller-Blenkle et al., 2010). On average, SEL_{ss} of 163 dB re 1 µPa^{2}s at 750m and SEL_{cum} of 196 dB re 1µPa^{2}s at 750m were measured at the Bligh Bank during monopile-driving (Norro et al., 2013).

In a controlled environment, Bolle et al. (2012) exposed newly hatched sole *Solea solea* larvae to noise resembling piling noise at 100 m. No difference in immediate mortality or mortality up to 7 days after exposure was observed between the control and exposed groups. However, the few studies concerning fish larvae leave many questions unanswered (Booman et al., 1996; Govoni et al., 2006; Bolle et al., 2012). Defining the sound level thresholds causing mortality, injury, hatching failure, and delayed or abnormal development should have priority. Particular developmental stages which are more vulnerable than others should be identified. Overall, the ecological impact of these effects should be assessed and, if significant, taken into account by policy makers.

Given the scarcity of data on the impact of noise on fish and fish larvae, criteria for underwater noise or accompanying legislation in relation to fish are rare. The US Fisheries Hydro-acoustic Working Group formulated interim criteria for the maximum noise levels that fish could be exposed to without causing non-auditory tissue damage. The interim criterion for maximum SEL_{cum} for fish of 2 grams or more is set at 187 dB re 1µPa^{2}s, and for fish less than 2 grams at 183 dB re 1µPa^{2}s (Oestman et al., 2011).

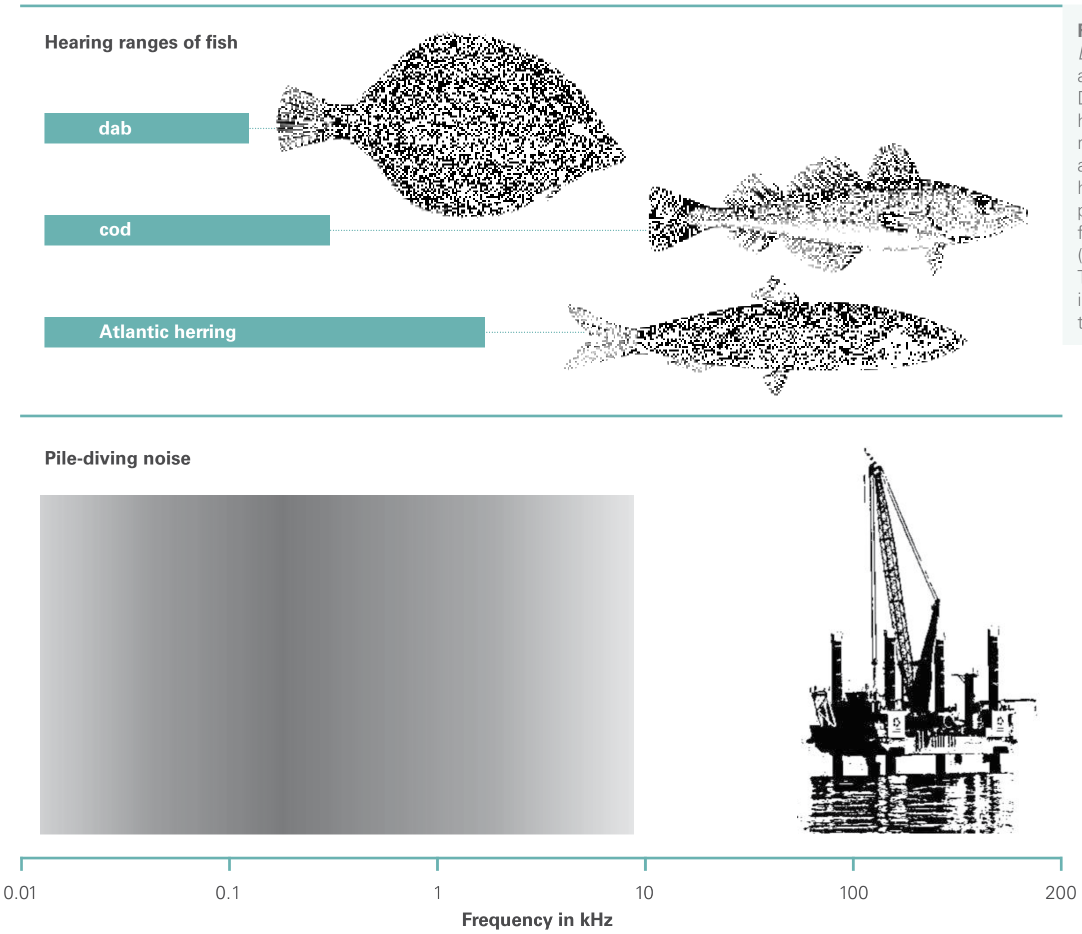
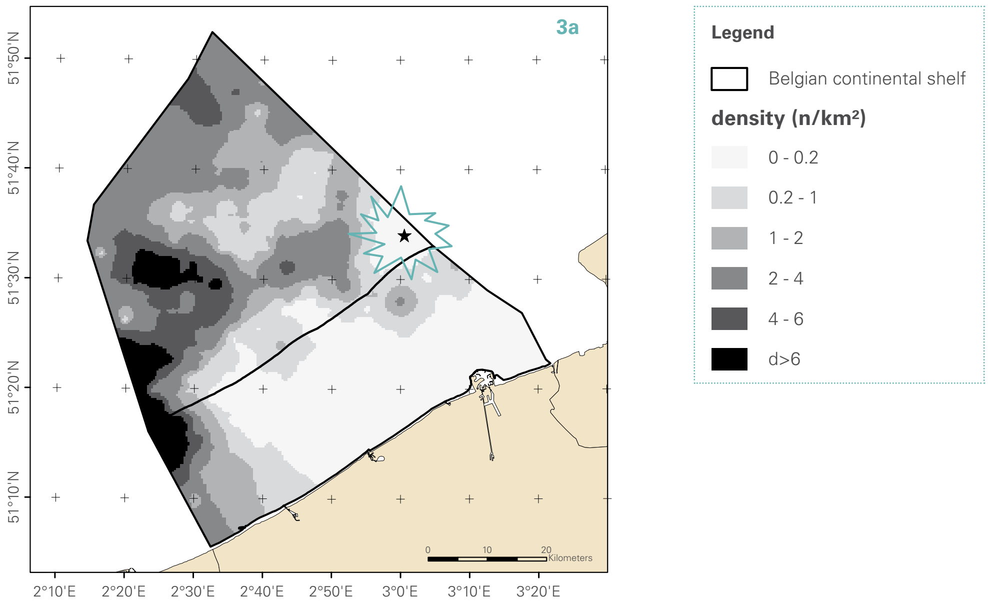


Figure 2. Hearing ranges of dab *Limanda limanda*, cod *Gadus morhua* and Atlantic herring *Clupea harengus*. Dab has no swim bladder and therefore has a narrow hearing range. The hearing range of cod is slightly wider as it has a swim bladder, and Atlantic herring has a wide hearing range due to a pair of elongated gas ducts extending from the swim bladder to the inner ear (based on Slabbekoorn et al., 2010). The grey scale represents the energy intensity level in the frequency range of the piling noise.

HARBOUR PORPOISES: SENSITIVE TO PILE DRIVING?

The estimated average densities of harbour porpoises over the surveyed area on 29 March (pre-piling phase) and 16 April (piling phase) were respectively 2.7 and 1.3 animals/km² (Haelters et al., 2012a). Before piling, harbour porpoises were unevenly distributed throughout Belgian waters, with the highest densities in the western and northern part (Figure 3a). During the piling event, no harbour porpoises were observed in a zone around and north of the piling location (Figure 3b). The results of the application of the model to the reference situation indicate a similar zone void of harbour porpoises (Figure 3c). While the model is able to reproduce the porpoise displacement in a wide area around the piling zone, outside of this area there are larger differences between the situation observed and the one modelled.

Both the results of the aerial surveys and the application of the model to a reference situation during pile driving indicated an apparent distance of disturbance of harbour porpoises of around 20 km in Belgian waters. This is consistent with the results of similar research (Brandt et al., 2011; 2012; Tougaard et al., 2009; 2011), and it is likely that a similar disturbance occurred in the adjacent Dutch waters. The observed disturbance distance could be the consequence of repeated piling events: as observed by Thompson et al. (2010), the distance over which harbour porpoises are disturbed becomes larger with each piling event.



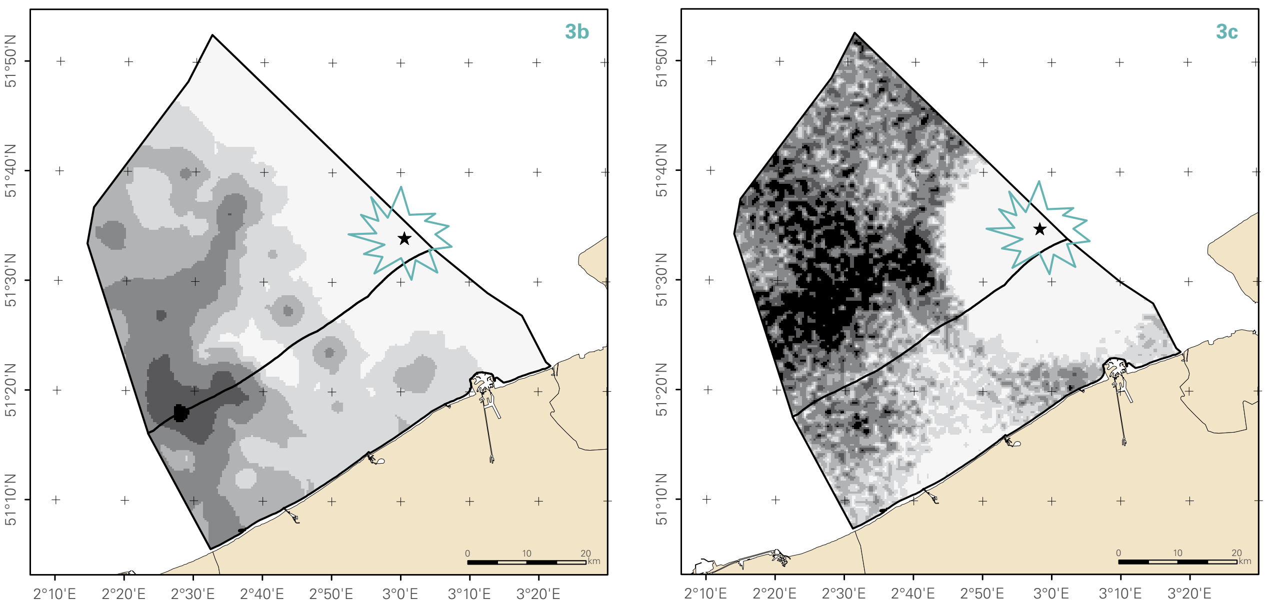


Figure 3. Density distribution maps: estimated before (left; 3a) and during piling (bottom left; 3b) on the basis of aerial survey data, and application of the model on the basis of the situation before piling (right; 3c).

The deviation between the model predictions and the density distribution estimates during piling outside the 20 km distance range indicate that there were likely other factors than piling that played a role in the spatial shifts of harbour porpoises between the reference survey and the survey performed during the piling. These could be food availability or seasonal movement. While harbour porpoises were very common in the survey area at the end of March 2011, their average density had halved by mid-April, probably due to a combination of disturbance by pile driving over a large part of this area and the onset of a general seasonal movement out of Belgian waters.

Harbour porpoises need to feed on a regular daily basis. Therefore prey availability is an important factor determining their distribution. Undoubtedly, pile driving disturbs harbour porpoises over a large area, with the population level consequences remaining unknown. Given the seasonally high densities of harbour porpoises in Belgian waters, thousands of these protected animals could be affected. The sub-lethal effects on individual harbour porpoises, with possible consequences at the population level (through effects on breeding frequency and longevity), and the cumulative effects due to the construction at several sites in the Southern North Sea, remain poorly understood.

Independent of construction operations, harbour porpoises have shown important shifts in their overall distribution pattern within the North Sea during the last decades (Hammond et al., 2013). Next to the effects of construction operations, it is therefore necessary to have a good understanding of such natural background shifts. They need to be taken account of, as the current management measures include a temporal exclusion of piling activities based on seasonal harbour porpoise densities.

FUTURE MONITORING

Harbour porpoises

We presented a model to simulate the disturbance effects observed during pile driving in 2011. However, any extrapolation of the model should be treated with care. The piles driven in 2011 for example, were relatively small (jacket foundations) and it can be expected that the piling of larger piles (monopiles) leads to increased disturbance distances due to increased noise levels. It is therefore advisable to test the model during different piling conditions with different noise levels, but also with different recurrences in the disturbance events. A model extension should further aim at comprising the effects of noise mitigation techniques and the effects of simultaneous piling at several sites within e.g. the southern North Sea.

Next to data from aerial surveys, data collected using an array of passive acoustic monitoring devices, moored following the gradient of noise level, could help to better understand the disturbance effects. It is evident that the investigations of the impact of piling on harbour porpoise distribution and abundance need to be combined with acoustic measurements.

For piling operations at the different wind parks, amongst others the floating crane SVANEN was used.

Fish

A multidisciplinary study combining biology, acoustics, physiology and biochemistry has been designed to examine the impact of the construction and operational noise of offshore wind farms on fish in Belgian waters. The focus will be on the impact of impulsive noise on fish eggs and larvae, since these 'passive drifters' cannot actively escape the exposure. The European sea bass *Dicentrarchus labrax* (Figure 4) has been chosen as a model species for round fish, especially for the physoclist fish which are lacking a connection between their gut and swim bladder. Sea bass is a commercially important species in the Southern North Sea, and eggs, larvae and fry are year-round available from the Ecloserie Marine de Gravelines (France), which makes it an excellent model species.
The first part of the study deals with the impact of pile driving noise. The worst case scenario will be analysed on board of a piling platform (Figure 5), while the impact at 500 m will be examined from a rigid-hulled inflatable boat (RHIB). In parallel, noise exposure experiments will be carried out under controlled conditions in the laboratory. The embryonic and larval development of fish exposed to different noise levels will be monitored and compared with control groups through different replicates.

In the second part of the study, the impact of long-term exposure to operational noise will be studied under controlled conditions in the laboratory. During their embryonic and larval development, fish will be exposed to different operational noise recordings. Possible chronic effects of operational noise on growth, weight, physiological stress, morphology, survival, and behaviour will be examined.

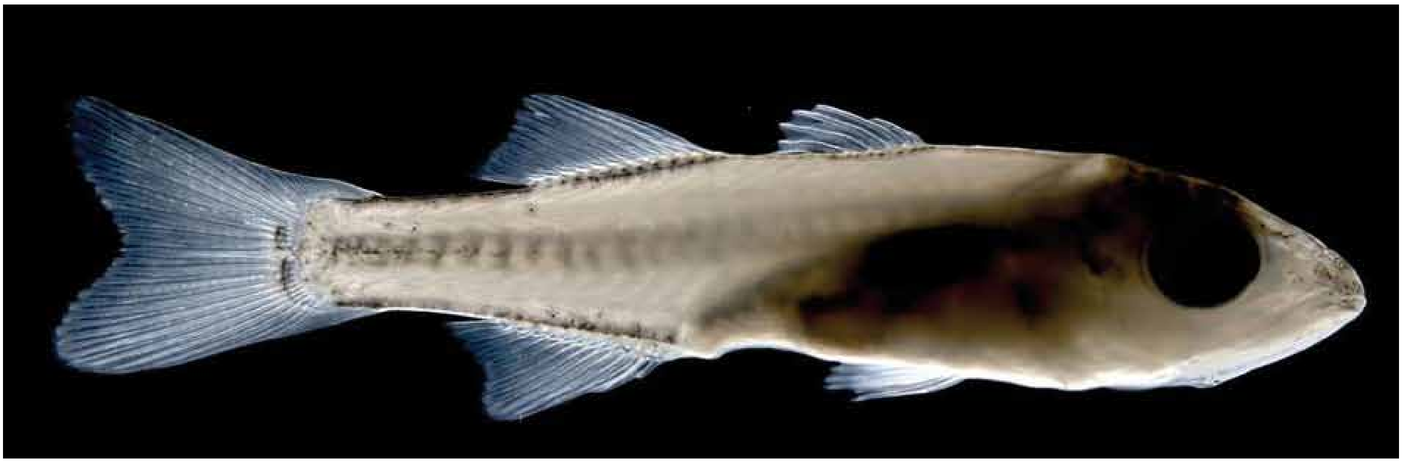
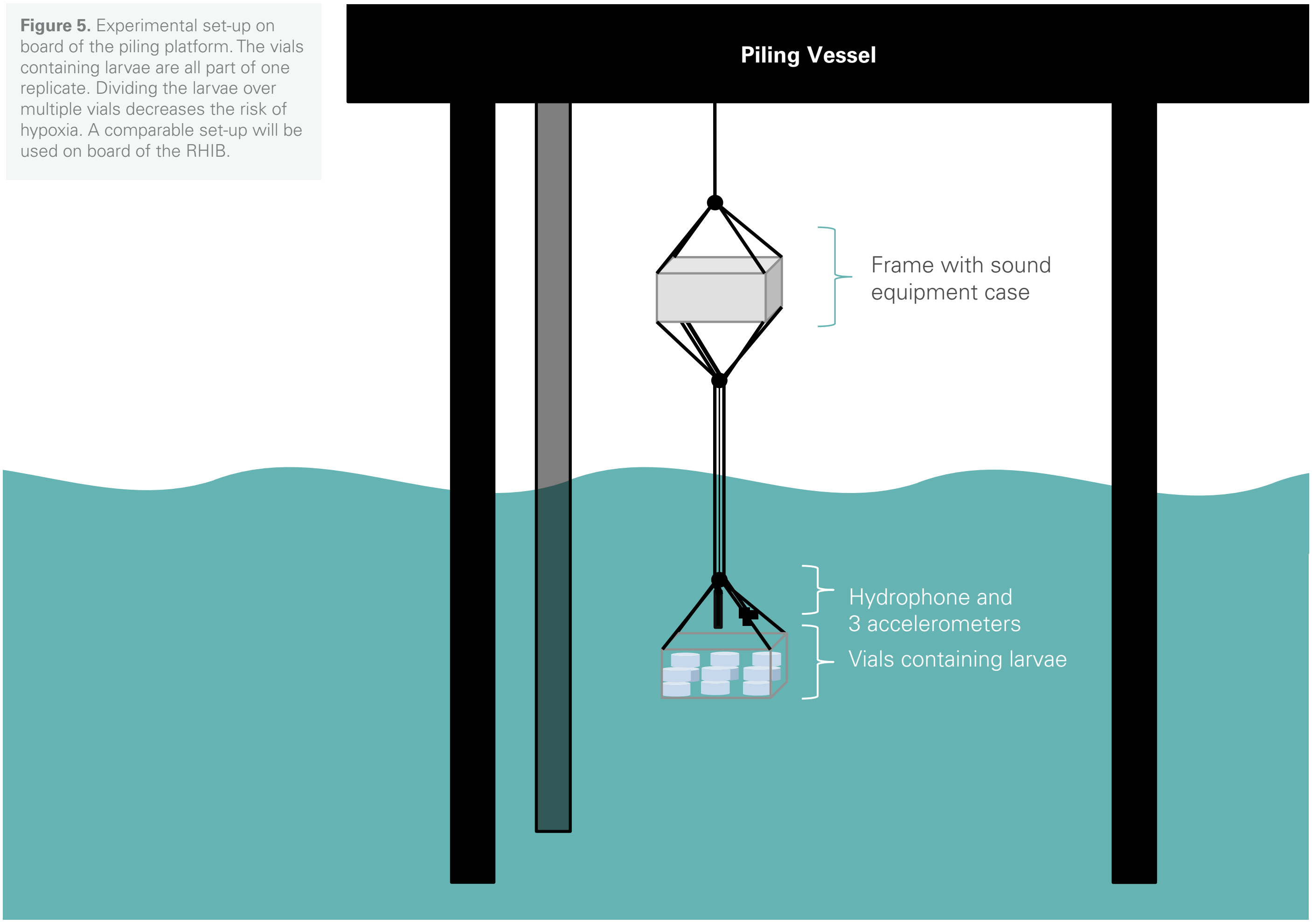
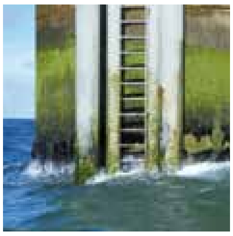
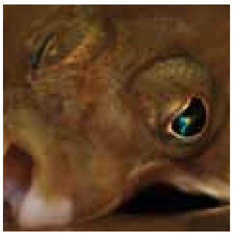


Figure 4. European sea bass *Dicentrarchus labrax* juvenile.

Figure 5. Experimental set-up on board of the piling platform. The vials containing larvae are all part of one replicate. Dividing the larvae over multiple vials decreases the risk of hypoxia. A comparable set-up will be used on board of the RHIB.



The harbour porpoise is the smallest and most common cetacean of the North Sea.

PART II

EVALUATING ANTICIPATED « POSITIVE » ENVIRONMENTAL EFFECTS

CHAPTER 8

Fisheries activities change in the vicinity of offshore wind farms

Sofie Vandendriessche, Kris Hostens, Wouter Courtens and Eric Stienen

Changes in fisheries activity in the vicinity of the wind farms were described based on Vessel Monitoring System (VMS) data of commercial vessels and ship-based survey data of recreational fishing vessels for the period 2010-2011. The VMS density maps show increases in the number of registrations north of the Thorntonbank Phase 3, west of the Thorntonbank Phase 2, and south of the operational turbines at the Bligh Bank. A slight decrease was seen south of the Thorntonbank. Concentrations of recreational fisheries activity at the wind farms were reduced in 2010-2011: observations of anglers decreased and the link with wind farms seemed mostly gone.

INTRODUCTION

In the Belgian part of the North Sea (BPNS), the construction of offshore wind farms has given rise to the establishment of areas closed to commercial fishing activity. Following such closures, different effects on both the ecosystem and on patterns of fishing activity have been observed (e.g. Murawski et al, 2000; Grizzle et al, 2009) and can therefore also be expected to manifest themselves in the BPNS. These effects comprise (1) the establishment or recovery of spawning and nursing grounds, (2) the recovery of benthic communities and diversity within the area, and (3) edge effects[1] (also known as fringe effects) along the borders resulting from displacement of fisheries activities and changes in fishing intensity (Anonymous, 2004). The latter effect can be evaluated using VMS data of trawlers and ship-based survey observations of recreational fisheries originating from the Belgian part of the North Sea.

VMS data originate from a fishing vessel monitoring system (VMS), which is a program of fisheries surveillance in which satellite transmission equipment installed on fishing vessels provides information about the vessels' position and activity. This is different from traditional monitoring methods, such as surface and aerial patrols, on-board observers, logbooks or dockside interviews. VMS data constitute a cost-effective tool for the successful monitoring, control and surveillance of fisheries activities. In this respect, they are an excellent tool for monitoring compliance with closed-area regulations and for investigating changes in fisheries distribution and effort in the vicinity of such closed areas. Since 2005, all European Community vessels automatically transmit vessel identification, date, time, position, course and speed either hourly or every 2 hours.

Recreational and small-scale fisheries (vessels <15m) are not subject to VMS surveillance. Since these fishery types have been estimated to represent a meaningful proportion of total fishing effort in the BPNS (Depestele et al, 2008; Lescrauwaet et al, 2013), other ways of estimating fishing effort by these small vessels have to be considered. In this respect , visual surveys are complementary to VMS data, since they can provide an estimate of the spatial distribution and the presence of hot spots of small scale fishing activities (Maes et al, 2005; Goffin et al, 2007; Depestele et al, 2008).

The aim of the described analysis was to investigate changes in fisheries activity in the vicinity of the existing wind farms at the BPNS based on Vessel Monitoring System (VMS) data and ship-based survey data.

[1] **Edge effects** relate to the influence that a habitat edge can have in determining species composition and processes within a habitat. Edge effects can be considered as, or to influence, patterns in biological and physical parameters such as species richness, predation, food availability, disturbance and temperature (Murcia, 1995)

Fishing vessel trawling near a wind farm

DATA SOURCES AND ANALYTICAL METHODS

Aerial and ship-based surveys show that especially Belgian and Dutch, but also French, British and Danish fishing vessels operate within the Belgian Part of the North Sea (Depestele et al, 2008). These are mostly trawlers, but gill and trammel netters, long liners and bottom seiners were also observed in the area. Recently, Belgian Vessel Monitoring System (VMS) data (2006 – 2011) have been made available by the Belgian Sea Fisheries Service[2] for scientific research related to fisheries management. British data (2007 – 2011) were made available by the British Marine Management Organization, and Dutch data (2010 – 2011) were made available by the Dutch Ministry of Economic Affairs. Danish and French data were not available, but since they mainly reflect pelagic and trammel net fisheries (Depestele et al, 2008), their absence will not have a significant impact on the results.

Since metadata about fishing gear and engine power were not available for the majority of the data, speed filters could not easily be applied and no distinction could be made between fishing, steaming or other activities. Consequently, the analysis is limited to "fishing vessel presence" rather than representing "fishing intensity". Only the results on the years 2010-2011 are presented.

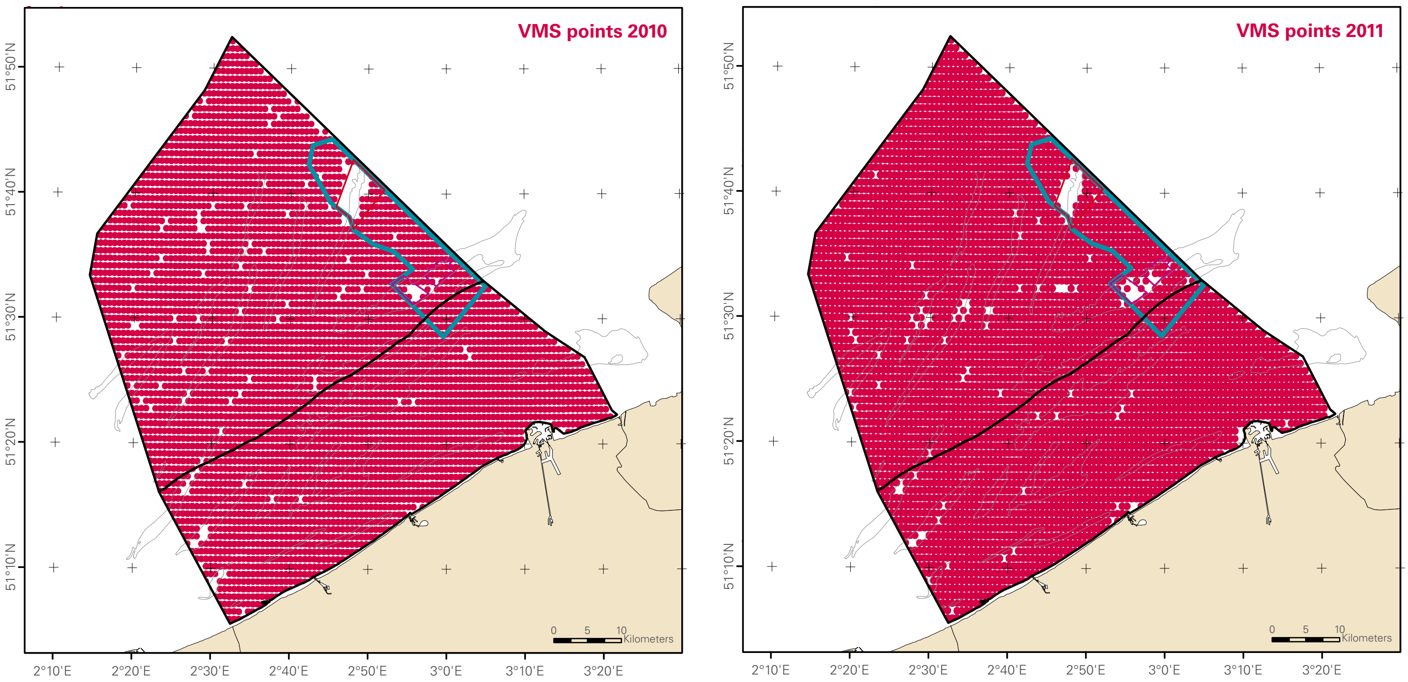
All data were plotted on BPNS maps representing the number of VMS registrations per 3 km² grid cell, since this proved to be an adequate resolution for VMS data with a 2 hour interval (Mills et al, 2007). The data were processed and visualized using Microsoft Access and ArcView 10.0 (ESRI Inc, 2010). The data on small-scale and recreational activities originate from intensive ship-based seabird surveys performed by the Research institute for Nature and Forest (INBO). During these surveys, observation records of vessels are standardized,. For more details on the methodology see chapter 5. All data were again plotted on BPNS maps per 3 km² grid cell.

[2] All primary data on vessels sailing under the Belgian flag were supplied by the Department of Agriculture and Fisheries – Sea Fisheries Service / Departement Landbouw en Visserij – Dienst Zeevisserij

RESULTS AND CONCLUSIONS

When plotting all VMS registrations on the BPNS map (Figure 1), we clearly see that fishing vessels, mostly trawlers, are virtually everywhere, except in the wind farms that are either operational or under construction. As more turbines are installed, the areas without trawlers enlarge on the map. Still, intrusions in the wind farms and their safety buffers are regularly reported (Anonymous, 2011), and are visible on the map as VMS registrations within the concessions.

Figure 1. Maps showing unprocessed VMS registrations as dots (2010-2011).



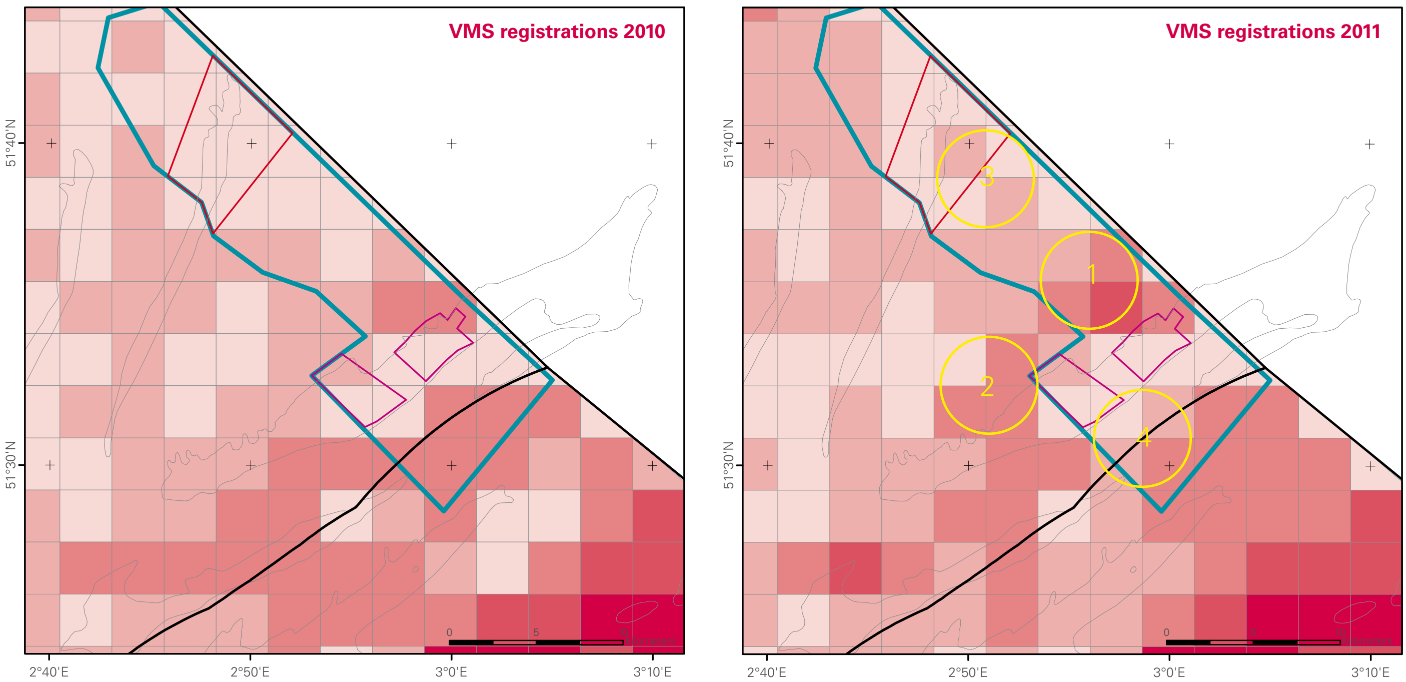
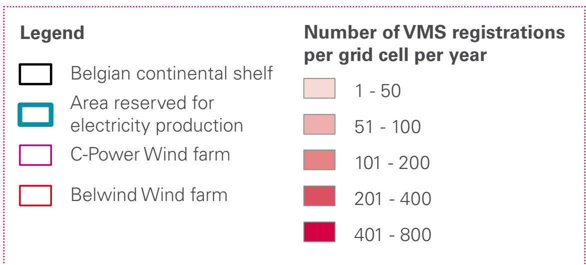


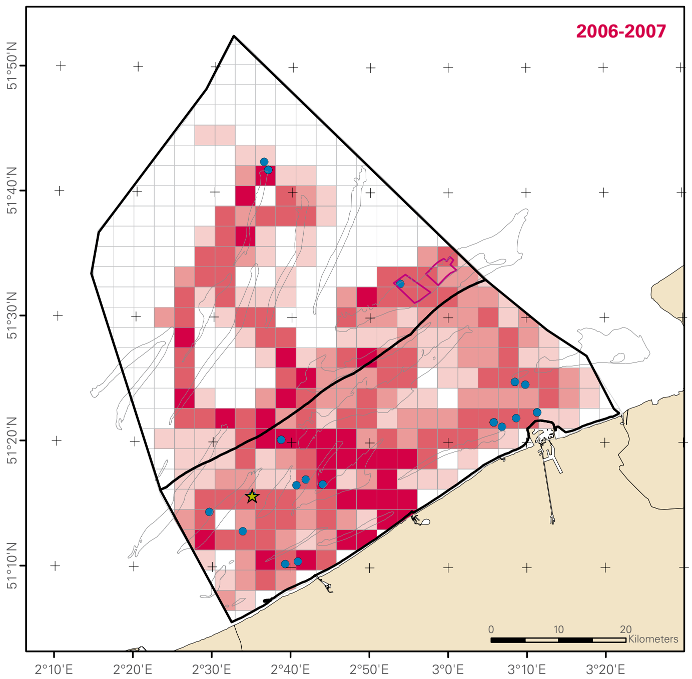
Figure 2. BPNS maps representing the number of VMS registrations per 3 km² grid cell for the years 2010-2011 for fishing vessels sailing under the Belgian, Dutch or British flag. Colors represent a gradient in numbers of VMS registrations per grid cell per year. Circles and numbers represent areas in the vicinity of the wind farms with an increase or a decrease in number of VMS registrations.

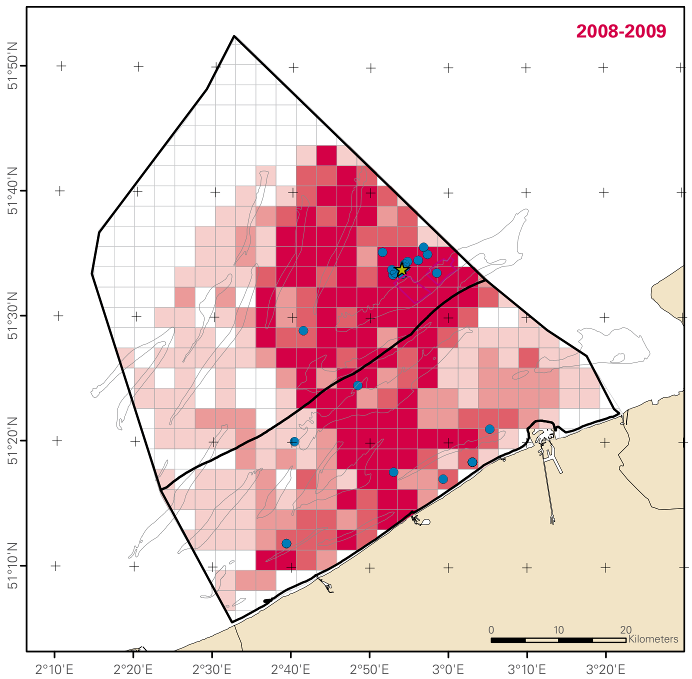


The VMS density maps show that the number of VMS registrations per grid cell generally decreases from the coast to the off shore areas. In the vicinity of the existing wind farms, some changes were observed in vessel presence between 2010 – 2011. An increase in the number of registrations can be seen north of the Thorntonbank Phase 3 (zone 1 on Figure 2, 97% increase in encircled area), for which turbines were constructed from April 2011 onwards (Brabant et al, 2012b). A similar increase was seen west of the Thorntonbank Phase 2 (zone 2 on Figure 2, 55% increase in encircled area), constructed in the same period. At the Bligh bank, a slight increase was seen south of the operational turbines (zone 3 on Figure 2, 39% increase in encircled area). A slight decrease in the number of VMS registrations was seen south of the Thorntonbank (zone 4 on Figure 2, 19% decrease in encircled area). A comparison of the data of the different flag states indicates that these changes were mostly due to the activity of Dutch vessels in the area.

The results of the current analysis and of earlier analyses based on Belgian VMS data from 2006 – 2009 (Vandendriessche et al, 2011) indicate that the presence of wind farms has an effect on the activity of fishing vessels in the area, and that the permanent closure of the concessions has resulted in a moderate increase in activity in the areas surrounding the concessions. This might either be a redistribution effect or it may indicate a local change in the availability of commercially interesting fish species. Results on the presence of demersal fish in the vicinity of wind farms (see chapter 10) showed no major differences concerning the species of commercial interest, so the observed changes in fishing vessel presence are likely the result of a redistribution process.
An increased trawling activity may result in effects with regard to soft-bottom macrobenthos, epibenthos and demersal fish, the so-called edge effects. Analysis of biological data, however, has indicated that these are minimal at present (see chapter 10).

To trace changes in small-scale and recreational fisheries in the vicinity of the wind farms, we compiled ship-based survey data from 2006 to 2011 (Figure 3). These data clearly show a concentration of recreational fisheries (mostly anglers) north of the Thorntonbank gravity based foundations in 2008-2009. This angler activity usually targets pelagic and bentho-pelagic species, of which high densities are present in the vicinity of the turbines (Reubens et al, 2010; Reubens et al, 2011). Although the intensity of surveys further increased in 2010-2011, observations of anglers decreased and the link with wind farms seemed mostly gone. This might be due to a number of reasons: the wind farms are quite far for angling day trips, there is less fish than expected, anglers have to respect a safety distance and cannot fish as close to the hard substrates and structure as with wrecks, etc. A questionnaire survey among anglers could shed light on this issue.





FUTURE MONITORING

The analysis of VMS data in the framework of wind farm monitoring so far, was either done on Belgian data, for which metadata were available, or on integrated data of different flag states, without metadata and for a limited time frame. In the first case, speed filters could be applied and métiers could be distinguished but realistic maps could not be drafted since data on foreign vessels were missing. In the second case, more realistic maps could be drafted, but no information on the activity of the vessel (fishing, steaming) and on the fishing gear could be derived. To get a complete picture of the evolution of fishing activities in relation to the Belgian wind farms, the integration of VMS data, logbook data and metadata of all vessels fishing within the study area since 2006 is required. Hence, scientists and administrators should continue to strive for an international exchange of data, taking into account confidentiality regulations and national and European laws. This can be done in the framework of the Common Information Sharing Environment (CISE) of the European Commission (EC COM 2010 584 final).

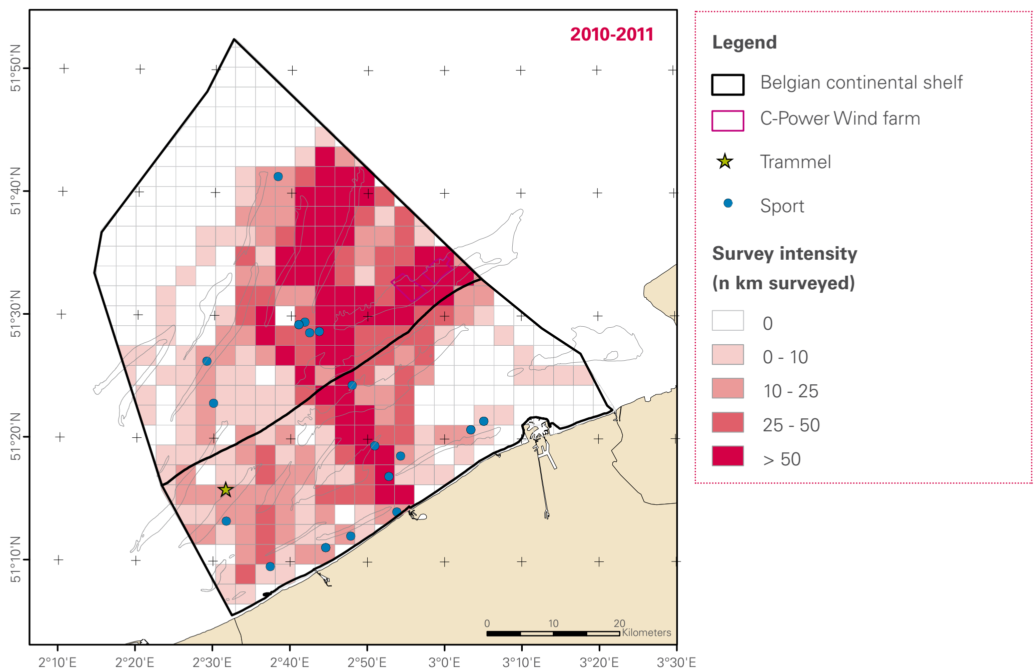


Figure 3. Point observations of trammel net activity (green stars) and recreational fisheries (blue dots) for the years 2006-2007(left), 2008-2009 (middle) and 2010-2011 (right), based on vessel observations during seabird surveys. The underlying red grid (3 km²) represents the survey intensity as the number of kilometers effectively sailed in each grid cell.

CHAPTER 9

The macrobenthic community around an offshore wind farm

Delphine Coates, Gert Van Hoey, Jan Reubens, Sarah Vanden Eede, Veronique De Maersschalck, Magda Vincx and Jan Vanaverbeke

The soft-substrate macrobenthic community was investigated at a large scale before and after construction of an offshore wind farm. To make a distinction between natural fluctuations of the macrobenthic community and construction effects of the wind farm on the macrobenthos a temporal study was carried out over 32 years followed by a detailed analysis of the monitoring data (2005-2012). A significant difference in community composition was observed between the macrobenthos of the Thorntonbank and the macrobenthic community in the control area during and just after construction, suggesting a short-term construction effect. An impact evaluation with monitoring data was also carried out using the benthic indicator BEQI.

INTRODUCTION

The soft-substrate macrobenthos (fauna larger than 1mm living in the seabed) constitute an essential link in the trophic organisation of the marine ecosystem. By being an important food source for many organisms such as demersal fish, changes within the macrobenthos could modify crucial relationships within the marine food web. Macrobenthic communities provide an ideal component for evaluating the ecological effects of offshore wind farms on the marine environment as they are mainly determined by the sedimentological and hydrodynamic characteristics of the seabed (Hiscock et al., 2004; Kunitzer et al., 1992) and therefore relatively stable in space and time. However, these communities are influenced by many natural and human induced factors such as commercial fishing, sand extraction, eutrophication and climate variability (Hiscock et al., 2004; Jennings et al., 2001; Kroncke et al., 2011). Therefore, it is essential to place monitoring data within a wider time frame and identify the long-term natural fluctuations of the occurring macrobenthic communities on the Thorntonbank and Gootebank (Van Hoey et al., 2007b).

Scientists, managers, and the industry often collaborate in order to gain knowledge concerning the effects, when implementing a certain activity, on the ecological, physico-chemical and socio-economic status of the ecosystem. To unravel the detailed patterns and cause-effect relationships of the construction of offshore wind farms, a thorough analysis of the monitoring data is carried out in this study. However, in the light of the environmental impact assessment (EIA) processes and management advice, it is necessary to have tools that provide a quick signal of the occurring changes and an alarm when an unwanted situation is reached. Therefore, indicator tools (such as BEQI, Benthic Ecosystem Quality Index [www.beqi.eu]), accompanied by threshold levels, were developed to assess the degree of impact of anthropogenic activities (Van Hoey et al., 2011).

The construction and exploitation of offshore wind farms have two direct effects on the soft sediment macrobenthos, firstly through a direct loss of its natural habitat. For example, a loss of 0.11 km² seabed was predicted for the offshore wind farm on the Thorntonbank (Ecolas, 2003). Secondly, the introduction of hard substrates in a sandy area attracts different organisms, those colonizing the foundations and those that are associated with the structures, affecting the surrounding soft substrate communities by predation or organic enrichment (Coates et al., 2012; Kerckhof et al., 2009; Krone et al., 2013a; Wilhelmsson and Malm, 2008). Anticipated secondary effects of offshore wind farms during construction (dredging activities or turbidity changes) and during the operational phase (fisheries exclusion and hydrodynamic changes), could produce an essential effect over a longer time scale. The most common commercial fishing method in Belgian waters is beam trawling, disturbing over 80% of the seabed in the Belgian Part of the North Sea (Ecolas, 2003).The exclusion of all fishery activities within the wind farm concession areas will lead to a decrease of fishery intensity (Lindeboom et al., 2011), but a possible increase of trawling along the outside border due to a displacement of fishing efforts (see chapter 8).

The key objectives of this chapter:

1. Investigating the long-term fluctuations, by a temporal analysis of the macrobenthic communities on the Thorntonbank and Gootebank. This was carried out over a period of 32 years by incorporating historical data from 1980-1998 (Marine Biology Research Group UGent and ILVO-Bioenvironmental Research group) with the monitoring data from 2005-2012.
2. Carrying out a more detailed analysis of the 2005-2012 timeframe by distinguishing different zones (eastern and western impact, control and edge zones) within the Thorntonbank and Gootebank.
3. Applying the benthic indicator BEQI (Benthic Ecosystem Quality Index) to evaluate possible changes in the characteristics (density, species composition and number of species) of the soft substrate benthic ecosystem within and around the Thorntonbank wind farm during and after construction (Van Hoey et al., 2007a).

SAMPLING AND ASSESSMENT STRATEGY

Benthic monitoring

Within the framework of the wind farm monitoring programme, sediment and macrobenthic communities were sampled with a Van Veen grab (0.1026m²) on the Thorntonbank and Gootebank between 2005 and 2012, during autumn (Figure 1). Both sandbanks are mainly characterised by coarse, sandy sediments (De Maersschalck et al., 2006) with a water depth around 20 meters. A BACI (Before After Control Impact) sampling design (Smith et al., 1993) was applied (see chapter 10 for further details) with the baseline (Year-0) monitoring carried out in 2005. The construction of six gravity based foundations was finalised in 2008. Installation of 48 jacket structures was carried out during 2011 and 2012, prohibiting sampling in 2011 and limiting sampling to the control and edge areas on the Thorntonbank in 2012. Therefore, no impact samples are available for 2011 and 2012 (Table 1).

The following macrobenthic samples were available from the Thorntonbank and Gootebank area:

- Historical data of stations (one to six stations according to the year) sampled in 1980, 1985, 1986 and 1998 (three replicates per station).
- T0 monitoring in 2005 (one replicate per station) in five different zones: Gootebank control (GC), Thorntonbank control (TC), edge (TE), eastern impact (TI E) and western impact zone (TI W).
- T1 (2008), T2 (2009), T3 (2010), T5 (2012) monitoring during and after construction in the Thorntonbank wind farm, with one or three replicates (from 2010 onwards) per station.

When analysing data over longer time periods it is essential to use a uniform dataset throughout the years. At every sampling event, the first replica was selected for every station (except for BEQI analyses, see later) for analysing the changes in macrobenthic communities over longer periods and within the monitoring programme.

Table 1. Schematic representation of the different phases of the Thorntonbank wind farm and the macrobenthic monitoring data on the Gootebank (GC), Thorntonbank control (TC), Edge (TE), eastern impact (TI E) and western impact zone (TI W). GBF = Gravity Based Foundation

Thorntonbank soft benthic windfarm monitoring data					
2005 (T_0)	**2008 (T_1)**	**2009 (T_2)**	**2010 (T_3)**	**2011 (T_4)**	**2012 (T_5)**
Baseline monitoring	Construction Phase I (6 GBF at TI W)	Operational Phase I	Operational Phase I	Construction Phases II & III	Construction & Operational Phases I - III
GC – TC – TE – TI E – TI W	GC – TC – TE – TI E – TI W	GC – TC – TE – TI E – TI W	GC – TC – TE – TI E – TI W	No monitoring data	GC – TC – TE

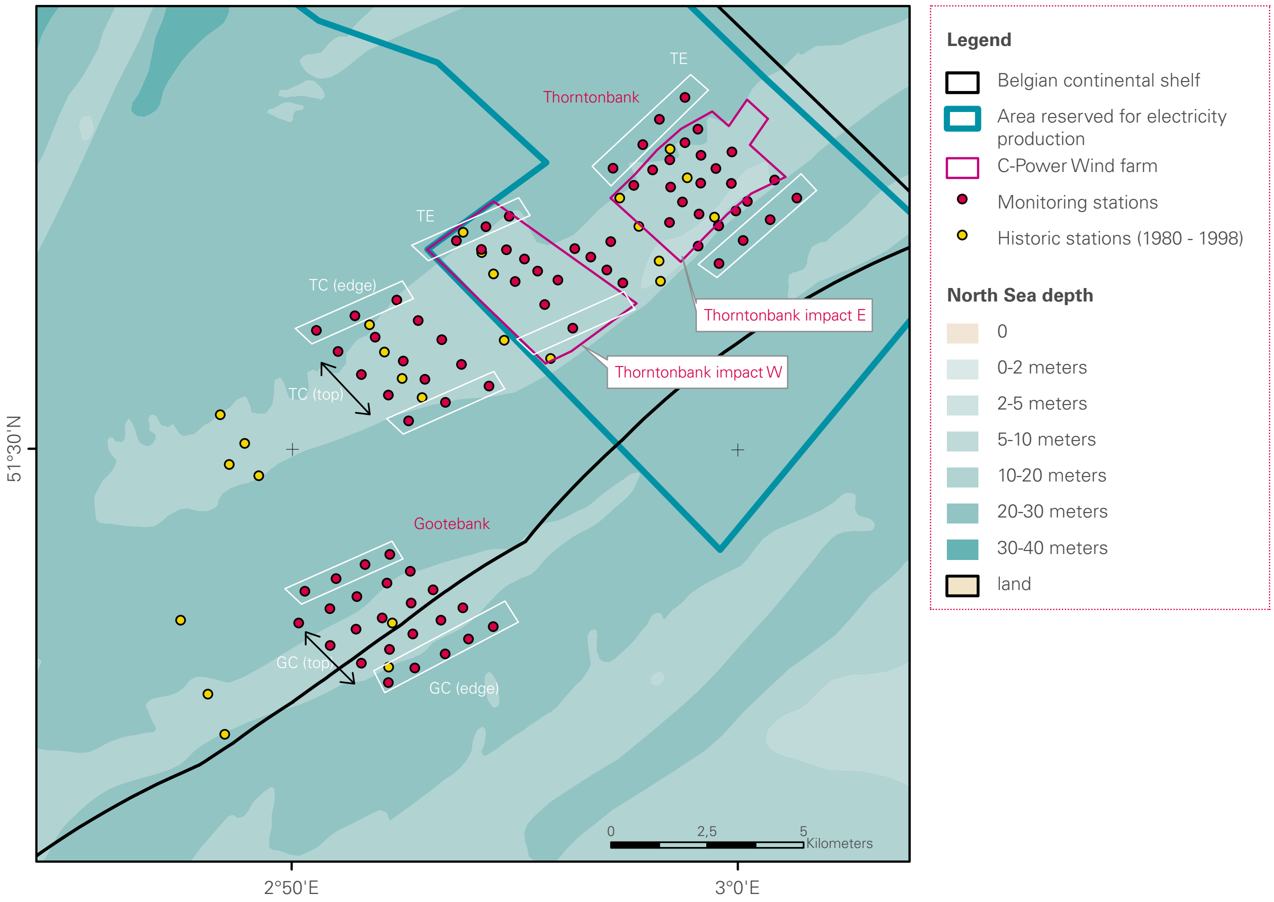


Figure 1. Large scale monitoring on the Thorntonbank with impact zones TI E (eastern), TI W (western), edge (TE) and control (TC). The Gootebank was sampled as a reference

Assessment strategy BEQI

The benthic indicator, BEQI (Benthic Ecosystem Quality Index, www.beqi.eu), evaluates the difference in macrobenthic characteristics (density, biomass, number of species and species composition) between two datasets (e.g. control versus impact). The outcome is scaled between 0 and 1 into 5 classes (bad [<0.2], poor [0.2-0.4], moderate [0.4-0.6], good [0.6-0.8], high [0.8-1]). When the BEQI value reaches a value below 0.6 (boundary between moderate and good), we judge that the difference between the two datasets (control – impact) is unwanted and a closer look to the result is advised. In order to execute a proper indicator assessment of a possible impact, it is important to take the natural variability in habitat characteristics, the statistical power and the selection of the control data into account (Van Hoey et al., 2010).
An important aspect in assessing the differences in benthic characteristics between areas is that they do not deviate naturally, due to differences in habitat characteristics (such as sediment type, depth, etc…). Therefore, different areas within the assessment design were recognised: The top of the eastern and western impact zones (concession area [TI W and TI E]), the edge of the eastern and western impact zone (the border of the concession zone [TIE W and TIE E]), a Thornton control zone ([TC], top/edge) and the Gootebank control zone ([GC], top/edge). Possible influences on the assessment outcome due to a difference in macrobenthic habitat type are minimised in this way.

For an indicator assessment, statistical power i.e. a sufficient number of samples within each pair-wise analysis (control-impact) is important for a confident assessment (Van Hoey et al., 2010). The assessment designs were therefore based on all data (three replicates per station) within each zone/period (see sampling strategy). To have sufficient control data, the data from the Thorntonbank and Gootebank control zones were analysed together. The BEQI tool assigns the confidence of the assessment based on the variability within the data into three classes: good, moderate and poor. In this study, the confidence of the assessment results are coded into following categories (Table 7): (1) the amount of impact samples are much higher (more than 3 samples) than the amount of control samples (grey), (2) two of the three analysed parameters show a moderate confidence score (cursive), (3) one of the three analysed parameters show a moderate confidence score (bold), (4) all parameters show a good confidence score (red).

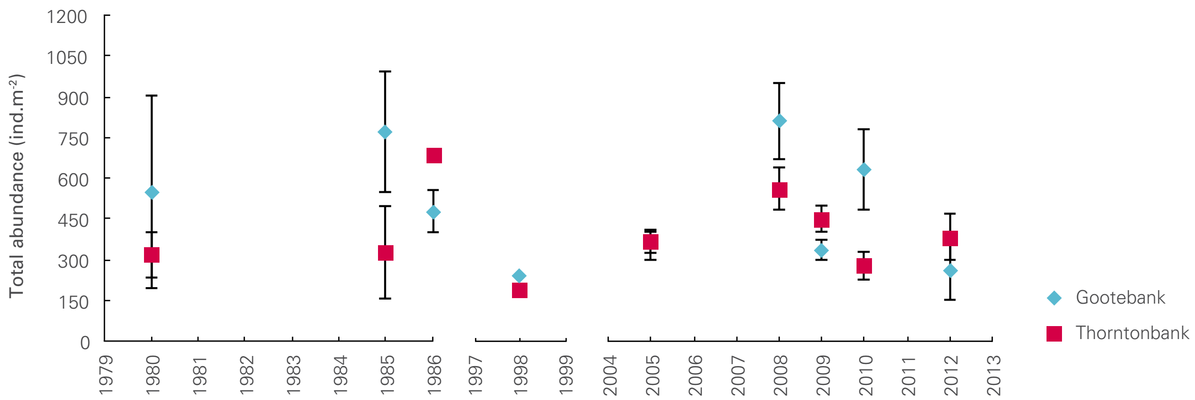
Finally, an appropriate selection of the control data is advised, because different types of control data will have an influence on the final indicator judgement (Van Hoey et al., 2013). To prove this, we used different assessment designs:

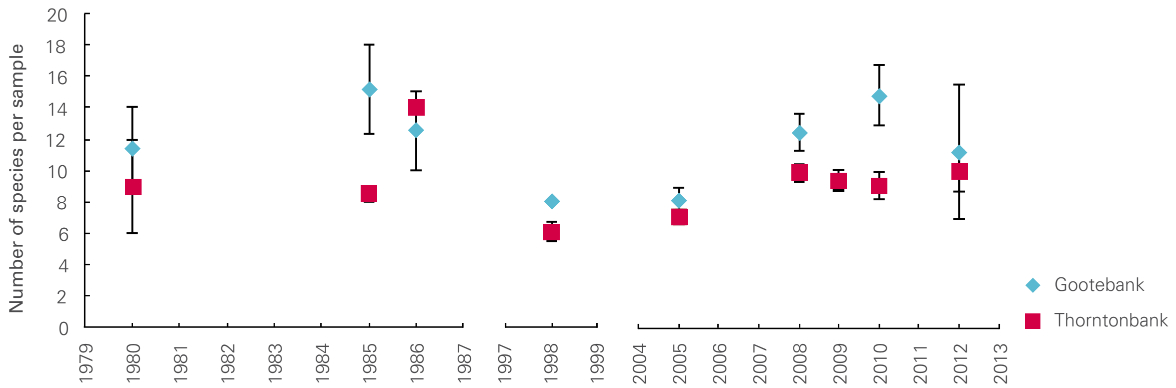
1. The benthic characteristics within the Thorntonbank impact zone (no separation between eastern and western and top and edge) are compared with the benthic characteristics in the control area (Thornton and Gootebank):
   a. Within each year
   b. Over time: control data from before 2005 and control data from 2005 (T0).
2. The benthic characteristics of the different areas (top, edge) within the two separate Thorntonbank impact zones are compared with the benthic characteristics in the respective areas (top, edge) in the control zones (Thornton and Gootebank).
   a. Within each year
   b. Over time: control data from before 2005 and control data from 2005 (T0)

LONG-TERM FLUCTUATIONS

Over a period of 32 years, the long term data of the soft-substrate macrobenthos show a clear inter-annual variability in average macrofaunal abundance on the Thorntonbank and Gootebank. Densities on the Thorntonbank reached a peak of 682 ind.m^{-2} in 1986 while the Gootebank densities showed a maximum in 2008 (812 ind.m^{-2}). Minimum values were measured for both sandbanks in 1998 with 180 ind.m^{-2} on the Thorntonbank and 244 ind.m^{-2} on the Gootebank (Figure 2, upper panel), illustrating a likely effect of the extremely cold winter temperatures and negative North Atlantic Oscillation index in 1995/1996 (Neumann et al., 2009; Reiss et al., 2006). In the baseline year of the wind farm monitoring (2005), the macrofaunal abundance was similar on both sandbanks. From 2008 onwards, the macrofaunal densities on the Gootebank showed a higher inter-annual variability in comparison to the Thorntonbank. The average number of species per sample followed the same trend with a minimum average in 1998 of six macrofaunal species per sample on the Thorntonbank and eight on the Gootebank (Figure 2, lower panel). From 2008 onwards, the inter-annual variability of the number of species with a range from 9 to 10 species on the Thorntonbank was fairly stable. In comparison to the Thorntonbank, the Gootebank illustrated an inter-annual variability with peaks in 2008 and 2010.

Figure 2. Upper panel: Average total macrobenthic abundance (ind.m^{-2}) ± standard error and lower panel: Average total number of macrobenthic species per sample ± standard error for the Thorntonbank and Gootebank from 1980 to 2012





The typical macrobenthic (*Nephtys cirrosa*) community on the Thorntonbank and Gootebank are only dominated by a few species (Table 2). Dominant species were defined as species with a mean contribution of more than 15% to the mean total density. In the time period between 1980 and 1986 the macrofaunal community on the Thorntonbank was mainly dominated by the white catworm *Nephtys cirrosa* and the mysid shrimp *Gastrosaccus spinifer*. From 1998 onwards, three species had a re-occurrence in dominance: the polychaete worms: white catworm (*N. cirrosa)* and bee spionid *(Spiophanes bombyx)* together with the amphipod *Urothoe brevicornis* (Figure 3). The dominant species on the Gootebank showed a greater inter-annual variability over the 32 years. A clear community shift occurred during the construction year in 2008 with the dominance of the opportunistic *S. bombyx* on both sandbanks. However, the dominance disappeared from 2009 onwards.

Table 2. Dominant species and their mean contribution to the mean total density in terms of percentage for the Thorntonbank and Gootebank from 1980 to 2012

	Dominant species %			
	Thorntonbank		**Gootebank**	
1980	*Nephtys cirrosa*	**20**	*Bathyporeia elegans*	**22**
	Gastrosaccus spinifer	**19**	*Nephtys cirrosa*	**13**
	Oligochaeta sp.	**16**		
1985	*Gastrosaccus spinifer*	**36**	*Scoloplos armiger*	**13**
1986	*Bathyporeia elegans*	**27**	*Ophelia borealis*	**21**
	Nephtys juvenile	**19**		
1998	*Nephtys cirrosa*	**49**	*Nephtys* juvenile	**24**
			Gastrosaccus spinifer	**20**
2005	*Nephtys cirrosa*	**33**	*Urothoe brevicornis*	**25**
	Urothoe brevicornis	**28**	*Nephtys cirrosa*	**25**
2008	*Nephtys cirrosa*	**28**	*Spiophanes bombyx*	**38**
	Spiophanes bombyx	**18**		
2009	*Nephtys cirrosa*	**39**	*Nephtys cirrosa*	**28**
2010	*Nephtys cirrosa*	**28**	*Nephtys cirrosa*	**13**
			Spio sp.	**12**
2012	*Urothoe brevicornis*	**18**	*Nephtys juvenile*	**14**
	Nephtys cirrosa	**15**	*Ophelia borealis*	**10**

Figure 3. The three most dominant species on the Thorntonbank and Gootebank

White catworm
Nephtys cirrosa

Bee spionid
Spiophanes bombyx

Urothoe brevicornis

When analysing the macrobenthic community composition between the Thorntonbank and Gootebank, a significant difference was measured from 2008 until 2010 (Table 3). The baseline situation in 2005 and all years before did not show any significant differences in community composition between the two sandbanks. In addition, the samples taken in 2012 revealed a possible evolution back to more comparable macrobenthic communities on both sandbanks. However, it should be taken into account that the impact samples within the Thorntonbank wind farm were missing in 2012.

Table 3. Differences in macrobenthic community composition between the Thorntonbank (TB) and Gootebank (GB) from 1980 to 2012. Statistically significant differences ($p<0.05$) in red and non-significant ($p>0.05$) in green (PERMANOVA)

	1980	1985	1986	1998	2005	2008	2009	2010	2012
TB vs. GB	green	green	green	green	green	red	red	red	green

WIND FARM MONITORING FROM 2005 TO 2012

To evaluate the differences measured in community composition between macrobenthic communities on the Thorntonbank and Gootebank in 2008, 2009 and 2010 (Table 3), a more in depth analysis was carried out by incorporating the different wind farm monitoring zones. There was a significant difference in macrofaunal community composition between zones from 2005 to 2009. The communities on the western impact zone (TI W), where the first six gravity based foundations were installed, only showed a significant difference with the control zones (GC and TC) and the edge zone (TE) in the construction year (2008) (Table 4). A recovery of the communities at TI W was visible in 2009 as differences were no longer significant, analogous to the baseline year in 2005. Analysis of the macrofaunal community composition based on biomass showed exactly the same results as shown in Table 4 with significant differences between TI W and GC, TC, TE in 2008. Macrobenthic communities on the eastern impact zone (TI E) showed significant differences with GC and TC in 2005 and with GC and TE in 2008 and 2009. As no construction activities were carried out in the eastern zone during this period the differences are illustrating the natural inter-annual variability in community composition between the different zones coinciding with the results in median grain size and total organic matter content (see further). From 2010 onwards no significant differences in community composition were detected (for both density and biomass) between the impact and control zones.

Table 4. Differences in macrobenthic community composition between Gootebank control (GC), Thorntonbank control (TC), edge (TE), eastern Impact (TI E), western Impact (TI W) zones from 2005 to 2012. Pairwise comparisons (PERMANOVA), with statistically significant differences ($p<0.05$) in red and non-significant ($p>0.05$) in green

		TI E	**TI W**
2005	GC	red	green
	TC	red	green
	TE	green	green
2008	GC	red	red
	TC	green	red
	TE	red	red
2009	GC	red	green
	TC	green	green
	TE	red	green

Turbines with gravity based foundations on the Thortonbank.

Dominant species showed a large inter-annual variability. In 2005, the macrofaunal communities of all zones were dominated by the white catworm *N. cirrosa* and the amphipod *U. brevicornis* (Table 5). The dominant species showed a change in 2008 with an increase of the bee spionid *S. bombyx*, possibly due to the high sand extraction activities in the area. In comparison to the control and edge zones, *N.cirrosa* showed a higher dominance (with a mean contribution of 39%) in the western Impact zone.

Table 5. Dominant species and their mean contribution to the mean total density in terms of percentage for the Gootebank control (GC), Thorntonbank control (TC), edge (TE), eastern Impact (TI E), western Impact (TI W) zones from 2005 to 2012

	2005		2008		2009		2010		2012	
	Species	**%**	**Species**	**%**	**Species**	**%**	**Species**	**%**	**Species**	**%**
GC	*Urothoe brevicornis*	25	*Spiophanes bombyx*	38	*Nephtys cirrosa*	28	*Nephtys cirrosa*	13	*Nephtys juvenile*	14
	Nephtys cirrosa	25					*Spio sp.*	12	*Ophelia borealis*	10
TC	*Urothoe brevicornis*	37	*Nephtys cirrosa*	27	*Nephtys cirrosa*	34	*Nephtys cirrosa*	22	*Urothoe brevicornis*	25
	Nephtys cirrosa	27	*Spiophanes bombyx*	17	*Spiophanes bombyx*	15	*Thia scutellata*	17	*Nephtys cirrosa*	13
TE	*Nephtys cirrosa*	30	*Nephtys cirrosa*	16	*Nephtys cirrosa*	32	*Nephtys cirrosa*	29	*Nephtys cirrosa*	16
	Urothoe brevicornis	28	*Spiophanes bombyx*	16					*Urothoe brevicornis*	15
TI E	*Nephtys cirrosa*	41	*Nephtys cirrosa*	32	*Nephtys cirrosa*	49	*Nephtys cirrosa*	29		
	Urothoe brevicornis	20	*Spiophanes bombyx*	21						
TI W	*Nephtys cirrosa*	32	*Nephtys cirrosa*	39	*Nephtys cirrosa*	42	*Nephtys cirrosa*	27		
	Urothoe brevicornis	30	*Spiophanes bombyx*	20			*Urothoe brevicornis*	19		

In 2008 and 2009, the western Impact zone on the Thorntonbank showed the lowest average number of species (6.7 ± 1.7 and 8.6 ± 0.8 respectively) in comparison to the other zones (Table 6). The average macrofaunal density was also lowest at TI W in 2008 (447 ± 207). The biomass of macrofaunal species on the Thorntonbank and Gootebank was measured after exclusion of the heart urchin *Echinocardium cordatum* as a few individuals of this species increases the average biomass of a sample considerably. The average macrofaunal biomass was lower for TI W in 2008 and 2009 compared to GC. Less pronounced differences were detected between the western impact zone and the Thorntonbank control zone stressing the importance of multiple reference areas in the monitoring design.

Over all zones, significant differences were measured in 2005 compared to 2008-2012 for the average number of species and biomass. The average macrobenthic densities showed significantly higher values in 2008 compared to the baseline in 2005.

Table 6. Average total macrobenthic abundance (ind.m^{-2}), average total species number per sample and average total biomass (mg.m^{-2}) ± standard error for the Gootebank control (GC), Thorntonbank control (TC), edge (TE), eastern Impact (TI E), western Impact (TI W) zones from 2005 to 2012

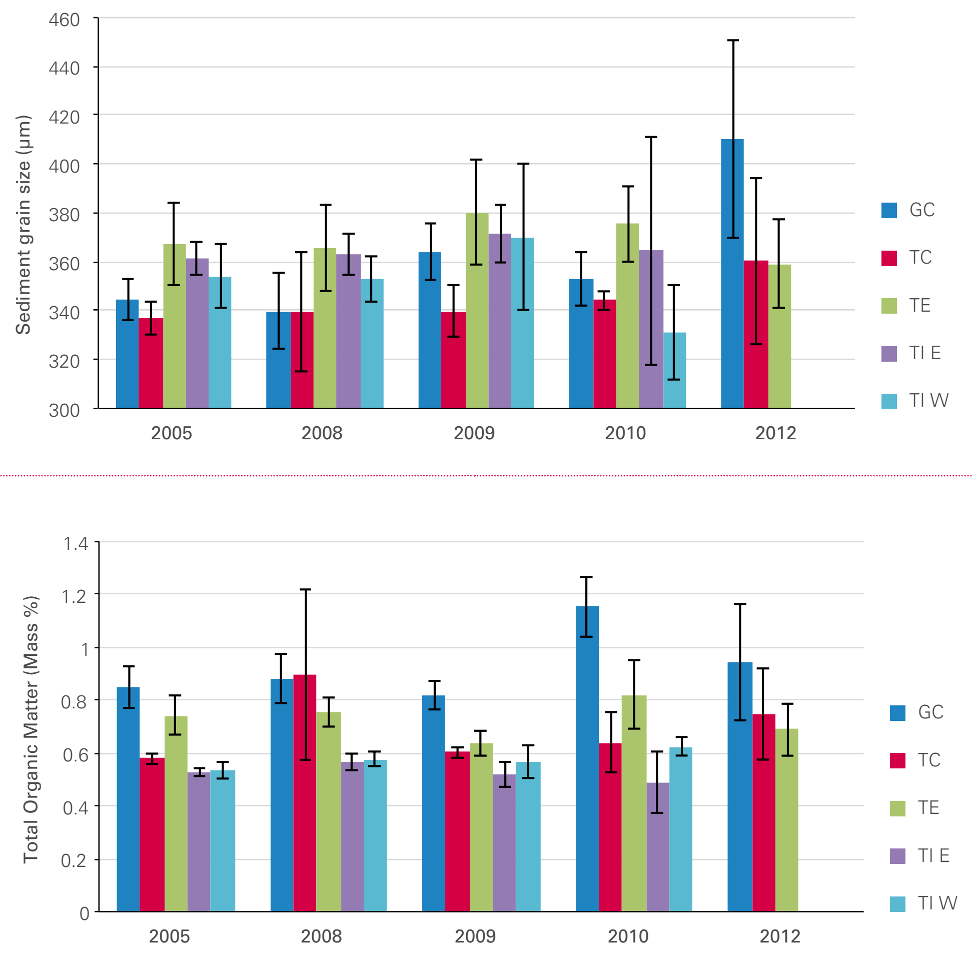
		GC	TC	TE	TI E	TI W
2005	Abundance	356 ± 57	472 ± 74	428 ± 105	231 ± 49	361 ± 67
	Species number	8.1 ± 0.9	13.0 ± 0.8	7.5 ± 1.1	5.7 ± 0.6	7.6 ± 1.1
	Biomass	690 ± 395	253 ± 100	205 ± 76	96 ± 15	164 ± 45
2008	Abundance	812 ± 141	449 ± 88	602 ± 158	661 ± 171	447 ± 207
	Species number	12.5 ± 0.7	10.1 ± 1.1	11.4 ± 1.2	9.8 ± 1.0	6.7 ± 1.7
	Biomass	2789 ± 677	1170 ± 340	3376 ± 1403	1789 ± 667	1578 ± 380
2009	Abundance	334 ± 37	555 ± 127	568 ± 126	323 ± 41	389 ± 77
	Species number	9.4 ± 0.7	9.7 ± 0.9	10.4 ± 1.1	8.7 ± 0.8	8.6 ± 0.8
	Biomass	958 ± 160	1471 ± 344	1002 ± 144	1515 ± 317	694 ± 104
2010	Abundance	630 ± 149	246 ± 98	279 ± 77	249 ± 112	356 ± 83
	Species number	14.8 ± 2.0	9.3 ± 3.0	8.7 ± 1.1	9.0 ± 3.0	11.5 ± 1.5
	Biomass	3294 ± 725	951 ± 265	1118 ± 265	886 ± 21	2495 ± 1676
2012	Abundance	261 ± 108	314 ± 128	410 ± 110	/	/
	Species number	11.3 ± 4.3	10.3 ± 1.7	9.9 ± 1.8	/	/
	Biomass	816 ± 152	1002 ± 203	758 ± 162	/	/

In the western impact zone, a significant effect on the soft-substrate macrobenthic community composition of the construction in 2008 was observed with a short-term decline in species richness and abundance in comparison to the control sites. At the end of 2007 and the first half of 2008, many preparation activities were carried out on the seabed of the Thorntonbank before the actual construction of the six turbines could start in the western zone. At a large scale, the main effect on the soft-substrate characteristics and relating communities will have been the dredging of the top loose sand layer and replacement with a gravel foundation (Brabant and Jacques, 2010). The control, edge and west concession zones on the Thorntonbank were also extensively subjected to sand extraction activities in 2008 with a total extraction volume of 37.550 m³ in comparison to 2.078 m³ in 2005 (FODeconomie, 2008). A local resuspension of fine sediment particles in the water column due to pre-construction activities could temporary obstruct filtration mechanisms of benthic species and prevent growth (Hiscock et al., 2002; Zucco et al., 2006). Sediment deposition onto the seabed could have had lethal effects to certain species declining species richness and significantly, but temporary, altering the benthic community in 2008. Previous studies have illustrated similar effects on benthic species as a result of the physical disturbance of pipeline construction activities with a full recovery after two to three years (Bernem, 1999).

Even though it is a fact that the Thorntonbank was subjected to mass industrial activities disturbing the seabed and its macrobenthic community during 2008, this was not significantly detected in the sedimentological measurements. The Thorntonbank and Gootebank are mainly characterised by coarse, sandy sediments with a grain size between 250 and 500µm (medium sands) (De Maersschalck et al., 2006). The average grain sizes from 2005 to 2012 ranged between 331 ± 20 µm and 410 ± 41µm with no significant differences between years or wind farm zones. For most years, including the baseline in 2005, a trend to higher average grain sizes at the eastern and western impact zones was measured in comparison to both control zones (Figure 4, upper panel). The main disturbance to the seabed was at the end of 2007 and the beginning of 2008, while the sampling was carried out during the autumn of 2008. These results suggest a limited change to the actual grain size of the seabed after the construction activities.

The total organic matter (TOM %) was measured as a second environmental variable. Lowest TOM percentages were always measured in the impact zones of the Thorntonbank with a minimum of 0.49 ± 0.12 % in 2010 at the eastern impact zone (Figure 4, lower panel). Higher TOM values were measured on the Gootebank with a maximum in 2010 of 1.15 ± 0.11 %. Within years, significant differences were measured between zones in 2005 and 2009. In 2005, these differences were measured between the Gootebank and TC, TI E and TI W as within the Thorntonbank zones themselves suggesting an existing natural difference between areas from the baseline study onwards. In 2009, only a significant difference was measured between the Gootebank and all four Thorntonbank zones.

Figure 4. Average median grain size (µm) (upper panel) and average total Organic Matter (Mass %) ± standard error (Lower panel) for the Gootebank control (GC), Thorntonbank control (TC), edge (TE), eastern Impact (TI E), western Impact (TI W) zones from 2005 to 2012



THE BENTHIC INDICATOR BEQI: A QUICK TOOL TO PICK UP SIGNALS OF CHANGES?

The applicability of BEQI in detecting significant changes in the soft-substrate macrobenthic ecosystem within and around the Thorntonbank wind farm was tested on abundance, species number and species composition. The average BEQI scores and the accompanying status (Table 7) classified the status in most periods and designs as good. Hence, there were no big differences between the benthic characteristics in the control and impact area. In other words, the differences fell within the expected natural variability within that area and year. Only in 2008 and for the edge area of the western impact zone in 2010 and 2012 certain designs indicated a moderate status. When the average BEQI scores were compared over the different years, the lowest values were measured in 2008. These observations can alert scientists and managers that an effect on the soft-substrate macrobenthic community was observed during the construction period.

In 2008, the six gravity based turbines were installed together with the displacement of sediments within the Thorntonbank impact zone. This activity could have influenced the macrobenthic characteristics in 2008, explaining why the macrobenthic community from the impact zone has deviated from the control in comparison to other years. Surprisingly, the changes were most obvious in the eastern impact zone (top and/or edge), not directly nearby the six turbines. Data from the top of the impact zone of the Thorntonbank are missing for years 2011 and 2012, preventing a direct impact assessment of this activity.

The moderate status scores in the western impact (edge) zone in most years (2008, but especially 2010, 2012) can be indications of local changes in benthic characteristics compared to what is expected from the edge areas in the control zones. Driving forces could have been the presence and construction of the turbines in that area and the possibility that fishing efforts could have increased around the closed concession zone (Vandendriessche et al., 2011).

Table 7. Average BEQI results for each design/period. Values in grey (design not appropriate), italic (power moderate for 2 parameters), bold (power moderate for density parameter) and red (adequate power). Status codes: blue: high status; green: good status; yellow: moderate status; orange: poor status

Design	Control	Area	Zone	2008	2009	2010	2012
1a	within year	Thornton impact zone	Top + Edge	**0.628**	**0.802**	**0.695**	0.698
1b	<2005	Thornton impact zone	Top + Edge	0.553	0.743	0.676	0.677
1b	2005	Thornton impact zone	Top + Edge	0.611	0.708	0.637	0.664
2a	within year	Eastern impact zone	Top	0.628	0.731	0.764	
2b	<2005	Eastern impact zone	Top	0.588	0.687	**0.607**	
2b	2005	Eastern impact zone	Top	0.542	0.764	**0.691**	
2a	within year	Western impact zone	Top	**0.674**	0.789	0.653	
2b	<2005	Western impact zone	Top	**0.618**	**0.716**	**0.728**	
2b	2005	Western impact zone	Top	**0.676**	0.697	**0.769**	
2a	within year	Eastern impact zone	Edge	**0.666**	**0.701**	0.641	0.713
2b	<2005	Eastern impact zone	Edge	0.57	**0.608**	0.625	0.699
2b	2005	Eastern impact zone	Edge	0.598	0.636	0.6	0.699
2a	within year	Western impact zone	Edge	**0.45**	**0.671**	0.44	*0.414*
2b	<2005	Western impact zone	Edge	*0.616*	*0.609*	0.538	*0.511*
2b	2005	Western impact zone	Edge	0.609	**0.625**	0.576	*0.524*

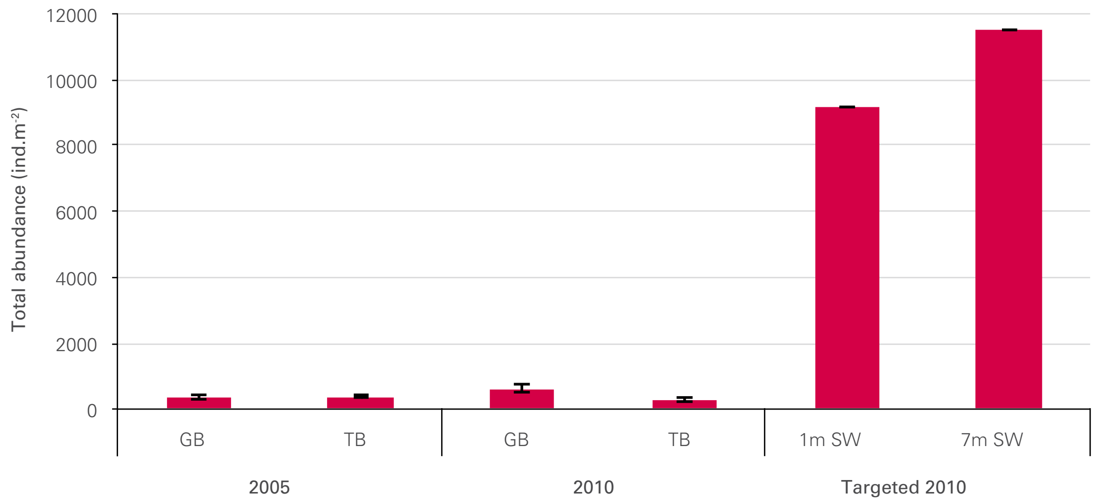
Table 7 illustrates the small differences in results between analyse designs (control dataset, or pooling of data), but shows some consistent patterns. Two aspects are essential in this type of analysis. Firstly, the choice of the control data, where we used three sets in this study: (1) data from the same year in an area outside the possible impact area, (2) data from the T0 situation (year 2005) or (3) 'historic' data from the location (from before 2005). In general, the analysis with control data within the year reveals slightly higher EQR values, compared to the use of temporal control datasets. This can be related to the fact that benthic characteristics show a year-to-year variability and therefore influence the assessment results. In the case of the selection of a temporal control dataset, it is also more appropriate to use a control dataset that contains different years. In this way, the temporal variability is reflected better and one year success of certain species is excluded.

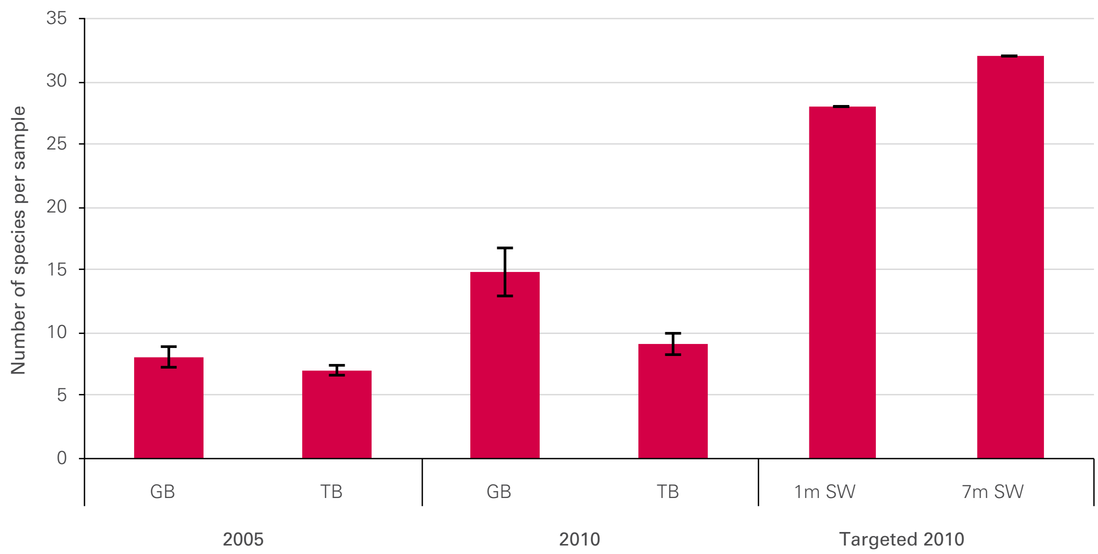
A second aspect that determines the results of an indicator analysis is the amount of samples available in the control/impact design. As outlined in Table 7, there are cases where the power of the indicator analysis was too low, due to a (very) low amount of impact samples or due to a lower amount of control samples compared to the amount of impact samples. The latest design is also unwanted; due to a lower amount of samples, the higher species richness observed is the result of sampling effort and not the natural situation of the macrobenthic community.

OVERALL CONCLUSIONS AFTER THE FIRST MONITORING PHASE

After the construction of six gravity based foundations in the western impact zone of the Thorntonbank in 2008, a temporary change in macrobenthic community composition was detected. Since then, the community has been recovering from the impact of installation activities. These results were confirmed through the assessment with the benthic indicator BEQI.
During the second and third construction phases of the jacket foundations in 2011 no monitoring samples could be obtained due to the exclusion of the research vessel within the whole Thorntonbank area. The results of the first monitoring phase illustrate the utmost importance of collecting samples during or straight after construction to determine the direct effects of any works carried out. The missing impact samples in 2011 and 2012 also make an assessment of the closure to fisheries within the wind farm difficult. However, during both years, samples were taken inside a second (but younger) wind farm on the Bligh Bank providing us with additional information on these missing links. Additionally, the BEQI indicator analyses illustrated some minor effects on the benthic characteristics at the edge of the sandbanks.
So far, no large-scale, immediate effects of the operational phase of the wind farm were detected. In Figure 5, a comparison is made between samples taken for the baseline in 2005, the large scale monitoring in 2010 and a smaller scale monitoring around one gravity based foundation in 2010 (see chapter 13). Total macrobenthic densities and number of species between the baseline year-0 in 2005 and after construction in 2010 fluctuate within the same range. However, the total macrobenthic densities, number of species and even biomass drastically increase in direct vicinity around one of the gravity based foundations and this sometimes up to a 50 meter distance (Coates et al., 2011; Coates et al., 2012). This substantial effect is handled in depth in chapter 13 but does show that direct effects of the operational phase on the macrobenthic communities are apparent but that it is possibly too early to detect these effects at a larger scale.

Figure 5. Upper panel: Average total macrobenthic abundance (ind.m-2) ± standard error and lower panel: Average total number of macrobenthic species per sample ± standard error for the large scale monitoring on the Thorntonbank (TB) and Gootebank (GB) in 2005 and 2010 and the targeted monitoring at 1 and 7m on a Southwest gradient around a gravity based foundation in 2010 (Chapter 13)





FUTURE MONITORING

It is of upmost importance to collect samples within every designated area including the impact zone straight after construction of any future offshore wind farm. Any direct or indirect effects at a large scale and over longer periods can then be detected more accurately. Nevertheless, in this study, the macrobenthos showed a recovery potential and the ability to adapt to new conditions.
Therefore, we advise to take following aspects into account, especially in function of an impact evaluation with benthic indicators:

- The same number (or more) of control samples and impact samples should be taken. A well-balanced amount for both areas should be defined, to have an adequate assessment power.
- If a temporal control dataset is needed, it is advisable to have a good spread of the amount of samples over time and have a relevant timescale. A T0 of one year does not seem ideal in this case.

Sieving collected sediments

CHAPTER 10

Between the turbines: soft substrate epibenthos and fish

Sofie Vandendriessche, Jozefien Derweduwen and Kris Hostens

With the construction of wind farms, new hard substrates are introduced in the marine environment. The sediment between the turbine rows and around the wind farms, however, remains soft. Still, the inhabiting fauna can be influenced by the presence of the turbines (reef effect) in the wind farm and the absence of fisheries (refugium effect). These effects were investigated for epibenthos, demersal fish and benthopelagic fish in the Thorntonbank and Bligh Bank wind farms. The analyses revealed some wind farm effects, but they were not consistent between wind farms. Fringe effects could not be shown.

INTRODUCTION

Since the start of offshore wind farm construction in Europe, a number of studies have described the reef effects of the new hard substrates on epibenthic fauna and on demersal and benthopelagic fish in their close vicinity (e.g. Wilhelmsson et al., 2006; Andersson et al., 2009; Reubens et al., 2011; Bergström et al., 2013; Reubens et al., 2013a). The sediment of the space between the turbines and their scour protection layers, however, remains soft. Still, the inhabiting fauna can be influenced by the presence of the turbines in the wind farm and the absence of fisheries (fisheries exclusion is in force in most European wind farms).
Wind farm effects include (1) depletion of phytoplankton by high densities of filtrating organisms on and around the turbine, which can negatively affect growth of filter feeders on the seabed (2) input of organic material from organisms associated with the turbines, as well as entrapment of material by the turbines, which could enrich the seabed and enhance abundances of deposit-feeding organisms, and in turn benefit predators on these, (3) predation by fish and crabs associated with the turbines, which could negatively affect abundances of prey species and (4) a reef effect enhancing abundances of pelagic fish species, and attracting flatfishes to the reef (Wilhelmsson et al., 2006; Andersson et al., 2009; Wilhelmsson et al., 2009). Additionally, underwater noise, vibrations and electromagnetic fields can cause disturbance and can influence the resident fauna (Wahlberg and Westerberg, 2005; Petersen and Malm, 2006; see also chapter 6).
The exclusion of fisheries activities from wind farms and their safety buffers may have positive effects within the closed areas (e.g. Jaworski et al., 2006), but also negative effects outside the wind farm borders due to a local reallocation of fishing effort (Berkenhagen et al., 2010). The effects of such reallocations on fauna inhabiting soft substrates are known as edge or fringe effects (see chapter 8).
The most detailed studies on soft substrate epibenthos and/or fish in wind farms have been carried out in Denmark, in the UK and in The Netherlands, but at different time scales and with different designs and sampling techniques. In Denmark, gill nets were combined with dredges and hydro-acoustics between turbines at distances up to 230m (Leonhard et al., 2011). The results showed changes in the fish abundances and community and in species diversity. Seven years after construction, small scale effects of single turbines were obvious, but impact effects on the wind farm scale could not be discerned from large scale population impacts. Van Deurs et al. (2013) focused on sandeels, for which negative effects on juveniles were observed. In the Netherlands (Lindeboom et al., 2011), short-term (2 years) monitoring results indicated no effects on the benthos in the sandy area between the OWEZ turbines, and only minor effects upon fish assemblages, especially near the turbines. At distances about 200 m from the turbines, there was an increase of sole, whiting and striped red mullet and a decrease of lesser weever in the wind farm in comparison to the reference areas. At the North Hoyle wind farm in the UK (Anonymous, 2005), there was no evidence of any major changes to invertebrate or fish numbers and distribution, based on trawl samples taken during the construction phase.

As in most European wind farms, the already constructed wind farms at the Thorntonbank and the Bligh Bank constitute patches of hard substrate on a seafloor dominated by sandy sediments. In the present study, we investigated whether the soft substrate epibenthos, demersal fish and benthopelagic fish living between the turbines and at the edges of the Thorntonbank and Bligh Bank wind farms have changed due to wind farm and fringe effects.

MONITORING DESIGN

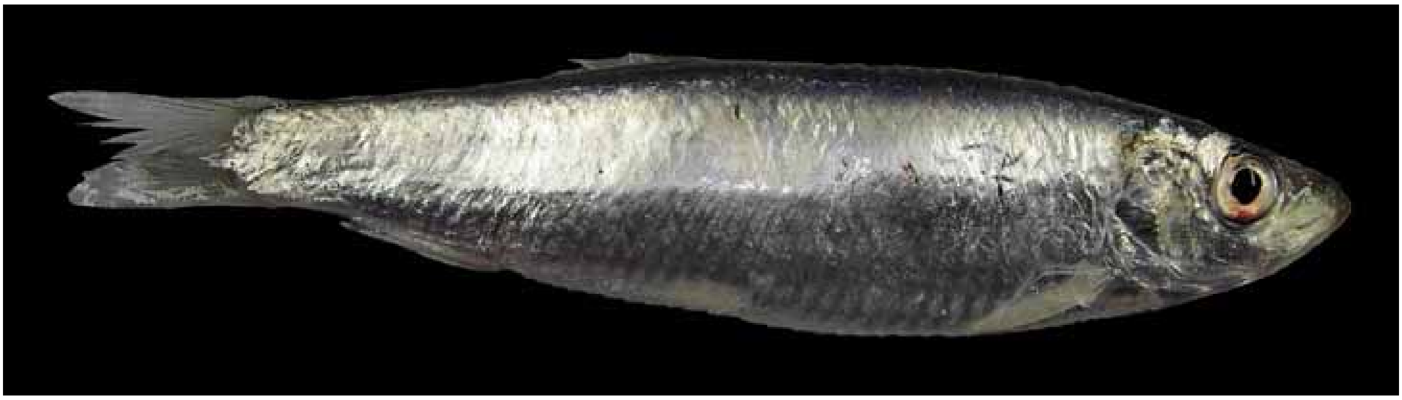
To study wind farm effects and fringe effects on the soft substrate fauna, trawl samples were taken within the wind farms, and more precisely between the turbine rows (at least 180m from the nearest turbine), just outside the edges of the concessions (fringe stations), and at reference stations well away of the concessions (Figure 1). On these track locations, fish fauna and epibenthos were sampled with an 8-meter shrimp trawl (22 mm mesh in the cod end) equipped with a bolder-chain. The net was towed during 15 minutes at an average speed of 4 knots. Data on time, start and stop coordinates, trajectory and sampling depth were noted to enable a correct conversion towards sampled surface units. The fish tracks were positioned following depth contours that run parallel to the coastline, thereby minimizing the depth variation within a single track. These sampling activities were repeated every six months (February-March and September-October) from 2005 to 2012 at the Thorntonbank (for construction periods, see chapter 2), and from 2008 to 2012 at the Bligh Bank (for construction periods, see chapter 2). From these samples, epifauna, demersal fish and benthopelagic fish were analysed in detail (see box 1). From 2005 onwards, the sampling design was adapted based on monitoring results and wind farm accessibility.

BOX 1: ecosystem components

Epifauna: fauna that live on a surface, such as the sea floor, other organisms, or objects. Epifauna of soft substrates are animals that live on the surface of sandy and muddy sediments, and include bivalves, snails, starfish, ophiuroids, shrimps and crabs.

Demersal fish: fish that live and feed on or near the bottom. These include flatfish such as sole and plaice, and small non-commercial species such as lesser weever and the reticulated dragonet.

Benthopelagic fish: fish that inhabit the water just above the bottom, feeding on benthos and zooplankton. These include whiting, pouting, herring, sprat and horse mackerel.



Pictures in Box1:
Common sea star *(Asterias rubens)*
Sole *(Solea solea)*
Sprat *(Sprattus sprattus)*

Figure 1. BACI sampling design showing trawl locations before construction and after construction (2012)

We tested wind farm and fringe effects for three ecosystem components (demersal fish, benthopelagic fish, epibenthos), for two seasons (autumn and spring), for two sandbank habitats (Thorntonbank and Bligh Bank) and for two subhabitats (sandbanks and gullies). Test were done on density, biomass and diversity data per ecosystem component, on community structure per ecosystem component, and on densities and size-frequencies of a selection of species.

The statistical analyses were based on the "Before After Control Impact" (BACI) design (Smith et al., 1993, see BOX 2), similar to the studies of van Deurs et al. (2013) and Leonhard et al. (2011). Since the number of years in the "after" group (i.e. years after construction) is still limited for parts of the wind farms (the jacket foundations of the Thorntonbank wind farm were constructed between 2011 and 2013) and since the BACI design does not easily pick up temporary effects, we also checked for differences between control and impact samples within particular years. The number of trawl samples included in the BACI design tests is given in table 1. Differences between treatment groups over the years were visualized using time evolution graphs. Non-parallelism in the trend lines (control versus impact) were interpreted as a possible sign of environmental impact.

				BC	BI	AC	AI
Thorntonbank	spring	wind farm effect	top	5	7	7	8
			gully	7	2	10	2
		fringe effect	gully	7	4	10	8
	autumn	wind farm effect	top	4	5	9	15
			gully	4	1	2	13
		fringe effect	gully	4	2	13	11
Bligh Bank	spring	wind farm effect	top	2	2	6	2
			gully	8	2	12	4
		fringe effect	gully	8	4	12	4
	autumn	wind farm effect	top	2	1	8	5
			gully	7	2	16	5
		fringe effect	gully	7	2	16	8

Table 1. Indication of the number of trawl samples included in each BACI test per treatment (BC: Before-Control; BI: Before-Impact; AC: After-Control; AI: After-Impact)

BOX 2: before after control impact – BACI

The BACI design describes an experimental approach and analytical method to trace environmental effects from substantial man-made changes to the environment. The aim of the method is to estimate the state of the environment before and after (BA) any change and further to compare changes at reference sites (or control sites) with the actual area of impact (wind farm area) (CI). In this approach, an impact, if it exists, can be detected as a statistical interaction in the difference between the impacted and control locations from before to after the disturbance. Graphically, evidence of an environmental impact is the non-parallelism of the response between the control and the treatment sites. In the figure to the right (Schwarz, 1998), the results in the first row above both show no environmental impact; the results in the bottom row all show evidence of an environmental impact.

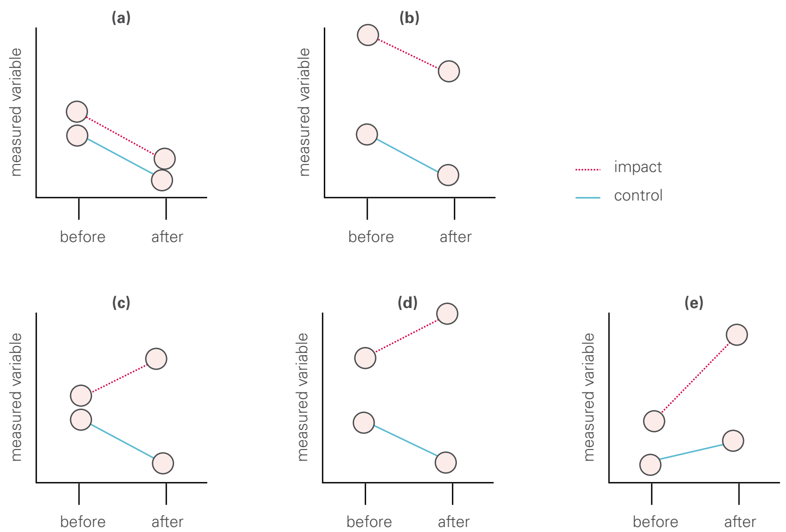


Figure 2. Summary of the results of the statistical analyses. Red text indicates significant effects (p<0.05) of the BACI interaction term. Blue text indicates significant CI effects within specific years (BACI effect not significant). Arrows indicate increase or decrease.

		THORNTONBANK WIND FARM					
		Spring			Autumm		
		Wind farm effect		Fringe effect	Wind farm effect		Fringe effect
		top	gully	gully	top	gully	gully
COMMUNITY LEVEL	Density						
	Biomass			epibenthos (BACI) ↑	epibenthos (2009) ↑		
	Species number					demersal fish (2008) ↓	
	Species composition						
SPECIES LEVEL	Density						
	Mean lenghth			whiting (BACI) ↑	dab (2011) ↓		

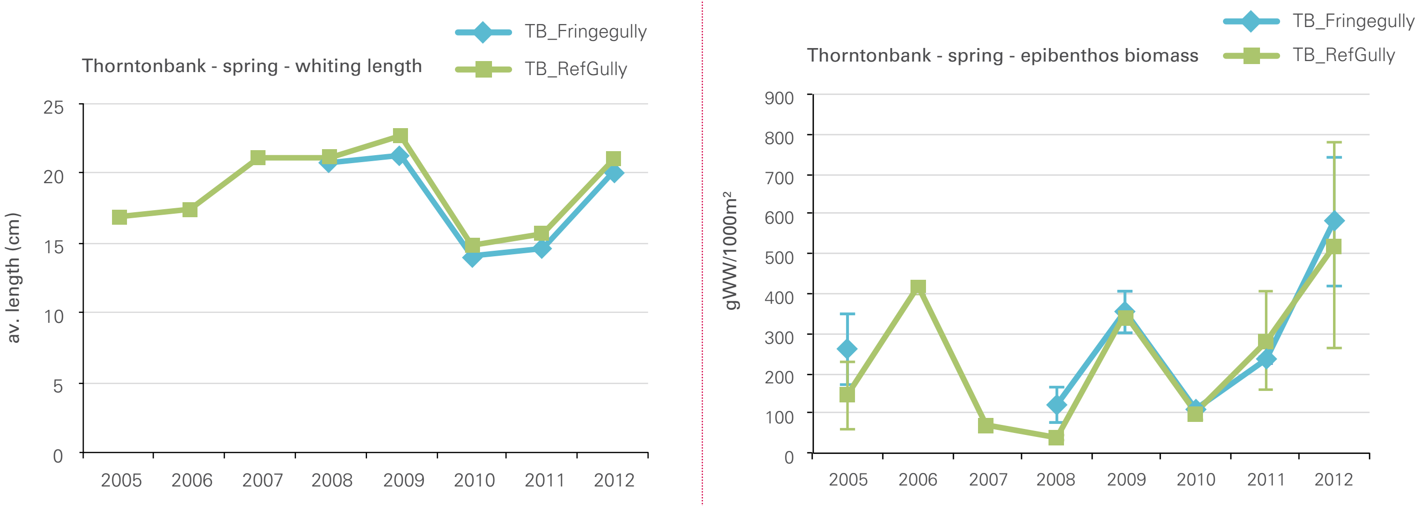
		BLIGH BANK WIND FARM					
		Spring			Autumm		
		Wind farm effect		Fringe effect	Wind farm effect		Fringe effect
		top	gully	gully	top	gully	gully
COMMUNITY LEVEL	Density						
	Biomass	epibenthos (BACI) ↑			epibenthos (BACI) ↑		
	Species number						
	Species composition					demersal fish (2012)	
SPECIES LEVEL	Density	Sea star, sole (BACI) ↑		sole (2012), dab (2012) ↑	sole (2012), dab (2012) ↑	sandeel (2012), ophiuroids (2009), urchin (2009) ↓	
	Mean lenghth						

FRINGE EFFECTS

Thorntonbank

Two significant fringe effects were observed at the Thorntonbank: increase of epibenthos biomass and whiting length (Figure 2). However, analysis of these results together with time series graphs and length frequency results (not shown) suggests that the differences were minor.

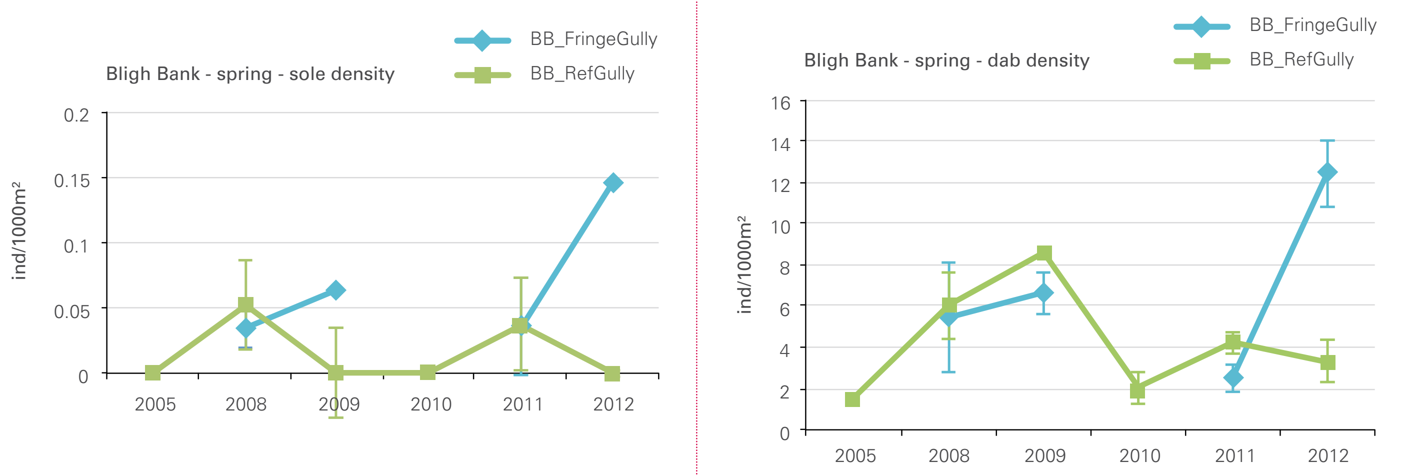
Figure 3. Time series graphs of whiting length (average length in cm ± SE) and epibenthos biomass (average g wet weight per 1000m² of seafloor ± SE) at the Thorntonbank in spring



Bligh Bank

At the Bligh bank wind farm, effects between fringe and control stations were only seen for sole (*Solea solea*) and dab *(Limanda limanda)* densities in spring 2012 (Figure 2 and 4). In both cases, the non-parallelisms between fringe and reference stations were striking and higher densities were observed in the fringe stations. However, these differences did not result in a BACI effect, so they might be either temporary or the first signs of a persistent fringe effect. These results indicate that fringe effects just outside the wind farm concessions could not be shown at this time.

Figure 4. Time series graphs of sole density (average number of individuals per 1000m² ± SE) and dab density at the Bligh Bank in spring

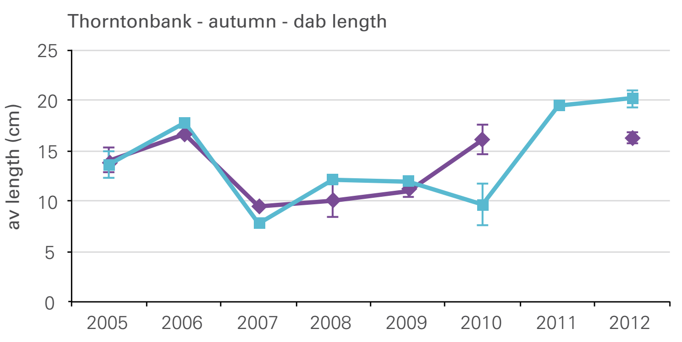


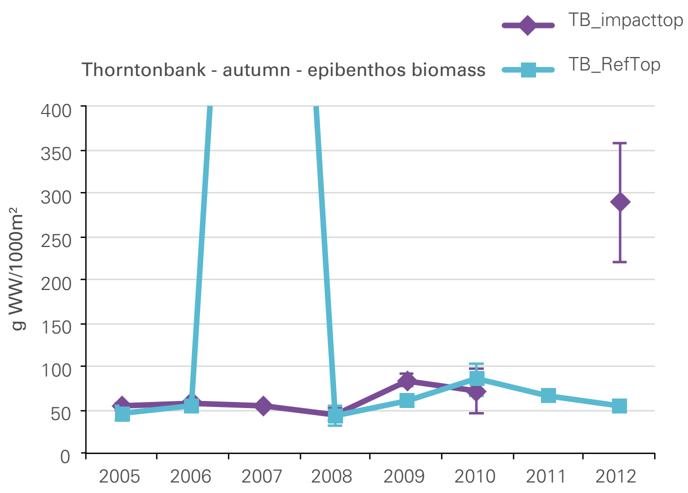
WIND FARM EFFECTS

Thorntonbank

At the Thorntonbank, no significant wind farm effects were observed with BACI analyses. However, significant differences between wind farm control and impacts stations were observed within particular years for dab mean length (2012), epibenthos biomass (2009), and species number of demersal fish (2009) (Figure 5). Epibenthos biomass was higher at the wind farm top stations in 2009 and 2012, but only the difference in 2009 turned out to be significant. In autumn 2008, the number of species within the demersal fish was lower at the impact gully station than at the reference stations, but this result was based on only 3 fish tracks.

Figure 5. Time series graphs dab length (average length in cm ± SE) and epibenthos biomass (average g wet weight per 1000m² ± SE)





Bligh Bank

Within the Bligh Bank data, a large number of non-parallelisms were observed within the time series of ecosystem and species parameters. Only a few of these turned out to be significant within the BACI framework:

- An increase in epibenthos biomass at the sandbank top stations within the wind farm, both in autumn and spring (Figure 6)
- Increases in the spring densities of the common sea star (*Asterias rubens*) at the sandbank top stations within the wind farm (Figure 6). Strongly increased numbers of sea stars were also observed at the gully stations, both at the Bligh Bank and the Thorntonbank (not significant). Densities were highest in 2011 at the Bligh Bank, and in 2012 at the Thorntonbank, i.e. 2 years after construction (not taking into account the gravity based foundations built in 2008). Comparison of density data and biomass data for this species, indicated that the increases seen in the gullies were mainly due to a recruitment of small individuals. At the sandbank tops, trends in density and biomass were similar.
- Increases in the densities of sole at the sandbank top stations within the wind farm, caused by the presence of some young individuals (16 – 22 cm) at the impact stations in 2012 and the total absence of sole at the reference stations.

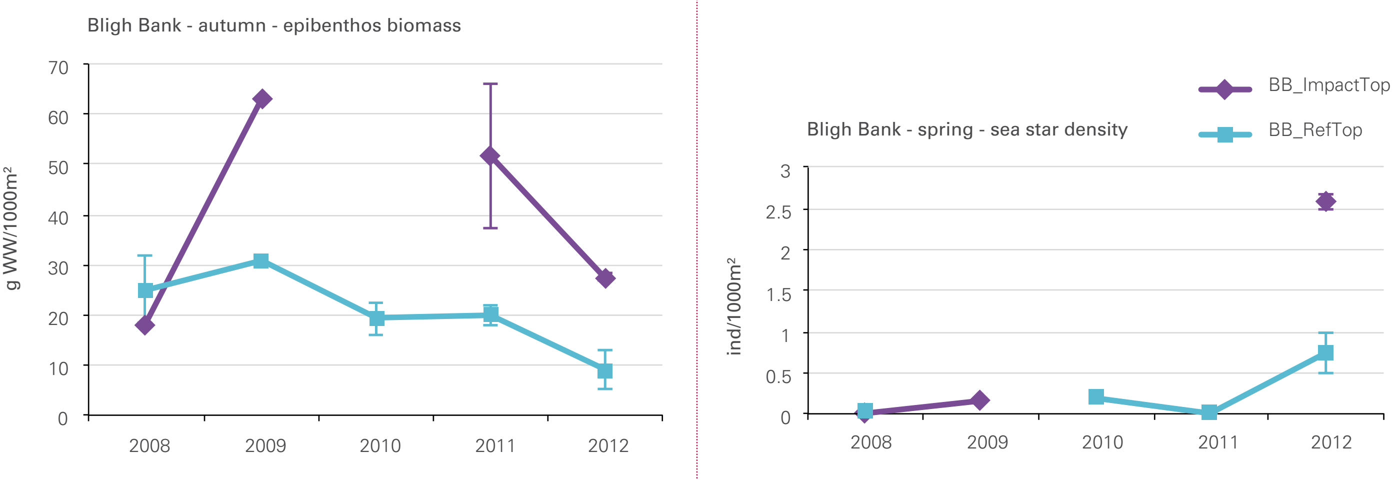


Figure 6. Time series graphs of epibenthos biomass (average g wet weight per 1000m² ± SE) and sea star sole densities (average number of individuals per 1000m² ± SE) at the Bligh Bank

Non-significant BACI-effects, but effects within specific years were observed for a number of factors (Figure 7):

- Dab and sole densities in autumn 2011 were relatively high at the impact top stations, but were again lower in 2012.
- The demersal fish species composition within the gullies of the Bligh Bank was significantly different from the one found at the reference stations in autumn 2012, which was mainly due to different proportions of solenette (*Buglossidium luteum*), sandeel (*Ammodytes tobianus*) and dragonet (*Callionymus lyra*). Only the differences in sandeel were significant.
- In 2009, densities of ophiuroids (*Ophiura ophiura*) and urchins (*Psammechinus miliaris*) were lower at impact stations compared to reference stations. Such a decrease in autumn 2009 (during piling activities) was also seen for squid (*Allotheutis subulata*), dragonet and dab, although not significant. For urchins, densities then spectacularly increased in 2011 – 2012 both in autumn and spring. A similar trend, although less strong was seen for ophiuroids and hermit crabs (*Pagurus bernhardus*). High numbers of young ophiuroids and sea stars, and clusters of urchins have also been observed on and near the turbines (F. Kerckhof, pers. comm.), so the observations from the surrounding soft substrates are probably the direct result of the presence of hard substrates. Especially for the urchins, which feeds predominantly on seaweed, hydroids, bryozoans and barnacles, the presence of hard substrates is of great importance. The increased densities, especially in the gullies, may result from dislodgment from the turbines and from the presence of coarse sediments around the wind turbines, which is the preferred habitat for green sea urchins. Additionally, urchins are prone to physical damage by trawling (Lokkeborg, 2005), so this species profits from the absence of beam trawl fisheries within the wind farm.
- Sandeel densities (*Ammodytes tobianus*) were lower at the impact gully stations in autumn 2012. Trends in sandeel are discussed in more detail in the next paragraph.

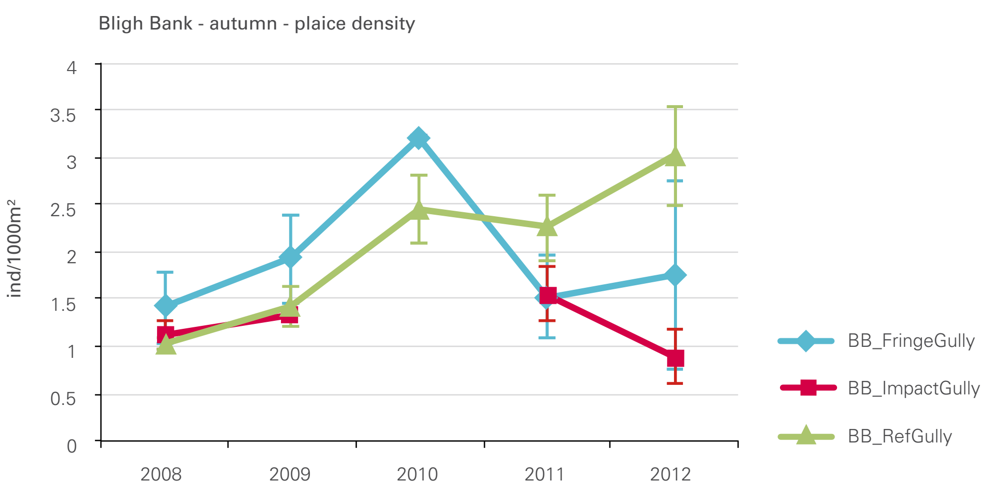
Figure 7. Time series graphs of sole, dab, ophiuroid and urchin densities (average number of individuals per 1000m² ± SE) at the Bligh Bank

Urchin *Psammechinus miliaris* at the Bligh Bank wind farm

We also made some observations that were not picked up by the statistical analyses but that are worth mentioning in the context of wind farm effects:

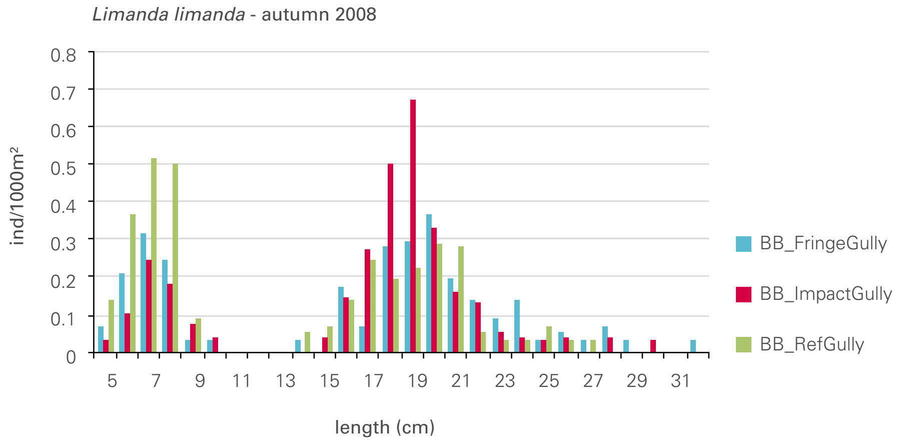
- For plaice (*Pleuronectes platessa*) density, there was a general increase in numbers over the years (Figure 8). In 2011, this trend was broken at the fringe stations, but again restored in 2012. In 2012, numbers had decreased in the impact gully stations, while numbers at other gully stations had increased. Plaice also seemed to be slightly bigger at the impact stations of the Bligh Bank in 2011 – 2012. No dramatic shifts in population structure were observed based on length-frequency analyses, but we did observe a small number of quite large animals (30-43cm), which had an important influence on the average length calculations. The presence of large plaice was also noted during diving operations in the Bligh Bank wind farm (J. Reubens, pers. comm.), and indicate a refugium effect for flatfish. This refuge hypothesis is also applicable to turbot (*Psetta maxima*). Although the time series analysis for this flatfish species was based on very few specimens, comparisons with catches elsewhere in the Belgian part of the North Sea suggest that wind farms might influence the density and size of this species: 4 out of 13 specimens caught in the Belgian part of the North Sea in 2011, for example, originated from inside the wind farm. These four turbots had an average length of 34 cm, while the average length of all other specimens was 23 cm.

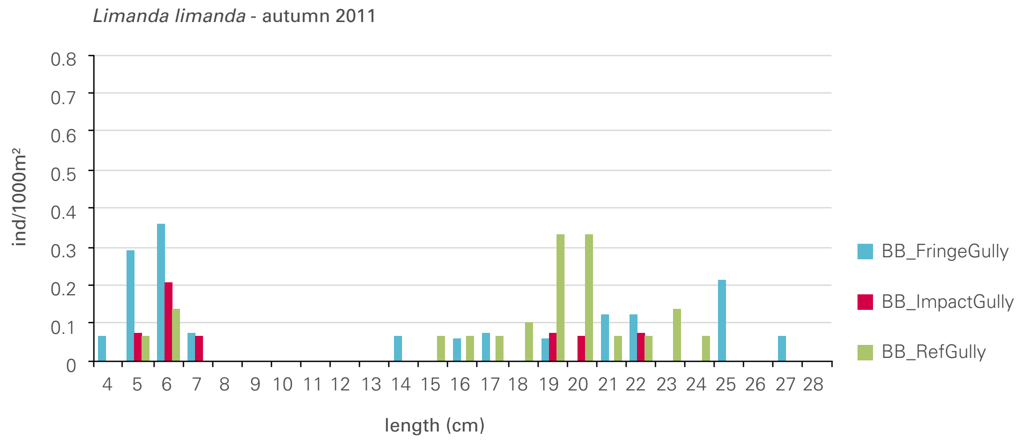
Figure 8. Time series graph of plaice density (individuals per 1000 m²) at the Bligh Bank

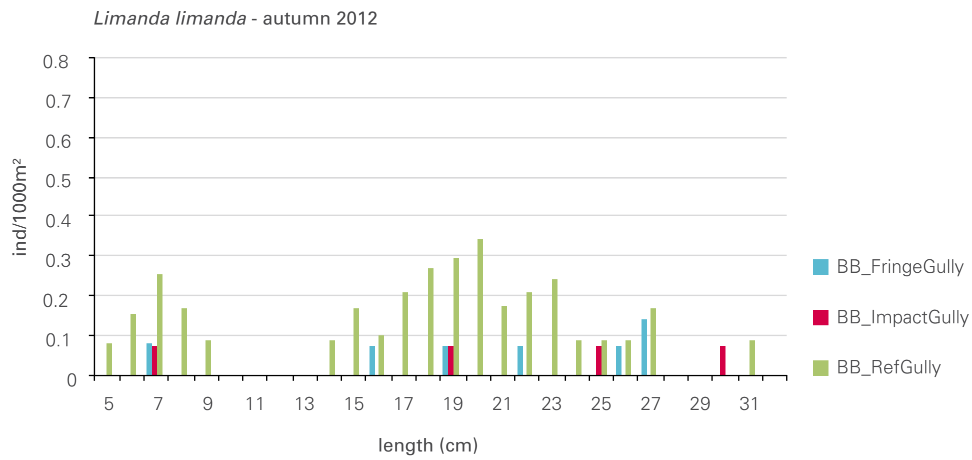


- The average length of dab was quite small in the impact gully stations in autumn 2011. When taking a closer look at the length-frequency distributions (Figure 9), we saw that, throughout the years, two size classes could be distinguished in dab for the reference stations. In autumn 2011, the number of fish from the larger size class was strongly reduced in fringe and impact stations. In autumn 2012, numbers were reduced in both size classes. It appears that dab is moving away from the fringe and impact stations, initially only larger fish, but recently also the smallest fish have mostly gone. This was confirmed by the density evolution graphs, that show decreasing densities at the impact stations, but also at the fringe stations. In spring 2012, it seemed to be the other way round: densities at reference stations remained similar, but the ones at impact and fringe stations increased.

Figure 9. Length distributions of dab (average number of individuals per 1000m² per cm size class) at the Bligh Bank gully stations in autumn 2008 – 2011 - 2012

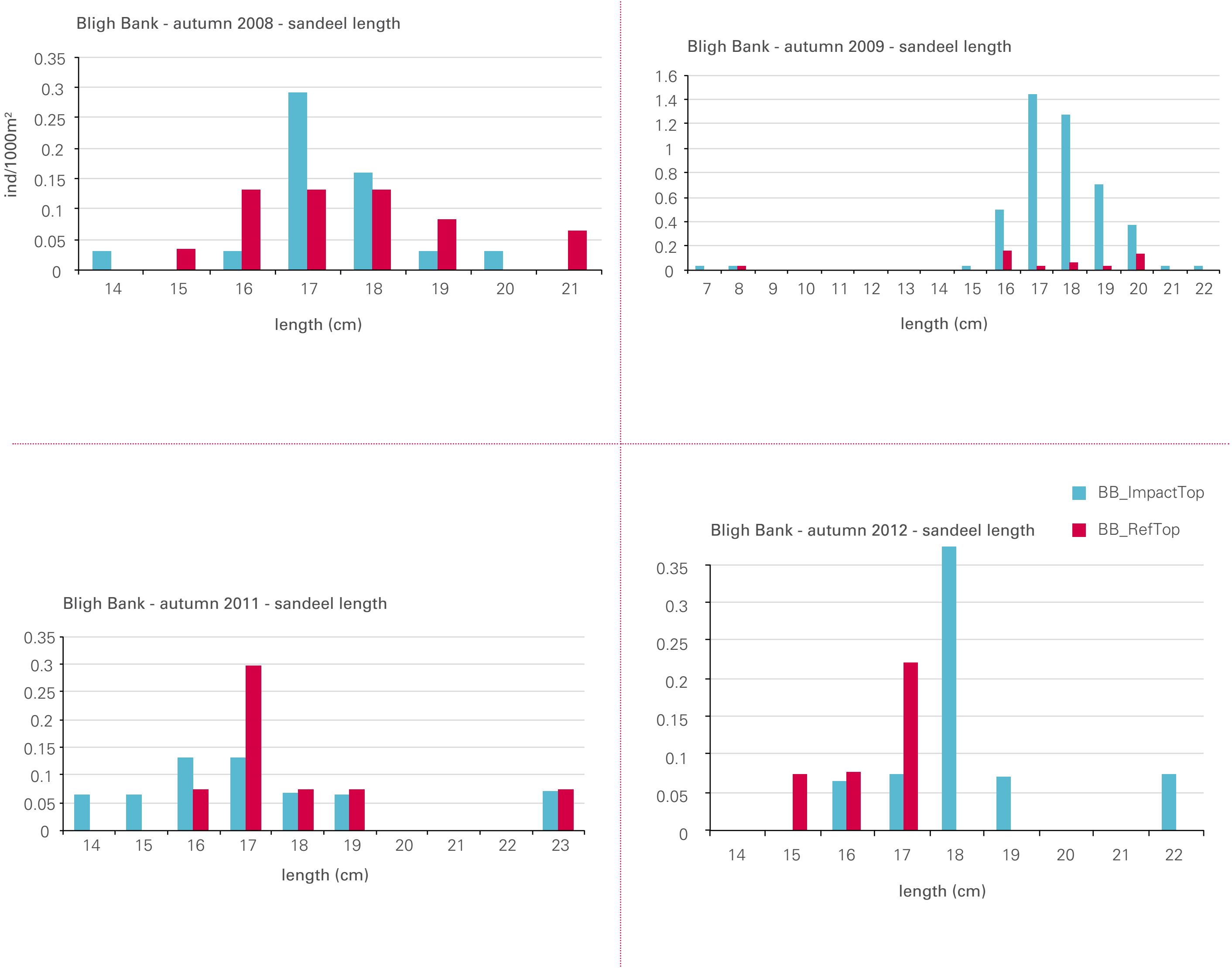






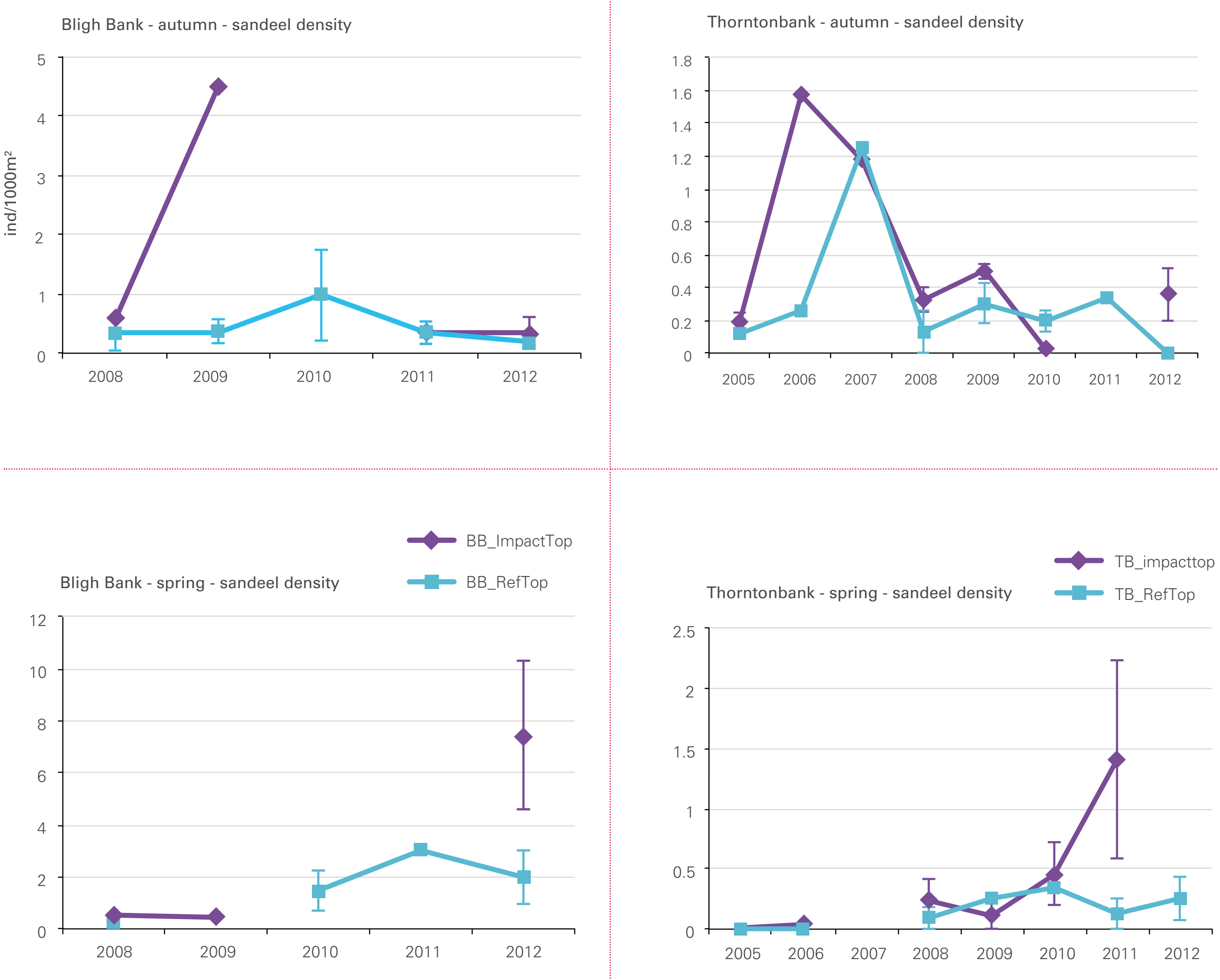
- The changes in sandeel (*Ammodytes tobianus*) size and density were not significant in the BACI design (except for impact gully stations in 2012, see above), but a few striking non-parallelism were seen in the density and size evolution graphs of the sandbank top stations. In 2008, the length frequency distribution was similar for all stations groups. In 2009 (during piling activities), the average length was similar, but we observed much higher densities of adults (>10cm) at the impact stations on the sandbank top. In 2010, no samples could be taken. In 2011, we observed more relatively small adult sandeels at the impact stations, while they were larger in 2012 (Figure 10).

Figure 10. Length distributions of sandeel (average number of individuals per 1000m² per cm size class) at the Bligh Bank top stations in autumn 2008-2009-2011-2012



Other than changes in size distribution over the years, we observed episodic increases of sandeel at both wind farms in both seasons at the sandbank top impact stations (Figure 11). This may be due to changes in the recruitment and pelagic activity of these fish (Van Deurs et al., 2012), but since effects on sandeel have been registered at the Horns Rev I wind farm in Denmark, density and size should be followed closely. At Horns Rev, increases during and shortly after construction were attributed to changes in grain size and in predator abundance (Leonhard et al., 2011; Van Deurs et al., 2012). Lindeboom et al. (2011) found no indications of wind farm avoidance by sandeels. Future development in the sandeel populations may be influenced by the development of the biological community at the hard substrate, resulting in an increasing number of predators attracted to the area (Anonymous, 2006). Consequently, a future focus on sandeels in the monitoring program is advised, including a sampling strategy that is more suitable for quantitative estimations of this species' densities.

Figure 11. Time series graph of sandeel densities (average number of individuals per 1000m² ± SE) at the Bligh Bank and Thorntonbank top stations



- Lobsters (*Homarus gammarus*) visit rocky habitats in search for shelter and food, thereby performing extensive migrations and using artificial hard substrata as stepping stones within extensive soft bottom areas (Krone et al.., 2013b). They have occasionally been observed by divers in a Swedish wave farm (Langhamer et al.., 2009) and at the scour protections of the gravity based foundations in Belgium (J. Reubens and A. Norro, pers. comm.). They were however not caught on Belgian soft substrates during monitoring campaigns in the last decade. In autumn 2012, a lobster strayed from the wind farm hard substrates into the sandy area between the turbine rows of the Thorntonbank wind farm. Such observations suggest that the reef effects caused by each turbine are expanding into the soft substrates between the turbine rows.

Thorntonbank trawl catch containing a lobster

CONCLUSIONS

All considered, some remarkable differences between wind farm impact and control stations were observed. The analyses revealed some wind farm effects in autumn 2009 at the Bligh Bank (e.g. decreases in dab, ophiuroids, squid and dragonet and increase in sandeel). At that time, the stations were sampled only weeks after the start of piling activities, so the observed changes were probably short lived construction effects. As for post-construction effects, we saw changes in demersal fish composition, a decrease in demersal fish species number, and an increase in epibenthos biomass. The changes in demersal fish may have resulted from the absence of fisheries in the area or local changes in sedimentology and infaunal communities. For commercially important flatfish, we observed higher densities (sole) and/or changes in length-frequency distribution (dab, plaice). This may signal a refugium effect, but bearing in mind that large flatfish such as sole do not stay within a wind farm for longer periods (Lindeboom et al., 2011), this effect will be limited. Dab on the other hand seemed to move away from the wind farms. The increase in epibenthos (e.g. sea stars, urchins, hermit crabs) probably resulted from the presence of hard substrates and their fouling communities and from the absence of fisheries. The increase, however, was mainly seen for dominant, scavenging species such as echinoderms and hermit crabs. Signs of recovery of populations of long living species vulnerable to trawling, as was seen for *Ostrea edulis* and *Sertularia cupressina* at Horns Rev (Anonymous, 2006), have not yet been observed at the soft substrates of Belgian wind farms.

Importantly, the observed effects were not consistent between wind farms. This weakens the BACI results, but is not surprising, given the differences in communities (De Backer et al., 2010), in sandbank topography (see chapter 2 and 4), in (historic) fisheries pressure (see chapter 8), differences in age of the wind farms and types of foundations used (see chapter 2). This inconsistency stresses the importance to replicate the monitoring activities across wind farms along the identified gradients.

Fringe effects could not be shown, both at the Thorntonbank and Bligh Bank wind farm. So, based on biological data on epibenthos and fish, we did not observe effects of changing fisheries activities in the area or overflow effects from the closed area constituted by the wind farms.

Even though the used design is appropriate for this type of impact studies, we still want to point out some considerations that were taken into account during the interpretation of the results. First, there is the risk of false positives in multiple testing. We tested two effects, three ecosystem components, two seasons, two sandbank habitats, and two subhabitats. Test were done on density, biomass and diversity data per ecosystem component, on community structure per ecosystem component, and on densities and size-frequencies of a selection of species. As more attributes are compared, it becomes more likely that the impact and control groups will appear to differ on at least one attribute by random chance alone (e.g. Benjamini & Hochberg, 1995; Verhoeven et al., 2005). Since this is an exploratory study, we did not correct for that at this time. Even then, the observed differences and trends were seldom statistically significant within the BACI framework. This is probably due to a number of factors. First, there is the limited number of post-construction observations (1 year for the Thorntonbank wind farm Phase 2, 2 years for the Bligh Bank wind farm), which strongly limits the power of the analyses. Additionally, it takes around three to five years before stable faunal communities are established after deployment of artificial hard structures (Jensen, 2002; Gray, 2006; Petersen & Malm, 2006), so the effects are likely to become more pronounced in the coming years. Secondly, the sampling distance relative to the turbines (>180m) is large as tracks are situated between turbine rows. The studies of Bergström et al. (2012, 2013) and of Wilhemsson et al. (2006) indicated that increased densities were limited to a radius of 20-160m from swedish turbines, depending on species and that smaller scale studies may be needed to document increases. For the Belgian case study, this may mean that increases between the turbine rows will remain very limited or that it will take a lot of time for the reef effects to expand into the space between turbine rows. Finally, the BACI design does not easily pick up small and gradual changes, so temporary effects or effects with a time lag relative to the actual impact can only be traced by careful and detailed analyses of the available data, taking into account the limitations of the design and the methodology.

FUTURE MONITORING

The results of the analyses indicate that it is essential to further extend the time series within the same design, and to replicate across wind farms along identified gradients. This will increase the power of the tests and shed light on the maturation of the new wind farm system. With time, wind farm effects are expected to extend increasingly into the soft substrates surrounding each turbine and each concession zone. The analyses also indicate that we should closely follow-up on wind farm effects concerning epibenthos, demersal flatfish and sandeel, and especially on species-specific information on length and density.
Based on the presented results, fringe effects could not be shown. Such effects may still occur in the following years and can be traced by an integrated analysis of biological data (as in the present study) and vessel monitoring system data (VMS) of Belgian and foreign vessels fishing in the eastern section of the Belgian part of the North Sea (Vandendriessche et al., 2011).


CHAPTER
11

Offshore wind farms significantly alter fish community structure - Aggregation of Atlantic cod and pouting

Jan Reubens, Steven Degraer and Magda Vincx

The numerous wind turbine foundations being constructed in the North Sea influence the ecosystem functioning and local biodiversity. Interactions within and between these artificial hard substrates and the surrounding soft substrate occur. In this study we assess the anticipated environmental impact on benthopelagic fish species. Catch per unit effort data was combined with length-frequency distributions to gain insights in the fish community structure near wind turbine artificial reefs. Atlantic cod and pouting dominate the community structure and show clear seasonal patterns in presence. Specific age groups are attracted to the wind turbine foundations.

INTRODUCTION

The marine environment is being intensively used by mankind for offshore activities and exploitation of marine resources. One of these activities is the development of offshore wind farms (OWFs) and in recent years they are arising all across the North Sea. The numerous wind turbine foundations add a substantial amount of artificial hard substrates to the marine environment, having an influence on local biodiversity and ecosystem functioning (Andersson et al., 2009; Wilhelmsson et al., 2006). Benthopelagic fish species are likely to be affected by the environmental changes and hard substrates have been reported to attract and concentrate fishes (Bohnsack, 1989; Leitao et al., 2008; Pickering and Whitmarsh, 1997). Several fish species such as pouting (*Trisopterus luscus*), Atlantic cod (*Gadus morhua*), mackerel (*Scomber scombrus*) and horse mackerel (*Trachurus trachurus*) have been observed in close proximity of wind turbine foundations (Leonhard et al., 2011; Reubens, 2013). The aggregation behaviour can be explained by several mechanisms (see chapter 14): 1) food availability and feeding efficiency, 2) increased shelter against currents and predators, 3) provision of nurseries and recruitment sites, 4) stress mediators.

In this chapter the anticipated impact will be assessed through the investigation of the benthopelagic fish community structure near wind turbine artificial hard substrates. Hereby we will focus on:

- Changes in the fish species community
- Abundance information (catch rates) of Atlantic cod and pouting
- Age structure of Atlantic cod and pouting

Line fishing, with fishing rod near the wind turbines

SAMPLING STRATEGY

We combined catch per unit effort (CPUE) data with length-frequency distributions of fish to gain insights in the fish community structure. To relate the community structure at the wind turbine artificial reefs to the surrounding marine environment, this habitat is compared with hard substrate (i.e. shipwrecks) and soft substrate (i.e. sandy areas) control areas (box). Data was gathered in the period 2009 – 2012 on a two-weekly to monthly basis.
Line fishing, with a fishing rod (hooks: Arca nr 4, bait: lugworm *Arenicola marina*), was performed at the different sites to quantify the CPUE data. Sampling was restricted to daytime hours and standardized as CPUE = $N_f/(N_p*T)$; with N_f the number of fish caught (ind), N_p the number of fishermen (fm) and T the duration of fishing in hours (h).
Length-frequency distributions were used to assess the age structure in the population. It allows to separate the cohorts present. Age-length keys help to correctly assign the cohorts to their age group (table 1 and 2).

BOX: Sampling strategy

- **Wind turbines**
  Thorntonbank, WGS 84: 51°33′N – 2°56′E
  Hard substrates made by gravity based foundation and surrounding scour protection of rocks and pebble

- **Shipwrecks**
  Kilmore, WGS 84: 51°23′N – 2°30′E
  LCT 457, WGS 84: 51°25′N – 2°44′E
  Hard substrates made by iron wrecks

- **Sandy areas**
  Thorntonbank, WGS 84: 51°31′N – 2°52′E
  Gootebank, WGS 84: 51°27′N – 2°52′E
  Soft substrates composed of medium sand

DATA OVERVIEW

Fish community structure at different habitats in the Belgian part of the North Sea

In total 19 fish species were encountered (from three types of sampling sites) (Figure 1). Comparable numbers of species were observed at all three sites, with 12, 11 and 12 species at the wind turbines, shipwrecks and sandy areas respectively. However, differences in species composition were found between the sites. Poor cod (*Trisopterus minutus*), saithe (*Pollachius virens*), black seabream (*Spondyliosoma cantharus*) and dragonfish (*Callionymus lyra*) were encountered only at the wind turbines, while dogfish (*Scyliorhinus canicula*), European flounder (*Platichthys flesus*) and common sole (*Solea solea*) were solely caught at the sandy areas. Sea bass (*Dicentrarchus labrax*) was present only at the shipwrecks.
The community structure clearly differed between the habitats. In general, across all three habitats, horse mackerel and mackerel are species typically present in our regions in late spring and summer, while whiting and dab are typical for autumn and winter. The wind turbines were characterized by Atlantic cod and pouting. At the shipwrecks, Atlantic cod, pouting and mackerel dominated the catches, while at the sandy areas mainly dab (*Limanda limanda*), whiting (*Merlangius merlangus*) and mackerel were caught.
Clear seasonal changes in community structure were observed at all habitats. At the wind turbines Atlantic cod and pouting dominate throughout the year, while in winter also bull rout (*Myoxocephalus scorpius*) is an important species while in spring and summer horse mackerel and mackerel contribute to the community. At the wrecks Atlantic cod dominates. Pouting contributes in summer and autumn, while mackerel and horse mackerel are mainly caught in spring and summer. Whiting has some importance in autumn and winter. At the sandy areas whiting and dab are dominant in all seasons except in summer, then mackerel takes over. In autumn pouting contributes to the community as well.

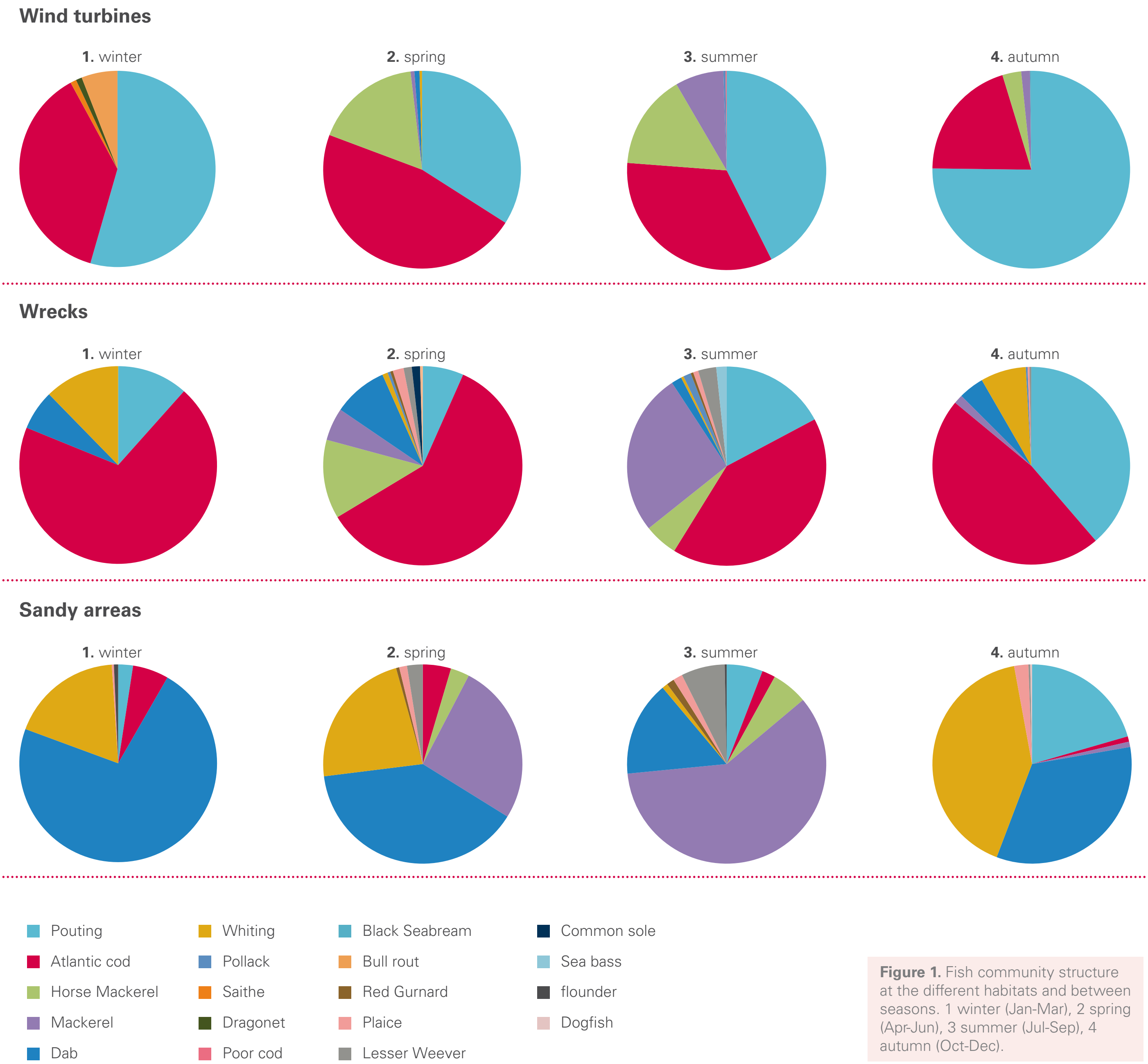


Figure 1. Fish community structure at the different habitats and between seasons. 1 winter (Jan-Mar), 2 spring (Apr-Jun), 3 summer (Jul-Sep), 4 autumn (Oct-Dec).

Temporal patterns in abundance of Atlantic cod and pouting

As Atlantic cod and pouting are species with a high commercial value and both were encountered in high numbers at the wind turbines, it was decided to investigate the catch rates of these species at the different habitats in closer detail to unravel whether they are attracted to a specific habitat.

Catch rates were compared for the period 2009 – 2012 and averaged (± standard deviation) per month. For Atlantic cod, much higher CPUE values were observed at the wind turbines compared to the other habitats (Figure 2). The catches were 2 to 12 times higher compared to the wrecks, and up to more than a 100 times higher compared to the sandy areas. Atlantic cod was seldom encountered at the sandy areas. At the wind turbines a clear seasonality in catches was observed. From December until April CPUEs were low (1.3 ± 0.3 - 2.5 ± 4 ind h^{-1} fm^{-1}) while from May until November CPUEs were elevated (3.2 ± 1.7 – 12.5 ± 13.4 ind h^{-1} fm^{-1}) with a peak in July. At the shipwrecks similar, yet less obvious trends were observed. Similar results were obtained for pouting. Highest CPUE values were found at the wind turbines, with catches 3 to more than 30 times higher and 9 to more than a 100 times higher compared to the shipwrecks and sandy areas respectively. Almost no pouting were present at the shipwrecks and sandy bottoms in the first half of the year, while from September until December some pouting were encountered. At the wind turbines a seasonal pattern in catch rates was found. In winter and spring (January until June) low numbers were caught (0.3 ± 0.4 – 4.2 ± 5.2 ind h^{-1} fm^{-1}) while from July until December catches increased and peaked in December (5.8 ± 4.5 – 20.9 ± 10 ind h^{-1} fm^{-1}). At the shipwrecks a similar, but less obvious trend was observed.

These seasonal patterns in CPUE are probably related to life-history characteristics (i.e. reproductive behaviour of adults). Both species are known to spawn in winter and early spring (Alonso-Fernández et al., 2008; Mello and Rose, 2005) during which they migrate to distinct spawning areas outside the study area. In this period, CPUE was very low at the different habitats in the Belgian part of the North Sea. Late spring to late autumn is the feeding and growing period for both species. During this period, much higher CPUE, especially at the wind turbines, was observed. Both types of artificial reefs are home to a diverse and abundant epifaunal community with many potential prey species for Atlantic cod and pouting (see also chapters 12 and 14). Local factors, such as the availability of prey species, predator pressure, habitat complexity and refuge possibilities likely contributed to the differences in aggregation between the habitat types.

Left side, school of pouting at a shipwreck; right side, Atlantic cod

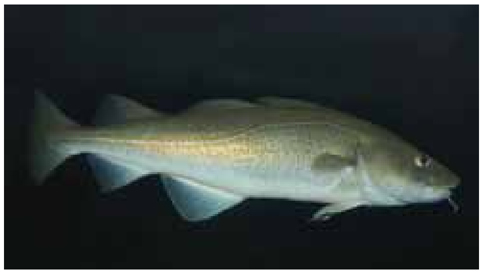
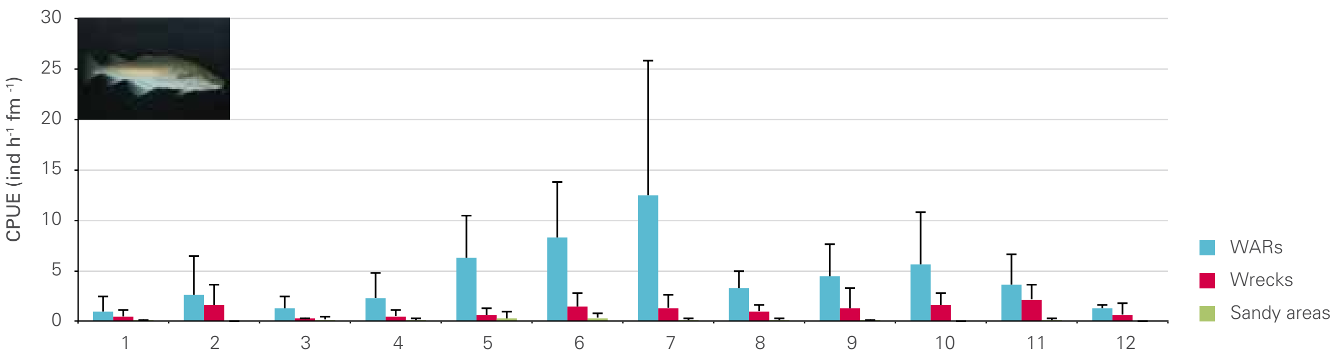
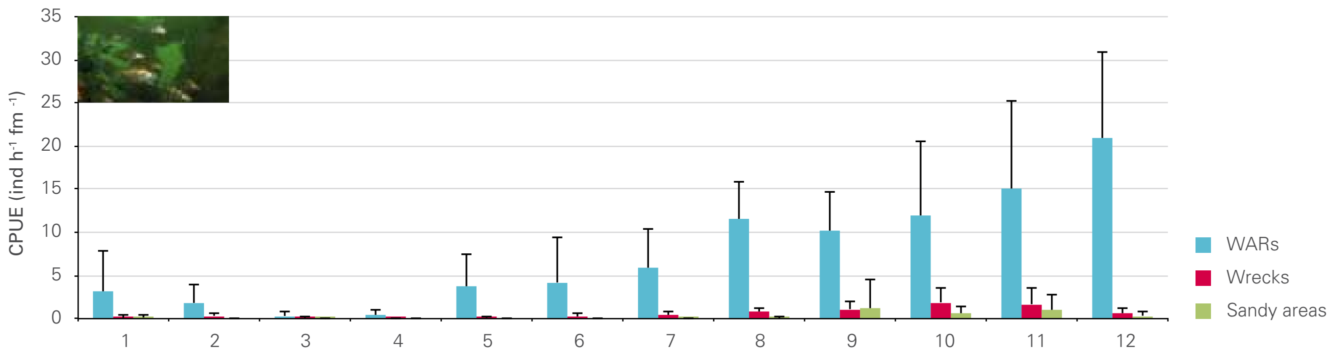


Figure 2. Average monthly catch per unit effort (CPUE) (with standard deviation) of Atlantic cod, *Gadus morhua* (upper panel) and pouting, *Trisopterus luscus* (lower panel) per habitat type. Data from 2009-2012. CPUE is defined as the number of fish caught in one hour by one fisherman.





Age structure of Atlantic cod and pouting

For Atlantic cod, the length-frequency distribution at the OWFs clearly revealed that the I-group was present year round (Figure 3); some II-group individuals were present as well, although in much lower numbers and mainly during the first half of the year. Thereafter, they were only sporadically encountered. At the shipwrecks the same trend was observed and some III-group cod were caught in winter and spring as well. At the Gootebank only few Atlantic cod were caught and their distribution was scattered over the year. Most of them belonged to the I-group. As only few fish were caught, clear length distributions could not be obtained.

For pouting, both the 0- and I-group were observed at the wind turbines (Figure 3). The first sightings of the 0-group were in August/September. The I-group was present year round, though was only well represented from May until October. The 0, I and II-group pouting were observed at the shipwrecks. In winter (January – March) the II-group was encountered, while the I-group was present from June onwards. The first 0-group pouting were observed in August/September. At the Gootebank pouting was mainly observed from September until December and only the 0-group was encountered.

Although not represented in the catches, other age groups may be present as well at the different habitats. Diver observations for instance, revealed the presence of juvenile Atlantic cod (0-group) at the wind turbines in May-June (sampling campaigns of 2011-2012). The individuals had an estimated average length of 5 cm. Pouting as small as 10 cm were also observed at the wind turbines. This suggests that other age groups are present but not efficiently caught using hook and line. Line fishing is a selective fishing technique and type and size of bait, hook design, fishing strategy and fish ecology all may influence the species and size selectivity (Løkkeborg and Bjordal, 1992). Prey preferences of fish are related to prey size, thus size of bait and hooks will influence the fish size caught. The size of the hook induces a lower and upper limit of fish sizes able to be caught. For small fish the hook may be too big, while big fish may no longer be efficiently hooked.

	Q1	Q2	Q3	Q4
0 year			16.8 (6)	19.9 (71)
1 year	26.5 (39)	29.7 (173)	35.2 (127)	43.3 (715)
2 year	49.3 (184)	51.0 (925)	53.2 (262)	54.6 (594)
3 year	64.1 (180)	68.3 (283)	65.0 (13)	61.2 (687)

Table 1. Average length-at-age per quarter for Atlantic cod, based on data from the ICES area IVc in the period 2009-2012. Age was determined by otolith analysis. Values are expressed as total length (cm). Q1 = Jan-Mar, Q2 = Apr-Jun, Q3 = Jul-Sep, Q4 = Oct-Dec. The numbers between brackets indicate the number of fish available for age determination.

	Male	Female
0 year	20.7	21.4
1 year	27.5	26.8
2 year	31.5	33.1
3 year	35.6	38.2

Table 2. Average length-at-age for pouting (for both sexes). Data are based on Merayo and Villegas (1994) and expressed as total length (cm). Values refer to length at the end of the year. Regression from standard length (SL) to total length (TL) is based on Hamerlynck and Hostens (1993); TL = 2.35 + 1.102 SL.

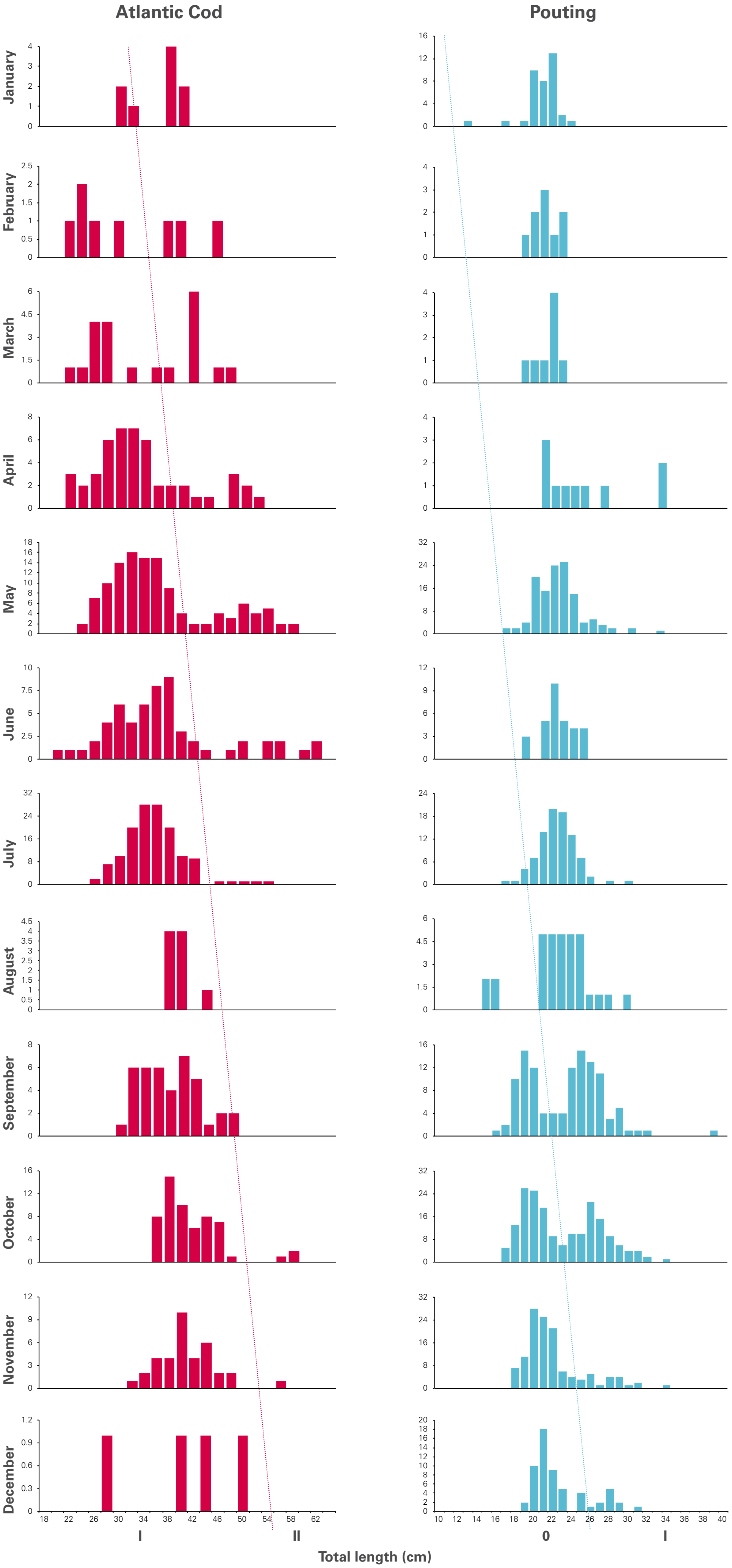


Figure 3. Length-frequency distribution of Atlantic cod, *Gadus morhua* and pouting, *Trisopterus luscus* at the OWFs with indication of the age groups. Values are expressed as total length (cm). Mind the differences in scale.

Take home messages

- Specific fish communities are observed at the different habitats (wind turbines, shipwrecks and sandy areas), with seasonal variability in the community structure.
- Atlantic cod and pouting are strongly attracted towards the wind turbines, but with a seasonal variation in numbers.
- Specific age groups are attracted towards the wind turbines
  - Atlantic cod: I and II group
  - Pouting: 0 and I group

FUTURE MONITORING

- Every type of fishing gear has a species-specific selectivity. The use of different fishing techniques will reflect the true community composition. For community composition estimates at the wind turbine artificial hard substrates, we suggest to combine line fishing with the placement of gill nets and diver observations. This will result in detailed information concerning the small-scale distribution and population structure of fish near wind turbines
- In this study, gravity based foundations (GBFs) were investigated as this was the only type present in the BPNS when the research started. Recently, monopiles and jacket foundations are implemented at several OWFs. Differences in reef effects are expected for the different foundation types. Jackets for instance, usually don't have a scour protection layer at the bottom. Varying hydrodynamic conditions and different fish behaviour are expected in comparison to the GBFs. Monopiles consist of steel, having different settlement characteristics for epifauna in comparison to the concrete foundation of GBFs; in addition do monopiles normally have a smaller scour protection.

fishing nets

CHAPTER 12

Fouling community on the foundations of wind turbines and the surrounding scour protection

Ilse De Mesel, Francis Kerckhof, Bob Rumes, Alain Norro, Jean-Sébastien Houziaux and Steven Degraer

The introduction of hard substrata in the mainly sandy environment of the Belgian part of the North Sea provides a new habitat to species that could previously not establish in the area. The community is dominated by the amphipod *Jassa herdmani,* the hydroids *Tubularia larynx* and *T. indivisa* and Actiniaria species, of which the plumose anemone *Metridium senile* is the most dominant. Only few species, especially those arriving early in the colonisation process, are able to establish a viable population. The vertical foundations and the complex three-dimensional structure of the scour protection harbour different fouling communities.

INTRODUCTION

With the installation of wind turbines, artificial hard substrata have been introduced in a mainly sandy environment. The foundations and the scour protection provide a new habitat in the Belgian part of the North Sea.

Hard substrata harbour significantly different benthic communities than the surrounding sandy seabed. Artificial hard substrata are known to be quickly colonised by fouling organisms, which are often new to the area (Horn, 1974; Schröder et al., 2006, Kerckhof et al., 2009). This results in increased local species richness. The species composition however generally does not reflect the community of natural hard substrata. Additionally, the artificial reefs may act as stepping stones for non-indigenous species, facilitating their expansion over the North Sea (Chapter 17). On the other hand, some positive effects have been illustrated as well.

A number of – economically important – (fish) species have been observed to aggregate around the foundations and scour protection of the wind turbines because they feed on the fouling community (Chapter 14) or find shelter. It is not expected that the introduction of the new fouling species endanger the natural diversity of the sandy sediments. It may alter the soft sediment benthic community in the vicinity of the turbines because of organic enrichment and deposition of epibenthic species and their derivate, but larger scale impacts are not expected (Chapter 13).

In this chapter we describe the colonisation patterns of the macrobenthic fouling community on the foundations and the scour protection of the gravity based foundations on the Thorntonbank and the monopile foundations on the Bligh Bank. On the Thorntonbank, at about 30 km from the coastline, six concrete, gravity based turbines have been installed in spring 2008. The Thorntonbank is situated on the edge between the clear water of the English Channel and the more turbid coastal water (Lacroix et al.,2004). The Bligh Bank, situated 40 km offshore, is influenced exclusively by English Channel water masses. The foundations of these turbines are monopiles. The construction started in autumn 2009. All foundations are surrounded by a scour protection. The aim of our study is to understand the colonisation process and to gain insight in the succession pattern on the artificial hard substrata. The focus of our research is on the subtidal fouling community.

BOX:
Vertical zonation

On the foundations of the wind turbines, a clear vertical zonation in the fouling community has been observed. During the first year of the monitoring, the depth-related patterns of the epifauna were analysed in detail, since then only a more general, visual inspection of the splash zone and intertidal zone are made, while the subtidal zone is continued to be studied in detail (see main text). The marine splash midge *Telmatogeton japonicus* has been dominant in the splash zone since the beginning of the monitoring. The intertidal fringe has evolved from a zone characterised by barnacles and the amphipod *Jassa herdmani,* towards a community dominated by the blue mussel *Mytilus edulis.* The mussels have settled on top of the barnacles. The barnacles extend their range until just above the *Mytilus edulis* zone. This zone is especially well developed on the concrete foundations on the Thorntonbank, where it has a width of about 1 m. Within this zone, some empty patches are present, due to predation and clumps of mussels falling off under pressure of the waves. On the steel surface of the monopiles on the Bligh Bank, the *Mytilus edulis* zone is much narrower and half a meter at most. It is not clear whether this is due to higher predation pressure, lower supply of larvae, or whether other factors are responsible. However, the *'Mytilisation'* of the shallow subtidal as has been reported in other parts of the North Sea, with dense mussel growth down to 10 m (Bouma and Lengkeek, 2012) or deeper (Krone et al., 2013a) was not observed in our study. The intertidal area is the zone with the highest number of non-indigenous species (Chapter 17). The subtidal zone on the foundations is characterised by a *Jassa-Tubularia*-Actiniaria community which is described in detail in this chapter.

Concrete gravity based (upper panel) and steel monopile (lower panel) foundations on the Throntonbank and Bligh Bank, respectively

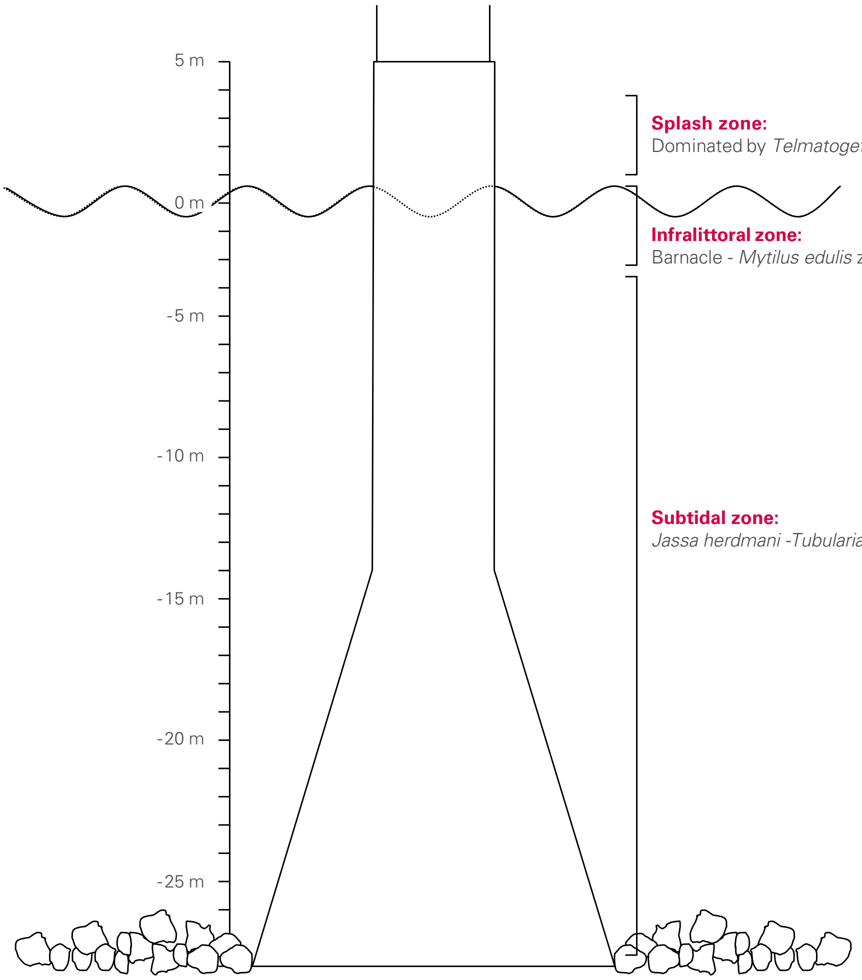


Figure: Schematic representation of the vertical zonation of the fouling community on the foundations of the wind turbines, illustrated with a gravity based foundation.

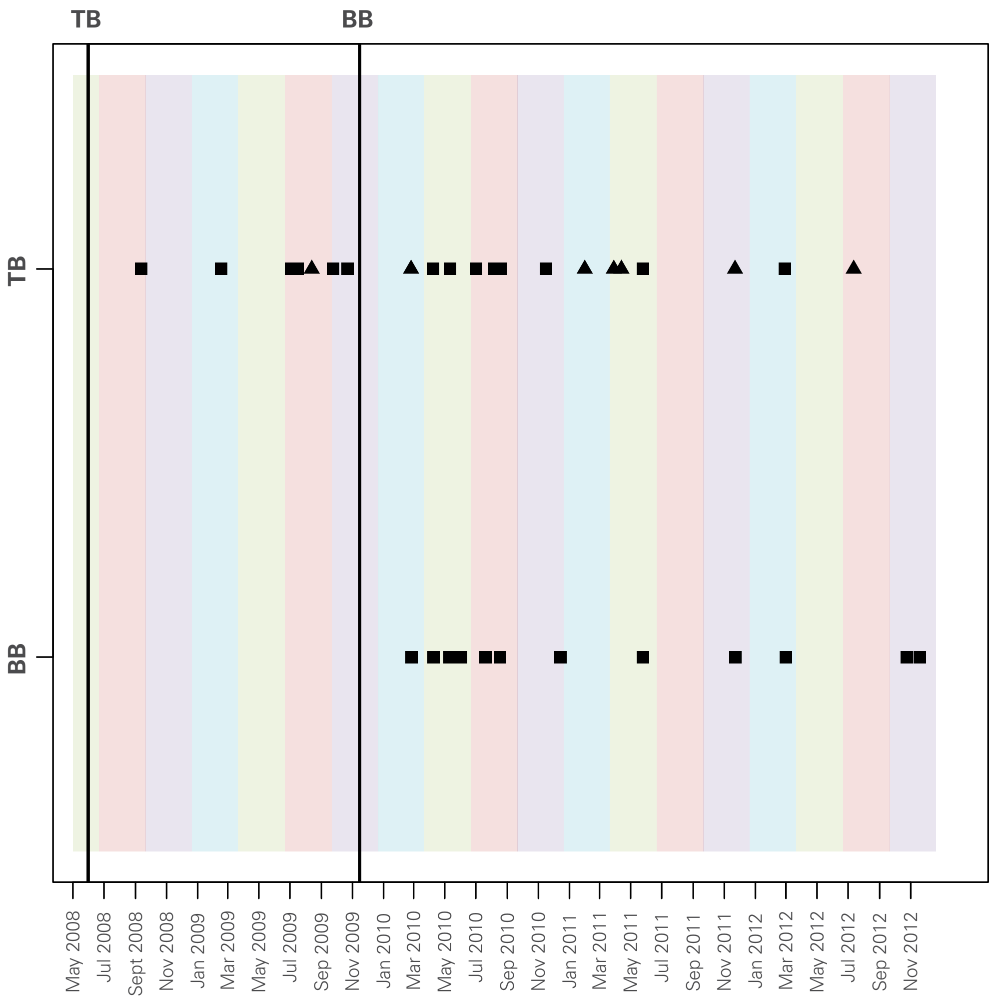
Aequipecten opercularis and a young *Asterias rubens*

RESEARCH STRATEGY

We started collecting samples of the fouling community shortly after the introduction of the first turbines. Initially wind turbines were present only on the Thorntonbank (2008), about one-and-a-half year later the first foundations were installed on the Bligh Bank. At each sampling occasion, one location was sampled in each wind farm. At the Thorntonbank, all samples were collected at the same location, while at the Bligh Bank, three different locations were sampled over time. The results of the first four years of monitoring are presented here.

During the first one to one-and-a-half year, samples were collected on the foundations by scientific scuba divers at different depths. Based on these results, the -15 m zone was identified as being representative for the deeper subtidal community (Kerckhof et al., 2010a). Afterwards, scuba divers scraped, samples of the foundations only at a depth of 15 m. The aim was to sample at least once each season, however due to unfavourable diving conditions, this frequency has not always been obtained (Figure 1). On the Thorntonbank, they also collected stones of the scour protection at a regular basis. In principle, three replicates of each sample were taken. Samples were analysed in the lab in order to investigate patterns in species composition and diversity. Organisms larger than 1 mm were identified to species level when possible or to a higher taxonomic level when the species level could not be obtained. Two components of the community can be distinguished: species that are counted (ind/m^2) and species of which the coverage (% coverage) is determined. Some tube-building organisms, such as the polychaete worm *Pomatoceros triqueter* or the amphipod *Jassa herdmani*, could be quantified in both ways. The coverage of the tubes could be determined or the number of individuals can be counted. In this study, we counted the species when possible. Most species that could not be counted are colonial forms, such as Bryozoa. The patterns observed in the scrapings are compared with those on the scour protection.

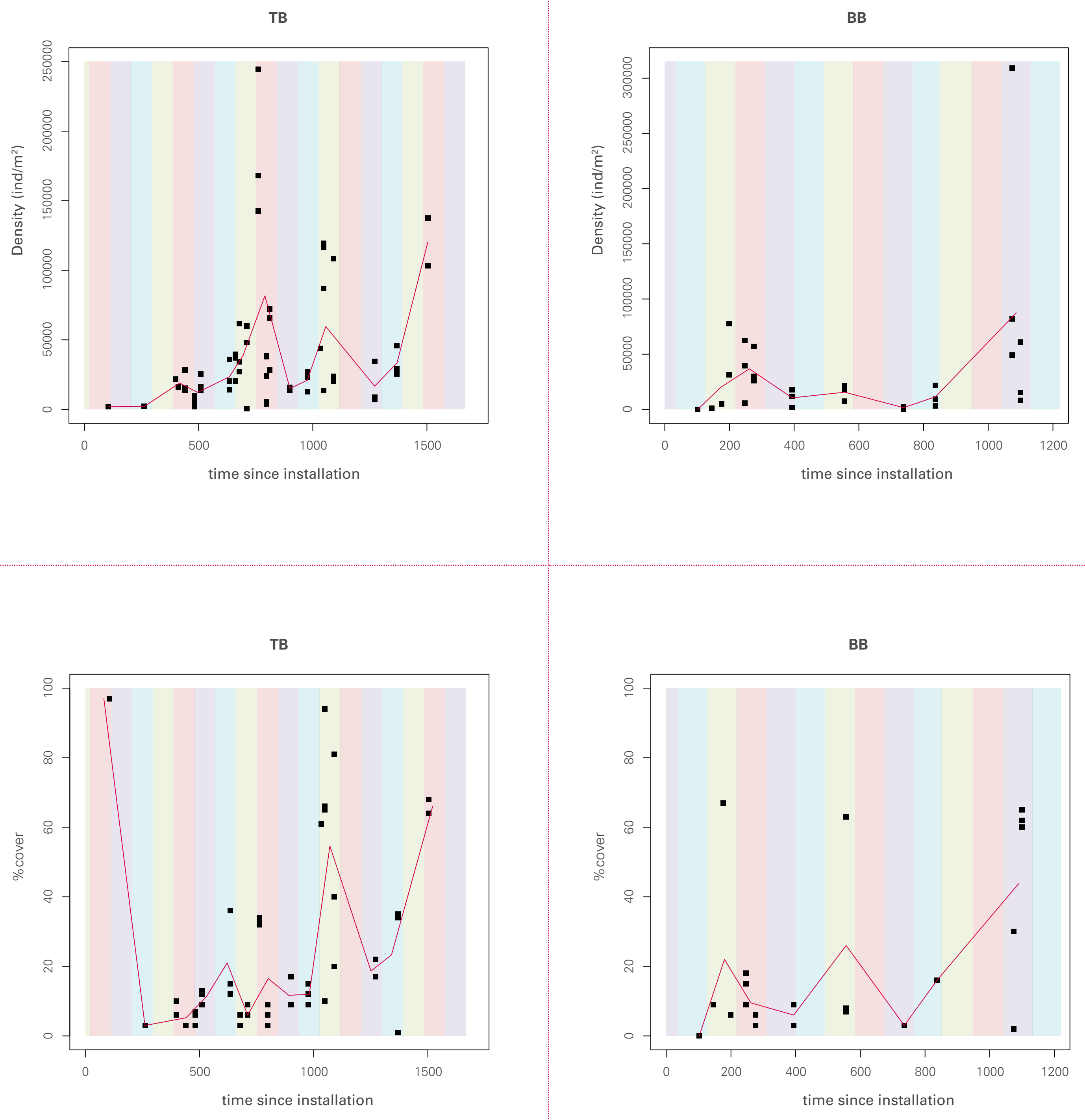
Figure 1. Sampling occasions on the foundations in the wind farm on the Thorntonbank (TB) and Bligh Bank (BB) with the indication of the start of the construction of both wind farms (vertical lines). Squares represent occasions at which only scrape samples on the foundations are collected, triangles represent occasions at which both scrape samples and stones of the scour protection were collected. The background colours represent the seasons (green: spring, red: summer, purple: autumn, blue: winter)



DENSITY AND DIVERSITY

Despite the huge variation between replicates and successive samplings, an increase in densities and coverage over the first two to three years is seen on the foundations of the turbines on the Thorntonbank, after which it more or less stabilises (Figure 2). A seasonal pattern appears, with highest densities (up to 2.5 10^5 ind/m^2, but mostly ranging between 1-1.5 10^5 ind/m^2) and coverage (on average 60-70%) in spring and summer. Although seasonal and long-term dynamics are less clear on the Bligh Bank, similar patterns seem to emerge (Figure 2).

Figure 2. Density (upper panels) and coverage (lower panels) on turbines of the Thorntonbank (left) and Bligh Bank (right). Black dots represent observations in each replicate; the red line connects seasonal averages. The background colours represent the seasons (green: spring, red: summer, purple: autumn, blue: winter). The numbers on the X-axis represent the number of days after installation of the foundations.



The high coverage observed at the first sampling occasion on the foundations of the Thorntonbank (80-100%) was due to an almost complete cover by the hairy sea-mat *Electra pilosa*. This is typically a fast coloniser, that quickly disappears again early in the succession. This dense coverage of *E. pilosa* was not seen on the Bligh Bank, probably because of the timing of the installation of the turbines in autumn, while on the Thorntonbank they were installed in spring. Also, the first sampling on the Bligh Bank was about one month later than on the Thorntonbank, so that the initial heavy colonisation could have been missed. After the heavy colonisation phase *E. pilosa* remained present in almost all samples on the Thorntonbank, but at a much lower density.

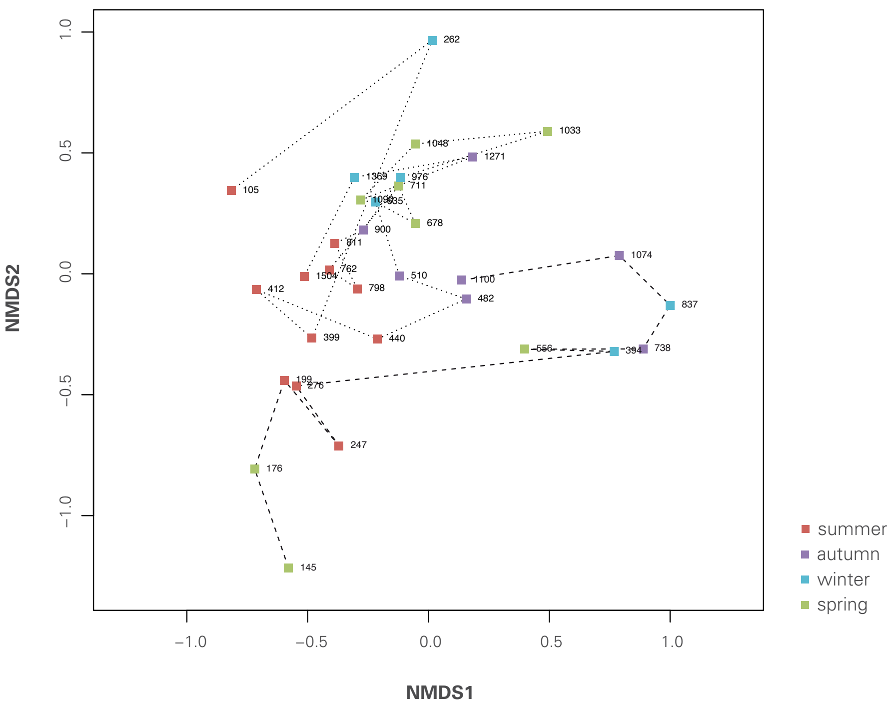
The total number of species found on the Thorntonbank (84) is higher than on the Bligh Bank (64). Although these numbers are biased by a lower sampling effort and a shorter sampling period on the latter, the number of species per sample is generally higher on the Thorntonbank as well, where more than 10 species per sample are found in 82% of the samples, but only in 25% of the samples on the Bligh Bank. Although both areas are situated close to each other (about 10 km apart), they are influenced by different water masses. The Thorntonbank is more affected by coastal waters than the further offshore Bligh Bank (Lacroix et al., 2004). The coastal water masses can transport more larvae or other pelagic stages of the fouling community to the foundations than the English Channel water on the Bligh Bank. On the other hand, the foundations on the Thorntonbank are made of concrete, while the foundations that are monitored on the Bligh Bank consist of steel. This might also affect the settling ability of the organisms (Andersson et al., 2009).

DYNAMICS IN THE COMMUNITY

Our results suggest that the species pool that shapes the community on the foundations of the turbines is established in a relatively short time span after their introduction in the marine ecosystem. On the Thorntonbank, out of a total of 84 species found on the foundations during the four years of monitoring, fourteen (17%) were present in more than 75% of the samples after their first appearance. They can be regarded as species that, after settling, have established a viable population. Most of these species (11 out of the 14 species) had arrived during the first year of the succession, two species arrived during the second year. A very similar pattern was seen at the Bligh Bank, where eight out of a total of 64 species found (or 13%) occurred in 75% of the samples after their first observation. Five of these arrived during the first year, and two during the second year.

A community analysis using Multidimensional Scaling (MDS), confirmed the hypothesis that a rather stable species pool was formed early in the colonisation especially on the Thorntonbank. The first year after the turbines have been installed, the samples collected in subsequent sampling events are situated far from each other in the plot, indicating large changes in the community composition (Figure 3). The distance between successive sampling occasions and between samples from different seasons decreases in the MDS plot, implying a decrease in community changes through time. We see mainly seasonal dynamics. Samples collected in summer are very similar to each other, both on the Thorntonbank and the Bligh Bank. The community composition appears to develop largely similar in both sites.

Figure 3. Multidimensional Scaling (MDS) of the communities on the turbines. The analysis was performed on all replicates. The centroids for each sampling occasion were calculated and are represented by the dots shown in the plot. The lines connect the subsequent samplings, the numbers indicate the number of days after the installation of the turbines, the colours represent the seasons. Data were forth root transformed prior to analysis.

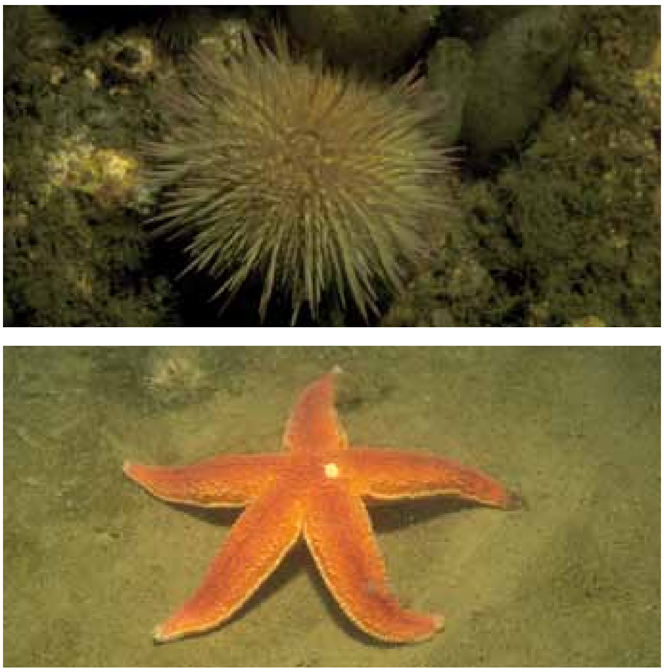


COLONISATION, PREDATION AND COMPETITION

Most species that are able to reach new offshore surfaces disperse as planktonic larvae, including many polychaete worms, crabs, barnacles and tunicates (Hiscock et al., 2002). On the other hand, some species do not have such a free living larval stage, for instance the tube-building amphipods *Jassa herdmani,* one of the first species to reach new hard substrata, and *Monocorophium acherusicum*. Juveniles of these species are able to effectively disperse by drifting in the water column (Havermans et al., 2007). The community of *J. herdmani* consists year round of adult and juvenile individuals, without an apparent seasonal pattern allowing them to invade new structures at all times.

Jassa herdmani

Besides the settling of new species, competition and predation are important biological processes in shaping communities. The most conspicuous predators on the foundations are common starfish *Asterias rubens* and sea urchins *Psammechinus miliaris*. Both species prey on a wide range of organisms. Although *A. rubens* shows some preference for bivalves, they also feed on polychaete worms, other echinoderms, barnacles or occasionally other small crustaceans. *Psammechinus miliaris* is an opportunistic predator that feeds on epifaunal species such as hydroids, barnacles, small bivalves, boring sponges or polychaete worms (Hancock, 1957; Lawrence, 1975). Their predation pressure can be that high that large parts of surfaces are cleared of organisms. This was observed on both wind farms by the divers collecting the subtidal samples. This enhances the dynamics within the fouling community as new larvae can settle on the bare substrata. Other predator species are more specific and closely associated with their prey. *Epitonium clathratulum* and *Odostomia turrita* are both small gastropods feeding on respectively the plumose anemone *Metridium* senile and the keelworm *Pomatoceros triqueter* (Robertson, 1963; Høisæter, 1989). Several nudibranch species we observed feed on *Tubularia* spp. and Bryozoa. The impact of these predators on their prey can be high, and might prevent species from dominating the community.



Psammechinus miliaris (above) and *Asterias rubens* (below)

Epitonium clathratulum

Odostomia turrita

The most prevalent means of competition in fouling communities is overgrowth (Osman, 1977). For instance, the dense mass of tubes build by *Jassa herdmani* can smother encrusting species such as Bryozoa or small barnacles. *Tubularia larynx* traps sediment around their basal stolon, smothering other species (Osman, 1977). *Metridium senile,* on the other hand, has the ability to smother newly settled organisms by sliding over them with its pedal disk (Nelson and Craig, 2011).

FEW SPECIES DOMINATE THE COMMUNITY

The communities found on the foundations at both locations were similar to what has been reported for other subtidal artificial hard substrata, at similar depths or deeper, in the southern North Sea (Zintzen et al., 2006; Bouma and Lengkeek, 2012, van Moorsel et al., 1991), and can be described as a *Jassa-Tubularia*-Actiniaria community. The relative abundance of each of the species differs between locations, but their presence is always recorded. On many artificial hard substrata, they often develop towards a climax community consisting of the *Metridium senile* biotope (Conner et al., 2004). This is quite different from natural hard substrata, where a dominance of these species is unusual.

The subtidal community on the foundation of the wind turbines on the Thorntonbank and the Bligh Bank is numerically dominated by the amphipod *Jassa herdmani* and the hydroids *Tubularia indivisa* and *Tubularia larynx*. Both *Tubularia* species have tubular stems with a polyp at the end. *Jassa herdmani* filters fine sediments from the water column to build tubes which can cover large parts of the substratum. It can smother other species and prevent new species from settling. Actiniaria species, are generally not numerically dominant, but because of their size, with diameters of up to 8 or 10 cm, they are conspicuous members of the fouling community.

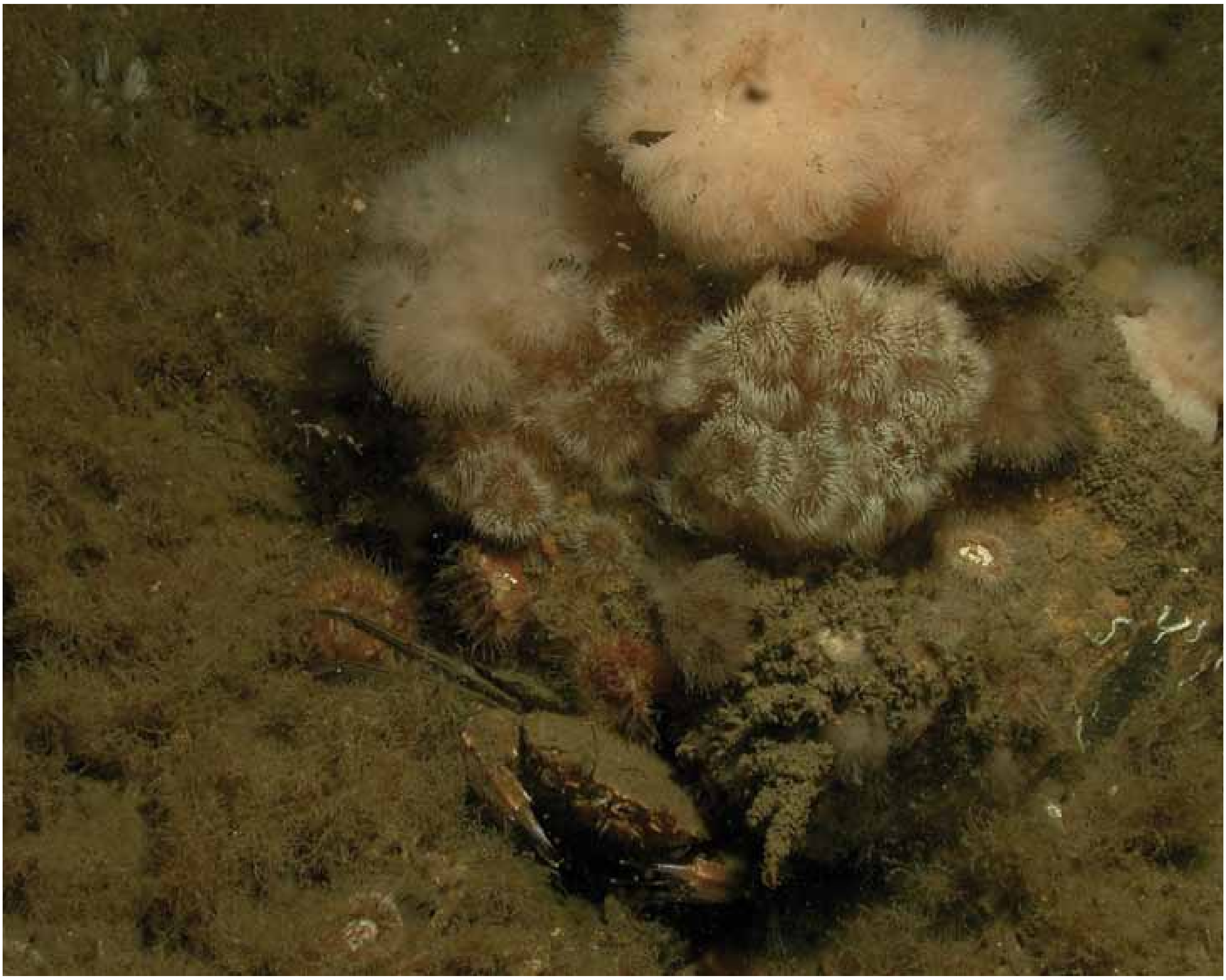
Jassa herdmani

Jassa reached the foundations soon after their installation and reached densities of up to 3 10^5 ind/m². *Tubularia larynx* colonised the substrata within one year after construction, and *Tubularia indivisa* followed one (Thorntonbank) or two (Bligh Bank) years later. Both *Tubularia* species show high dynamics in their coverage, both spatially and temporally. It seems that both thrive better on the Thorntonbank than on the Bligh Bank, with maximum coverage of respectively 90% and 60%. By building their stems, *Tubularia* species create a 3-dimensional structure, providing shelter and substrate for other species. In a study on shipwrecks, Zintzen et al. (2008a) found a positive correlation between the biomass of *T. indivisa* and the diversity of other fouling species. We did not detect a similar correlation between the coverage and the number of species.

Within the Actiniaria, *Metridium senile* is the dominant and most characteristic species on artificial hard substrata in the North Sea. This was also the case on the foundations of the wind turbines in the Belgian part of the North Sea. *Metridium senile* was more abundantly found on the Thorntonbank. It has the potential to be a strong structuring force within the fouling community by rapidly colonising new substrata, covering large areas, consuming free-swimming larvae and smothering new recruits (Nelson and Craig, 2011).

Tubularia indivisa

Metridium senile and *Necora puber*

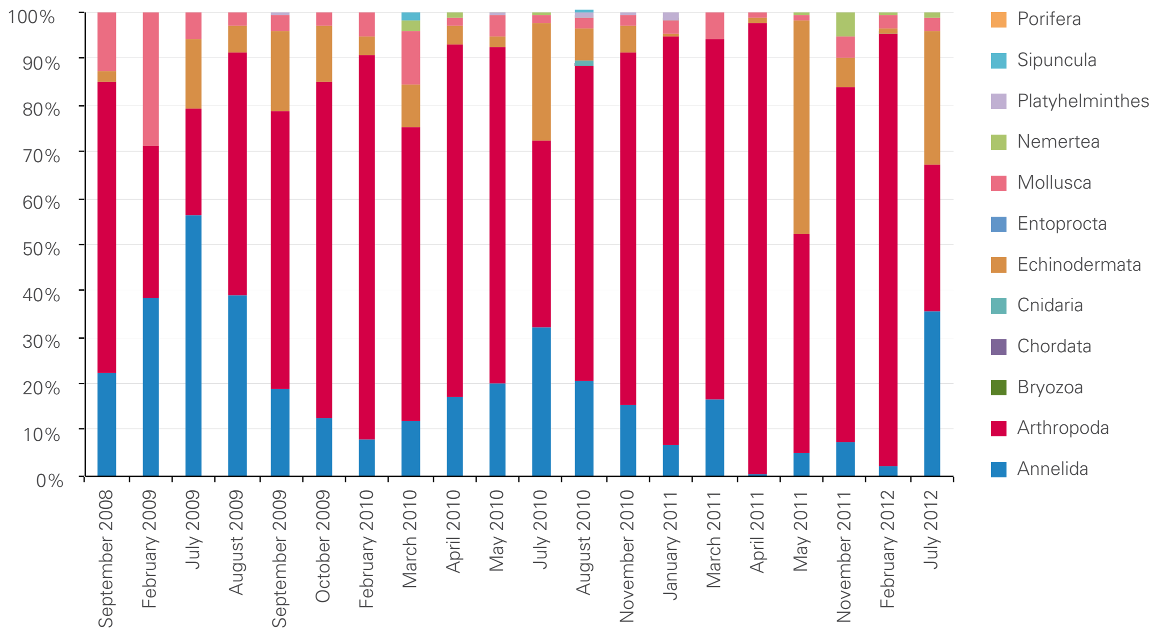


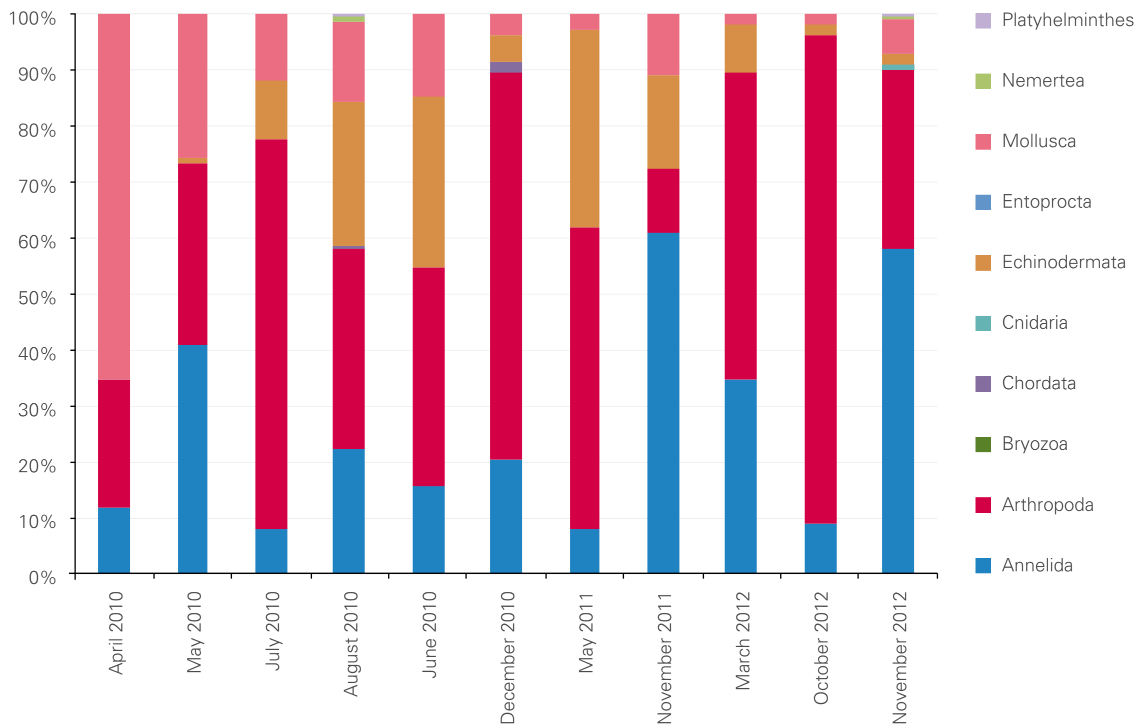
THE SUBDOMINANT SPECIES

The density of the subdominant community – i.e. the community without *J. herdmani,* Actiniaria species and both *Tubularia* species - is higher on the Thorntonbank than on the Bligh Bank, with maxima of respectively up to 2.1 10^4 and 9.0 10^3 ind/m².

The major Phyla in the subdominant part of the community throughout the monitoring are, at both sites Arthropoda and Annelida (mainly Polychaeta) (Figure 4).

Figure 4. Relative composition of the subdominant community (i.e. without *J. herdmani*, *Tubularia* species and Actiniaria species) at the Phylum level at the Thorntonbank (above) and the Bligh Bank (under)





Within the Arthropoda, acorn barnacles such as *Balanus crenatus,* are the first to appear in the subtidal succession series. *Balanus crenatus* is a typical pioneer species that generally, following an initial heavy settlement, quickly decreases in numbers after one or two years (Pyefinch, 1948). In our study, it is predated on mainly by the common starfish *A. rubens* and overgrown by other species.

Balanus crenatus

The long clawed porcelain crab *Pisidia longicornis* and the hairy crab *Pilumnus hirtellus* are two Decapoda that are common inhabitants of hard substratum communities (Ingle, 1980; Zintzen et al., 2008b). They are found on the foundations from the first summer onwards. Remarkably, we found only small individuals of *P. hirtellus* (< 1 cm) on the foundations. They do not seem to attain their maximum length of up to 3 cm in this habitat. On offshore buoys for instance, where the species also often occurs, they grow much larger.

Pisidia longicornus

Pilimnus hirtellus

From the second year onward, the main Arthropoda on the foundations were amphipods. In total, ten different species were identified, half of them restricted to one of the two areas. Three species were found only on the Thorntonbank (*Aora gracilis, Atylus swammerdami, Hyperia galba*), but all of them just at one sampling occasion, and two were found only on the Bligh Bank: *Caprella linearis* was found only once, while *Stenothoe marina* was found at four sampling occasions, but never exceeding 150 ind/m^2. Two other stenothoid species were found in both areas. *Stenothoe valida* is the most abundant, with maximum densities up to 7000 ind/m^2 on the Thorntonbank and 1000 ind/m^2 on the Bligh Bank. *Stenothoe monoculoides* occurred only occasionally, with overall only four samples where more than one specimen was found. Stenothoid species typically occur in close relationship with hydroids (Gili et al., 1995): we indeed found a correlation between the occurrence of *S. valida* and *Tubularia larynx,* which was more clear on the Thorntonbank than on the Bligh Bank.

Stenothoe sp.

On the Thorntonbank, the amphipod *Monocorophium acherusicum* managed to establish a population on the foundation, after *J. herdmani* already reached high densities. This is unexpected, since both species occupy a similar niche. They are both tube-building amphipods filtering fine sediments from the water column to build their tubes. We would expect a strong competition for space and resources.

Monocorophium sp.

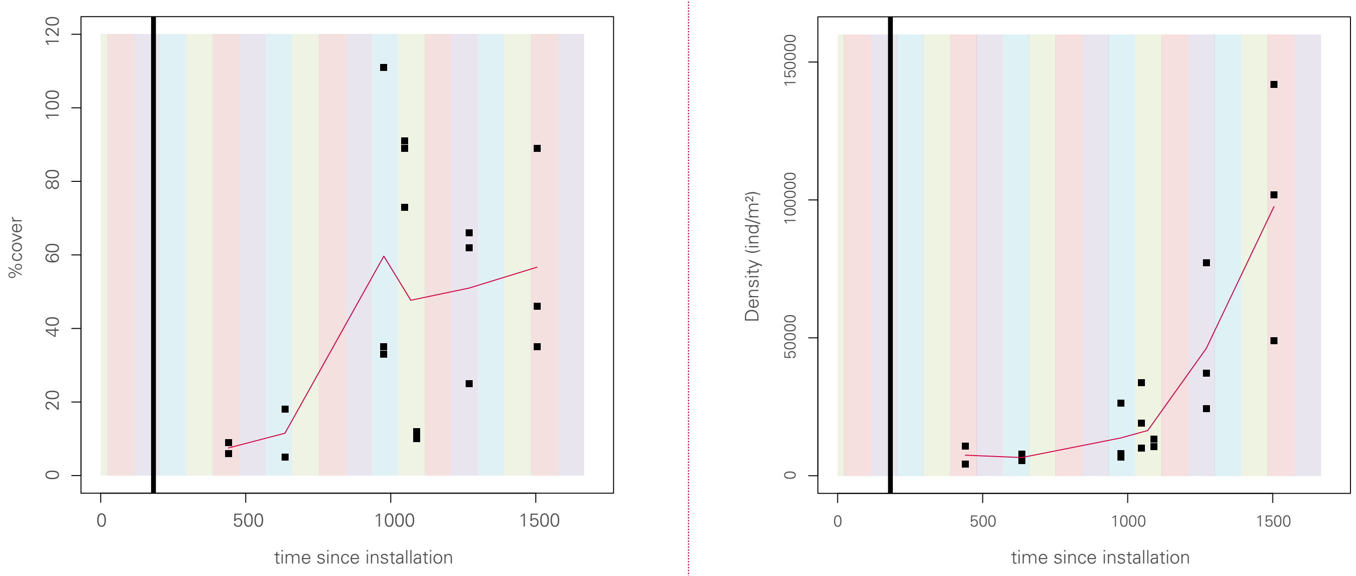
The polychaete worms showed a seasonal trend. *Phyllodoce mucosa, Lanice conchilega, Eunereis longissima* and *Harmothoe extenuate* were mainly found in summer. This results generally in higher polychaete densities (mostly more than 1000 ind/m^2) than in other seasons (generally less than 500 ind/m^2). The last two years of the succession, the keelworm *Pomatoceros triqueter* was the dominant polychaete species on the Bligh Bank, but their densities are highly variable (ranging from 60 to 4000 ind/m^2). *Pomatoceros triqueter* builds calcareous tubes firmly attached to the substratum and is characteristic for communities on both natural and artificial reefs. Its population seemed to be developing well on the foundations of the Thorntonbank in the second year of the succession, with densities up to 700 individual per m^2, but in the last year it did not exceed 100 ind/m^2. Other species thrive better on the Thorntonbank: the greenleaf worm *Eulalia viridis* and *Lepidonotus squamatus* are both observed at almost every sampling occasion on the Thorntonbank while they were only found at the start of the succession on the Bligh Bank.

Pomatoceros triqueter

THE SCOUR PROTECTION

The scour protection was studied on the Thorntonbank. The succession of the fouling community on the scour protection does not entirely develop in parallel with that on the foundations of the wind turbines. The seasonal pattern, as was seen on the foundations, did not appear and the scour protection seems to be colonised more slowly. The density of the countable species is still increasing at the end of the monitoring series, while the coverage seems to have reached its maximum (Figure 5). Total species density was generally higher on the foundations than on the scour protection. This is mainly due to the high number of *J. herdmani* on the foundations. This species was found in lower densities on the scour protection, but the numbers were considerably increasing at the end of the monitoring, with a maximum density of 1.1 10^5 ind/ m², while before it did not exceed 1.7 10^4 ind/m². When *J. herdmani* was excluded from the analysis, densities were not consistently higher on the foundations than on the scour protection or *vice versa*.

Figure 5. Coverage (%) and density (ind/m2) on the scour protection on the Thorntonbank. Black dots represent observations in each replicate; the red line connects seasonal averages. The background colours represent the seasons (green: spring, red: summer, purple: autumn, blue: winter). The numbers on the X-axis represent the number of days after installation of the foundations. The vertical line represents the approximate time the scour protection was put in place.



Similar to the foundations, species arriving early in the succession are more likely to establish than species arriving later. Out of a total of 80 species, 23 (28.8%) were found in more than 75% of the samples after the first observation. Twelve of these species were observed for the first time at the first sampling occasion, five at the two following samplings. At each sampling occasion, there are generally more species found on the scour protections than in the scrapings, on average respectively 33.8 and 27, and relatively more species are rare (on average 4.1 versus 2.1 species). The three dimensional complexity of the stones might provide a suitable habitat to a larger range of species. Additionally, the dense growth of mainly *J. herdmani* on the foundations can prevent the settlement of certain organisms. However, the sampled surface of the stones of the scour protection is sometimes higher, which can cause some bias as the chance of encountering more (rare) species increases with an increasing sampling surface.

The species composition differs between the foundations and the scour protection. *Monocorophium acherusicum* apparently thrives better on the scour protection than the other tube building amphipod *J. herdmani*, especially early in the colonisation period. Another amphipod that is mainly found on the scour protection is *Phtisica marina*, with maximum densities of 1500 ind/m², compared with 400 ind/m² on the foundations. During the last monitoring year, *P. marina* was no longer found on the foundations, while it still occurred on the scour protection with densities of up to 200 per ind/m². Within the stenothoid species, a spatial segregation occurs: *S. valida* was more numerous on the vertical surface of the foundations, while *S. monoculoides* was almost exclusively found on the scour protection.

The barnacle *Verruca stroemia* colonises the scour protection after *Balanus crenatus* has disappeared. The dense *J. herdmani* turf probably hinders the settlement of *V. stroemia* on the foundations. *Tubularia indivisa* en *T. larynx*, both dominant on the foundations (maximum coverage of 90%), are much less abundant on the scour protection, with a maximum coverage of 15%. Only Actiniaria are equally abundant in both microhabitats.

IN CONCLUSION

Similar colonisation patterns are observed on the Bligh Bank and the Thorntonbank. The subtidal community on the foundations of the wind turbines and scour protection are largely formed during the first two years after the substrata have been introduced in the marine system. Afterwards, several species reach the substratum, but most of them are not able to establish a population or become an important member of the fouling community. Most of the species found are hard substrata species, consequently they are new to the area.

Despite large overall similarities, also some differences in the community composition are found between the wind farms. Some species are restricted to, or develop better in, one area. This can be due to the different water masses that reach the windfarms, and/or the different type of substrata that are available, with concrete foundations on the Thorntonbank and steel monopiles on the Bligh Bank.

The species diversity of the fouling community on the scour protection is higher than on the foundations. This might be due to the higher complexity of the stony scour protection, providing a suitable microhabitat for a wider range of species. Additionally, because *J. herdmani* is less dominant and the stones are not densely covered by their tubes, the settlement of new species might be less hampered than on the foundations. On the other hand, the sampling surface of the stones is sometimes larger, increasing the chance of finding more (rare) species.

There appears to be a spatial segregation, with some species preferring either the scour protection or the foundations. Although both structures are artificial hard substrata, they constitute different habitats. The steep vertical structure of the foundations is unusual in the marine ecosystem, and has no natural counterpart in the North Sea. Because they lack any structural complexity, they can be expected to provide a particular environment. The fouling community we found is typical and similar to what has been described on vertical surfaces of for instance shipwrecks. The stones of the scour protection on the other hand, are more complex with differently orientated surfaces and holes where species can find shelter. This resembles more the natural hard substrata, however the community occupying the scour protection is different.

The long-term continuous monitoring has proven to be valuable in interpreting the patterns on the foundations. Yearly and seasonal variation is high, but the frequent sampling over a four year period, allowed a reliable interpretation of the data.

Hydractinia echinata covering empty *Balanus perforatus*

FURTHER MONITORING

In the future monitoring, we will continue to sample the wind farms that have been studied already for several years, and discussed in this chapter, but also (some of) the new wind farms yet to be built will be included (Chapter 2).

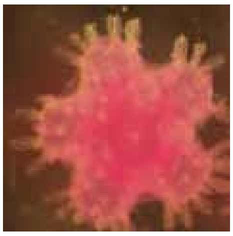
The monitoring program has until now focussed on detailed patterns at species level on and near a number of selected wind turbines. Emphasis in the future will be put on larger scale processes. The time series we collected has resulted in a good understanding of the colonisation and of the dynamics early in the succession. We see a stabilisation of the community development, especially on the foundations. The focus of the research will now move on to studying a larger surface area on the foundations to better understand the spatial heterogeneity. This will be done through the analysis of video and/or photo images. Video images allow qualitative analysis of large surfaces. The advantage of photo images is that the same quadrants can be observed repeatedly in a non-destructive manner, allowing the same area to be studied through time. With the knowledge of the food preferences of some – economically valuable – species, a better assessment of food availability for the higher trophic levels can be made, and a better knowledge of the position of the fouling community in the marine food web could be gained.

Another up-scaling will be done by shifting the focus from few wind turbines to the processes and dynamics along an onshore-offshore gradient. This will allow assessing the influence of environmental variables, such as suspended particulate matter concentration, on the colonisation trajectories and zonation patterns at offshore wind turbines.

For the monitoring of the scour protection, emphasis will be put on the use of the artificial reefs by larger animals, such as crabs and lobsters which can use the stony reef for shelter. Divers reported their presence, but the current sampling techniques do not allow studying their abundance and distribution over the reef. Traps can help analysing the megafauna community composition and their size and sex distribution. Video-based analyses or observations by divers will give better insights in their spatial distribution over the artificial reef.

The biological sampling, by scraping fouling of the foundations and collecting stones of the scour protection, will be continued, but the temporal resolution could be reduced, e.g. samplings once per year rather than once per season. Additionally, biomass will be determined, which will, in combination with the photo-images, allow a better understanding of the food availability for higher trophic levels.

Lobster *Homarus gammarus*

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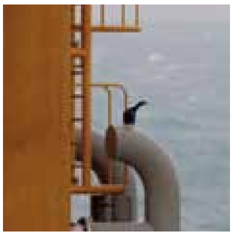
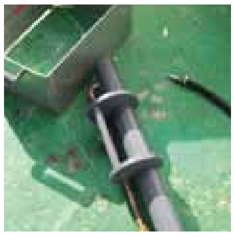
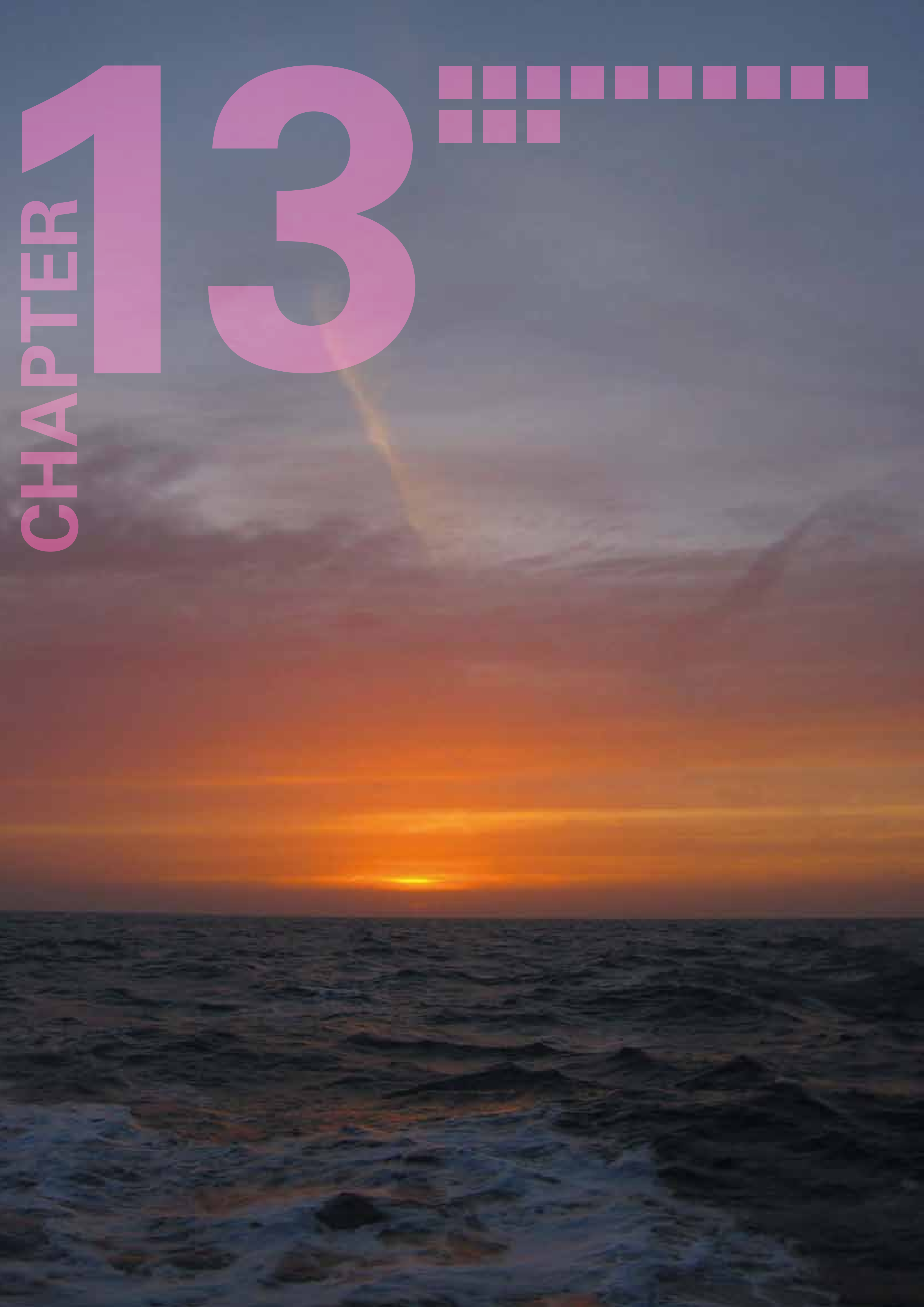




PART III

UNDERSTANDING ECOLOGICAL PROCESSES BEHIND OBSERVED PATTERNS – LOCALISED PRODUCTION, NET ECOSYSTEM PRODUCTION AND ATTRACTION

CHAPTER 13



Macrobenthic enrichment around a gravity based foundation

Delphine Coates, Yana Deschutter, Magda Vincx and Jan Vanaverbeke

Epifaunal growth and changing hydrodynamics alter the soft-substrate and macrobenthic community around a foundation. The sediment and macrobenthos was sampled close to a foundation from 2010 to 2012. Observations were most notable on the Southwest side with changes recorded up to 50 meter distance. A decrease in sediment grain size and increase of organic matter content was observed, together with an enriched macrobenthic community with a dominance of hard substrate related species. However, average densities of two bristle worms increased in comparison to the baseline studies, resulting in a young and dynamic macrobenthic community evolving away from the original (*Nephtys cirrosa*) community.

INTRODUCTION

The large scale monitoring programme revealed an effect on the soft sediment macrobenthic community straight after construction on the Thorntonbank in 2008, most likely due to the pre-construction dredging activities (Chapter 9). It was concluded that effects of the operational phase on the entire wind farm could only be measured over longer time frames or at a smaller scale. Previous studies around artificial foundations showed a change in the dominance structure of the macrobenthic community directly around foundations (1m distance), with an increase of predominantly mobile predators (Köller et al., 2006). An enhanced hard substrate community and changing local hydrodynamics around a foundation can also enrich the macrobenthic community in abundance and biomass (Maar et al., 2009). To detect local, short term effects after construction, a small scale study was initiated in 2010 following a close gradient of sampling around one gravity based foundation (GBF – D5 at the Thorntonbank). Only two years after construction (2010) it was obvious that the hard substrates were rapidly being colonised by epifaunal organisms (Kerckhof et al., 2012) together with an increase of pouting (*Trisopterus luscus*) and Atlantic cod (*Gadus morhua*) in the vicinity of the turbines (Reubens et al., 2010; Reubens et al., 2013a). This can cause an organic enrichment around the foundation, due to the depositional flow of faeces and other organic material onto the seabed (Coates et al., 2011; Köller et al., 2006). The enrichment of sediments around structures such as mussel farms has widely been reported before (McKindsey et al., 2011; Ysebaert et al., 2009). However, few surveys have been able to determine the effects of this process on macrobenthic communities around offshore wind farms (Zucco et al., 2006). Furthermore, the seabed around the foundation was thoroughly dredged and prepared before construction. Together with the installation of the foundation, its surrounding scour protection system and possible changing hydrodynamics, this could lead to changing sedimentological characteristics, also altering the benthic community directly around the foundation (Brabant and Jacques, 2010; Hiscock et al., 2002).

The main objective of this study was to investigate the organic enrichment and sedimentological characteristics of the surrounding sediments around a GBF between 2010 and 2012 and its possible effects on the macrobenthic community. The results were applied to hypothesise an extrapolation of the eventual small scale effects of organic enrichment to a large scale impact after longer exposure periods.

SAMPLING DESIGN

Sediment characteristics and the macrobenthic community were monitored in the vicinity of one GBF (D5) which was installed on the Thorntonbank in 2008 (Table 1). Over a period of three years (2010-2012) sediment samples were obtained around the foundation during spring along four gradients (Southwest, Northeast, Southeast and Northwest). Along every gradient, seven distances were sampled starting at one meter around the scour protection system (further named as foundation) to a maximum distance of 200 meters which was taken as a reference station (Figure 1). Samples on the Northeast gradient were limited to 1, 7, 100 and 200 meters due to the presence of high power cables on the seabed, preventing sampling at 15, 25 and 50 meters distance. The main tidal flow in this area runs along the Northeast and Southwest direction (Van den Eynde, 2005).

Table 1. Summary of the small scale monitoring phase carried out around one GBF from 2010-2012.

SMALL SCALE BENTHIC MONITORING D5 TURBINE THORNTONBANK				
2010	2011		2012	
Dive samples 4 gradients	1 Dive sample on Southwest	Van Veen samples	Dive samples on 4 gradients	Van Veen samples

Closest samples at one and seven meters were obtained by using an airlift suction device and benthic cores handled by SCUBA divers trained to a European scientific diving level. Samples taken at 15, 25, 50, 100 and 200 meters from the foundation were collected with a Van Veen grab from a small survey vessel (Box: Benthic sampling methods) with three replicates when possible. Due to the difference in sampling methods the samples were investigated separately. Logistical problems (weather conditions, construction works inside the wind farm, etc.), only allowed for a complete dive sampling in 2010 and 2012, and a complete Van Veen grab sampling in 2011-2012. Due to limited dive time, replication was very difficult to obtain, only providing two replicates on the Southwest and Northeast gradients in 2012 at one and seven meters. Replication on the Southeast gradient between 15 and 200 meters was missing in 2012 due to bad weather conditions. Sediment characteristics of the seabed, such as grain size and organic matter content, were analysed for every sample. The number of individuals per species (abundance) and the biomass were standardised per square meter and averaged for every station. Together with diversity indices (such as species number per sample) this data provides information on the evolution of the macrobenthic community in sandy areas surrounding the gravity based foundation.

Sampling in an offshore wind farm

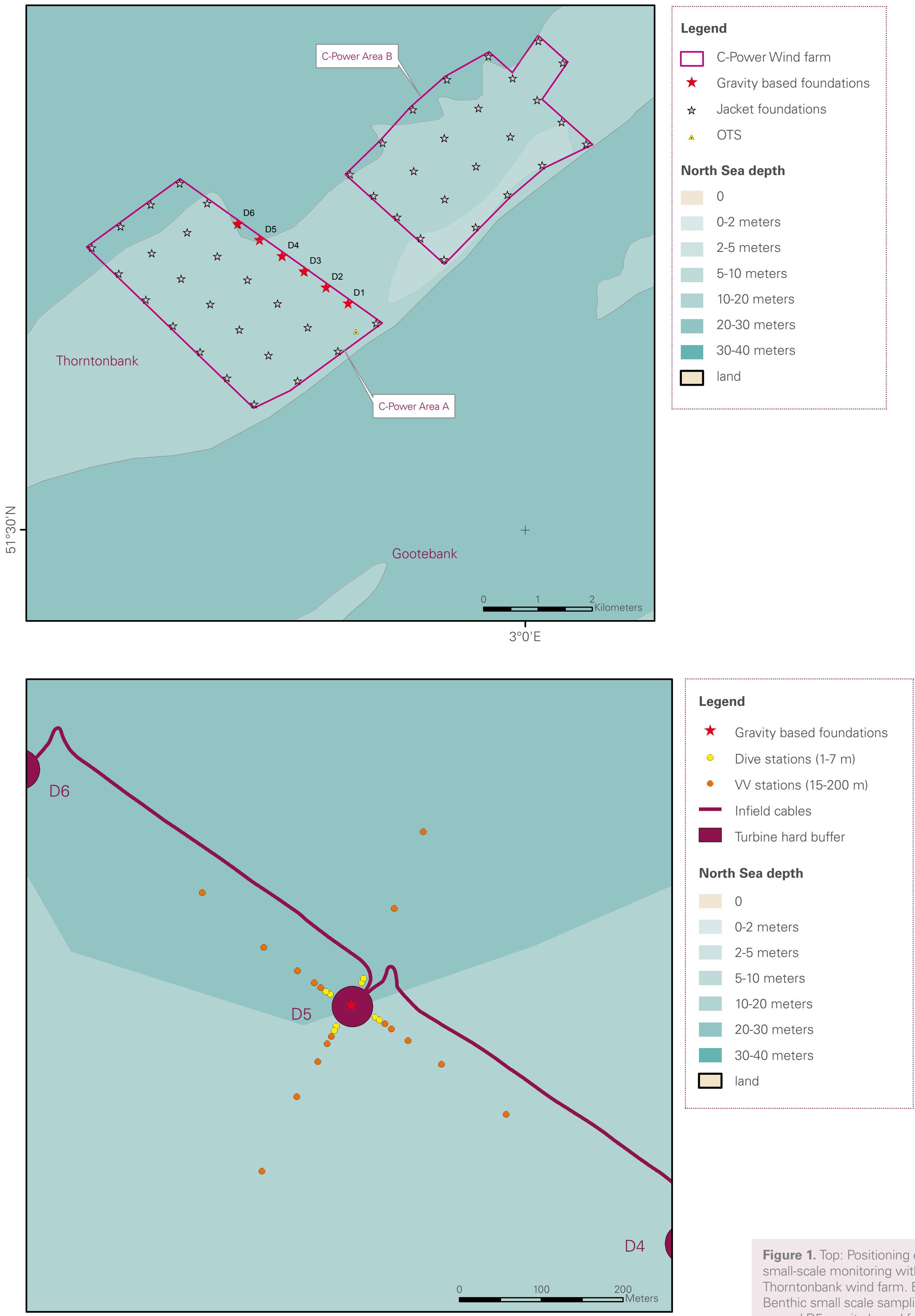


Figure 1. Top: Positioning of the small-scale monitoring within the Thorntonbank wind farm. Bottom: Benthic small scale sampling design around D5 gravity based foundation. Stations close to the turbine (yellow) were collected by divers, stations further away (orange) were sampled with a Van Veen grab.

BOX: Benthic sampling methods

Air-lift suction: A plastic cylinder open on both sides is used to sample benthic organisms in the soft sediment close to hard structures such as wind farms and wrecks. On one side, the cylinder is attached to a diving tank to produce the desired amount of pressure; suction is made by the movement of air inside the cylinder. The sample is collected in a mesh bag (0.5 mm) connected to the other side of the cylinder. A fixed amount of sediment can then be sampled using a metal frame (0.1026 m²) as a reference (www.mumm.ac.be).

Benthic cores: A frame with perspex cores with a diameter of 36 mm is taken down to the seabed by divers to sample vertical profiles of the sediment. These cores are sliced and dried in preperation for analysis of the grain size and organic matter content.

Van Veen grab: A grab sampler is the most common used device to sample benthic organisms in sandy sediments. When the device reaches the seafloor and the cable slackens, the grab digs into the seabed and closes. Grab samplers vary in size with 0.1026 m² as the most commonly used. For this research a smaller grab of 0.0247 m² was used due to the limitations imposed by the small research vessel. Through a lid on top of the grab, a sub sample for sediment analysis can be taken with a Perspex core.

THE ENVIRONMENTAL CHARACTERISTICS OF THE SEABED AROUND THE GBF

Across the Belgian part of the North Sea a wide variety of sediment types occur ranging from fine mud to coarse sands. The main sediment type recorded on sandbanks situated within the Belgian wind farm zone is coarse sands with an average grain size ranging from 250 µm to 500 µm (De Maersschalck et al., 2006; Reubens et al., 2009).

Near the D5 foundation, the average median grain size ranged between 275 µm and 430 ± 87 µm. An inter-annual variability was measured on all gradients except for the Northwest. Figure 2 (showing the values for the Southwest gradient), describes the main trend distinguished on all gradients (except the Southeast) with significantly lower grain sizes at 1 m from the foundation in comparison to the furthest station at 200 m.

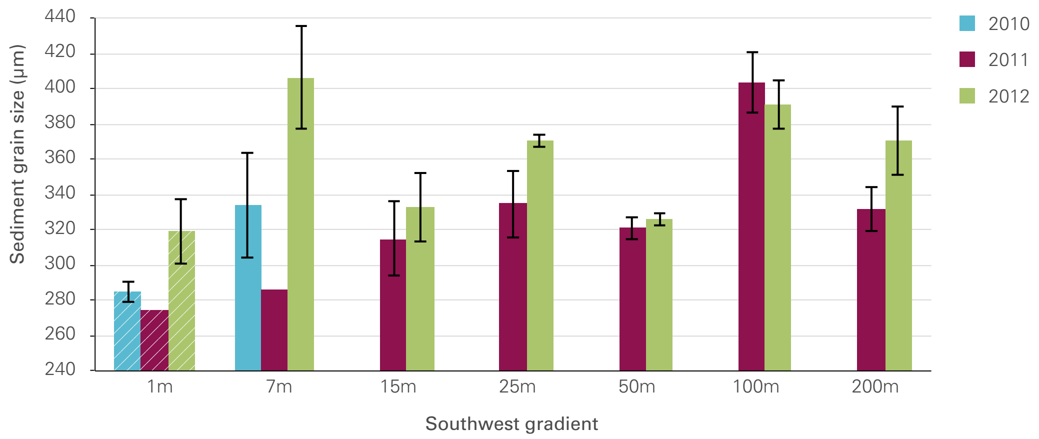


Figure 2. Average median grain size (µm) ± standard error from 1 m to 200 m on the Southwest gradient. Striped bar indicates significantly lower values ($p<0.05$) compared to 200 m by pairwise comparisons (PERMANOVA).

During the construction phase in 2008, the seabed was levelled out by dredging and replaced by a foundation layer containing crushed gravel. After construction, a scour protection system (Figure 1) consisting of a filter layer with a crest diameter of 55.5 m at D5 and an upper armour layer with a crest diameter of 51 meters was installed (Brabant and Jacques, 2010; Peire et al., 2009). At first, this process will have affected the sedimentological characteristics of the seabed around the foundation but due to a strong inter-annual variability between 2010 and 2012, changing hydrodynamics will have most likely dominated the refinement process with declining current speeds along the Southwest and Northeast gradients.

The average total organic matter (mass %) ranged from 0.27% at 1 m distance (2010, Northwest) to 2.46% at 15 m distance (2012, Southwest) from the GBF. One peak value of 9.79% at 7 m distance from the GBF was recorded in 2011 on the Southwest gradient (Figure 3). Apart from that, no clear trends or significantly different organic matter contents were measured. However, in comparison to the large scale monitoring (Chapter 9) where a maximum average of 1.15% was recorded, the average total organic matter around the GBF shows a trend to higher values. These results suggest that the organic material of species growing on the hard substrate (foundation and the scour protection) are contributing to the changing sedimentological conditions of the seabed.

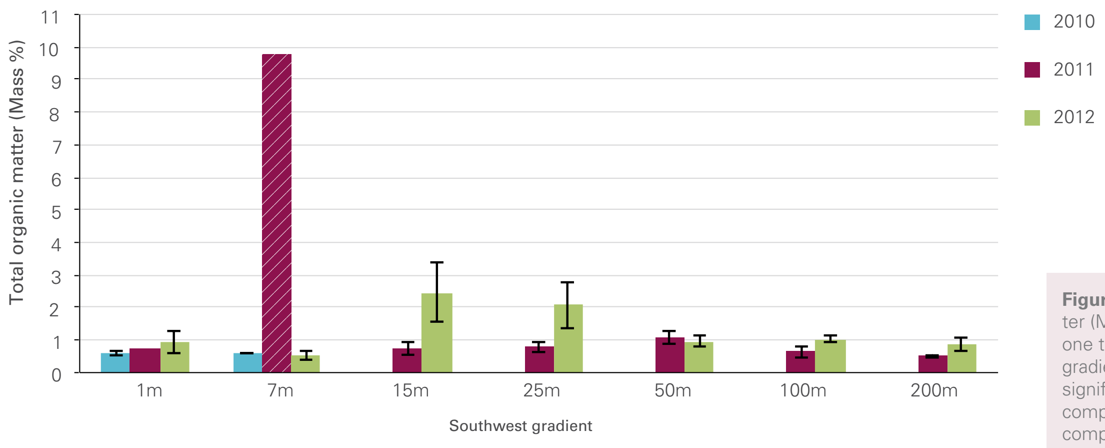


Figure 3. Average total organic matter (Mass %) ± standard error from one to 200 m on the Southwest gradient. Striped bar indicates significantly lower values ($p<0.05$) compared to 200 m by pairwise comparisons (PERMANOVA).

A CLOSE UP ON THE SPECIES COMPOSITION DIRECTLY AROUND THE FOUNDATION

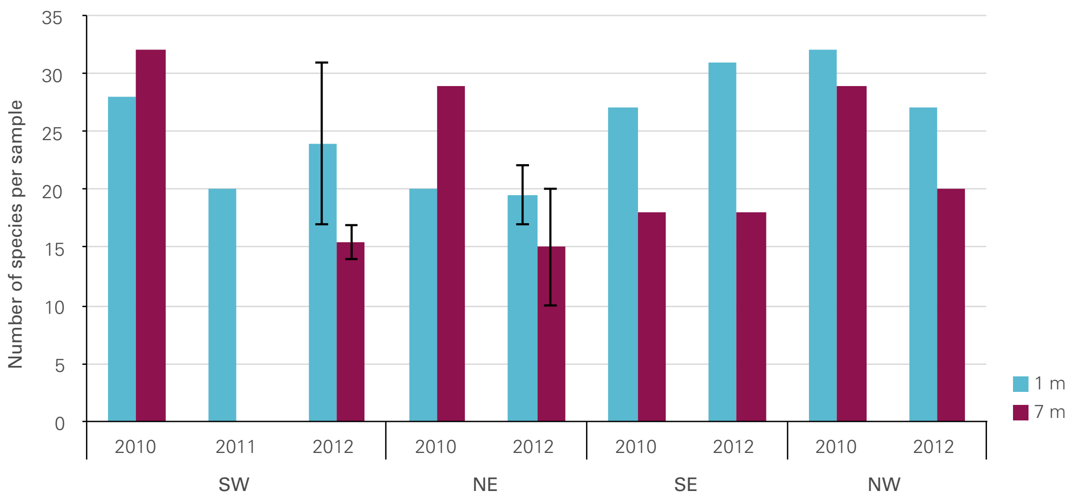
Near the scour protection system at 1 and 7 m, the highest average macrofaunal density, biomass and number of species were measured on the Southwest gradient in 2010 (Figure 4). In 2012 however, a maximum average biomass was only measured on the Southwest gradient. Higher densities and number of species were observed along the Southeast gradient.

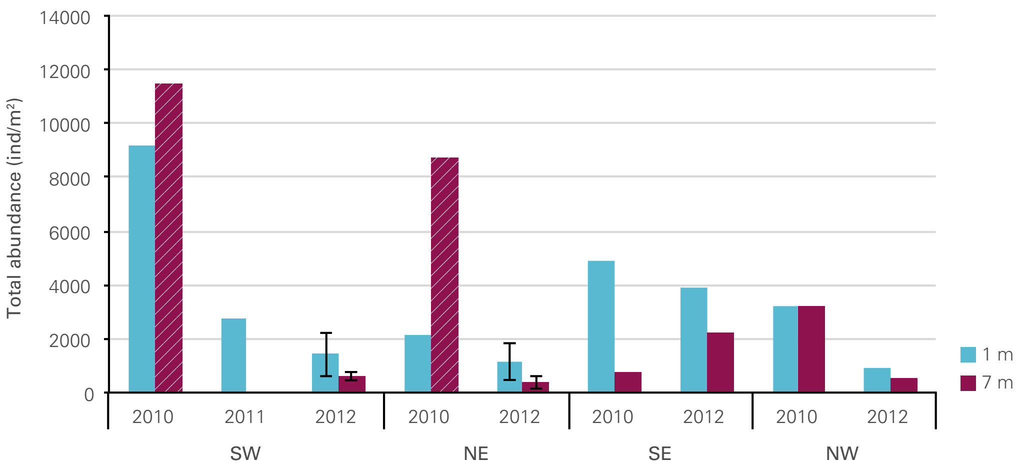
In 2010, the maximum average number of species per sample was 32 both for the Northwest and Southwest gradients at 1 and 7 m respectively (Figure 4, top). The average minimum was recorded on the Southeast gradient at 7 m with 18 species per sample. Slightly lower species richness was measured in 2012 ranging from 31 species at 1 m on the Southeast to 15 species at 7 m on the Northeast gradient.

An average maximum density of 9162 ind/m² was measured at 1 m and 11501 ind/m² at 7 m away from the GBF on the Southwest gradient in 2010. Lower densities were found in 2012 ranging between 3899 ind/m² at 1 m on the Southeast gradient to 361 ind/m² at 7 m distance from the GBF on the Northeast gradient (Figure 4, bottom).

Macrofaunal biomass followed a similar trend to the densities with a maximum on the Southwest gradient in 2010 and 2012. The biomass ranged from 9537 mg.m^{-2} at 1 m (Southwest gradient) to 498 mg.m^{-2} at 7 m distance (Southeast) in 2010. In contrast to the densities, the biomass in 2012 was comparable to 2010 ranging from 5864 mg.m^{-2} at 1 m (Southwest gradient) to 109 mg.m^{-2} at 7 m (Northeast).

Figure 4. Top: Average total number of macrobenthic species per sample ± standard error and Bottom: Average total macrobenthic abundance (ind/m²) ± standard error, at 1 and 7 m along the four gradients for 2010-2012. Striped bar indicates significantly higher values (p<0.05) between 2010 and 2012 within gradients by pairwise comparisons (PERMANOVA).





The high average macrofaunal abundance on the Southwest gradient in 2010 was mainly related to the occurrence of juvenile starfish (maximum of 4961 ind/m² at 7 m). Juvenile echinoderms showed dominance in 2010 on the Northeast and Northwest gradients with a maximum abundance of 2943 ind/ m² at 7 m on the Northeast gradient (Figure 5).

A similar assemblage of dominant species was recorded on the Southwest and Northeast gradients, with high densities for the juvenile starfish (*Asterias rubens*) and two polychaete worms (the sand mason *Lanice conchilega* and the bee spionid *Spiophanes bombyx*). A maximum density of 1949 ind/m² for *L. conchilega* and 1082 ind/m² for *S. bombyx* were both measured at 7m on the Northeast in 2010 (Figure 6).

A typical tube dwelling, hard substrate amphipod, *Monocorophium acherusicum,* had higher densities on the Northwest and Southeast gradients with a peak density at 1m on the Southeast gradient (2778 ind/m²). A second tube dwelling amphipod, *Jassa hermani,* illustrated a relatively stable distribution across the four gradients with average maxima in 2012 of 809 ind/m² at 1 m on the Southeast gradient and in 2010, 730 ind/m² at 7 m on the Southwest. As *M. acherusicum* and *J. herdmani* are one of the most abundant hard substrate species recorded within the wind farms (Kerckhof et al., 2012) it is not surprising that these mobile amphipods easily find their way to the soft substrate community.

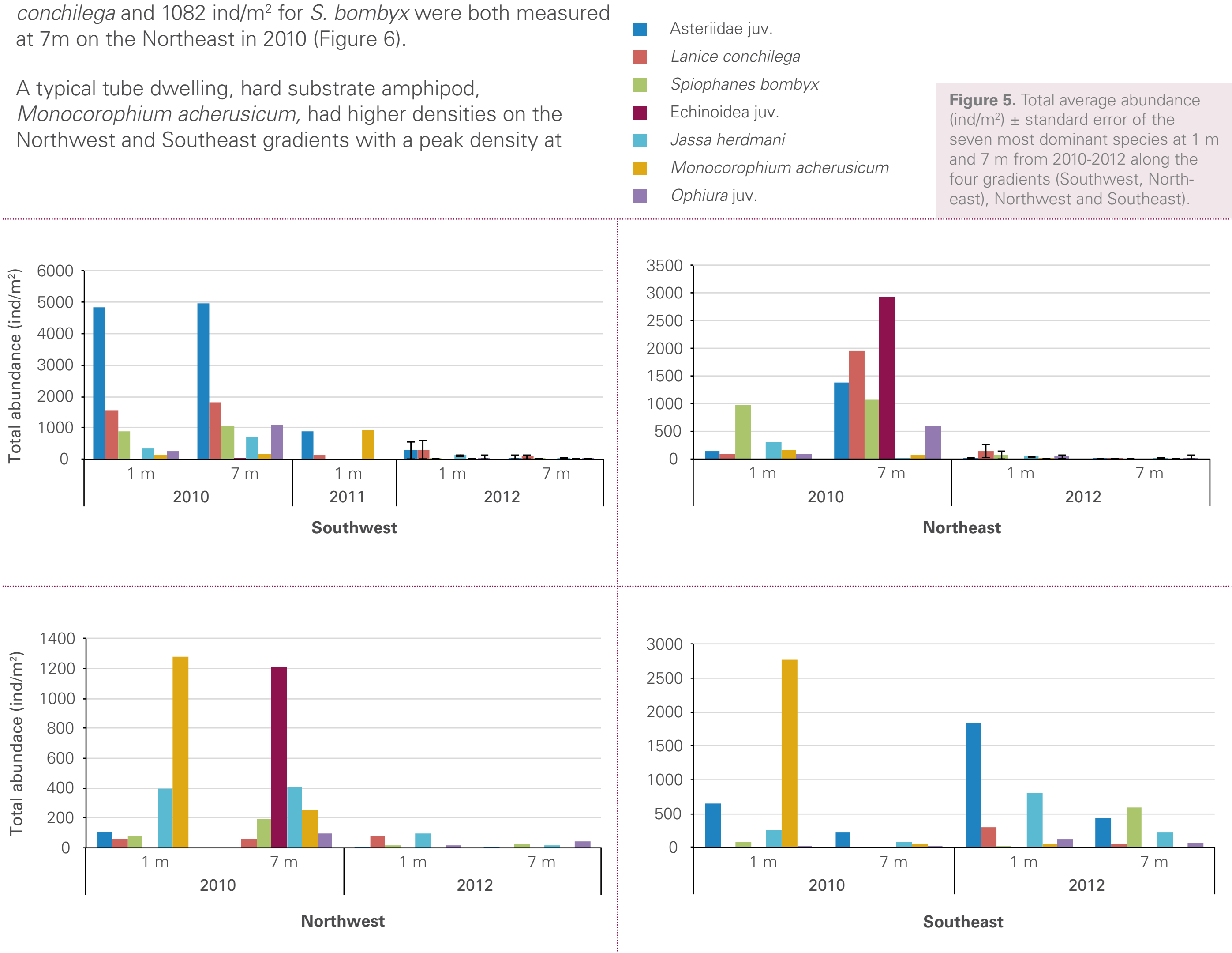


Figure 5. Total average abundance (ind/m²) ± standard error of the seven most dominant species at 1 m and 7 m from 2010-2012 along the four gradients (Southwest, North-east), Northwest and Southeast).

Figure 6. Dominant species around the GBF on the Thorntonbank

Left above:
Sand mason, *Lanice conchilega*

Right above:
Bee Spionid, *Spiophanes bombyx*

Left under:
Monocorophium acherusicum

Right under:
Jassa herdmani

AN EVER SPATIALLY EXPANDING BENTHIC ENRICHMENT?

From 15 to 50 m distance around the foundation, the average number of macrofaunal species per sample was significantly higher on the Southwest gradient in comparison to 200 m distance. In 2011, a maximum average of 25 species per sample was found at 25 m on the Southwest gradient and 18 species per sample at 25 m on the Northwest. A higher average of species richness was found in 2012 with a maximum average of 30 species per sample at 15 m on the Southwest gradient and 23 species per sample at 100 m on the Northwest (Figure 7).

The total number of species around the foundation was much higher in comparison to the baseline study carried out in 2005 (see chapter 9), where the maximum amount of species per sample did not exceed 15 (De Maersschalck et al., 2006). Biomass followed the same trend on the Southwest gradient with a maximum of 13461 mg.m^{-2} at 25 m in 2011 and 12009 mg.m^{-2} at 15 m in 2012.

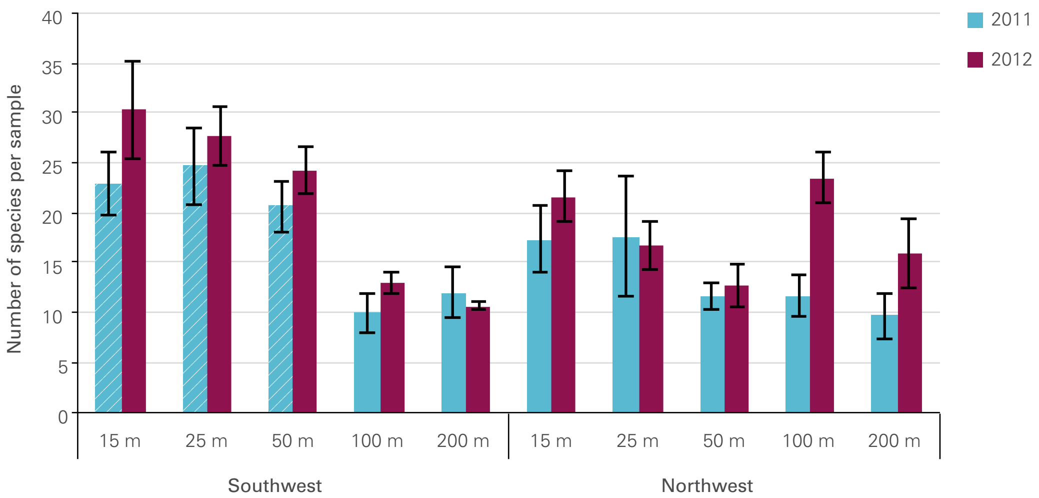
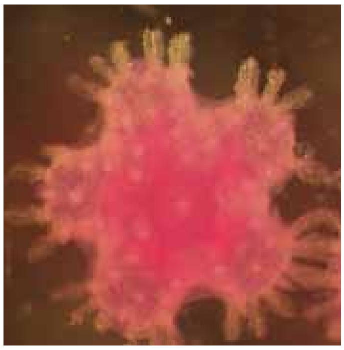


Figure 7. Average total number of macrobenthic species per sample ± standard error, from 15 to 200 m along the four gradients in 2011 and 2012. Striped bar indicates significantly higher values (p<0.05) compared to 200 m within gradients by pairwise comparisons (PERMANOVA).

An extremely high average density (62227 ind/m^2) was recorded in 2011 on the Southwest gradient at a 25 m distance from the foundation. Following the observations in 2010 at 1 and 7 m, these high densities along the Southwest gradient were caused by the occurrence of countless number of juvenile starfish (Figure 8). The spawning time and recruitment intensity of the starfish *A. rubens* has a large inter-annual variation depending on many environmental factors such as temperature and food availability (Guillou et al., 2012). Their absence during 2012 in the samples from 15 to 200 m could therefore be caused by a lower recruitment, as juvenile starfish still remained detected at 1 m on the Southeast gradient (Figure 5).



Juvenile phase of *Asterias rubens* (Asteriidae juv.)

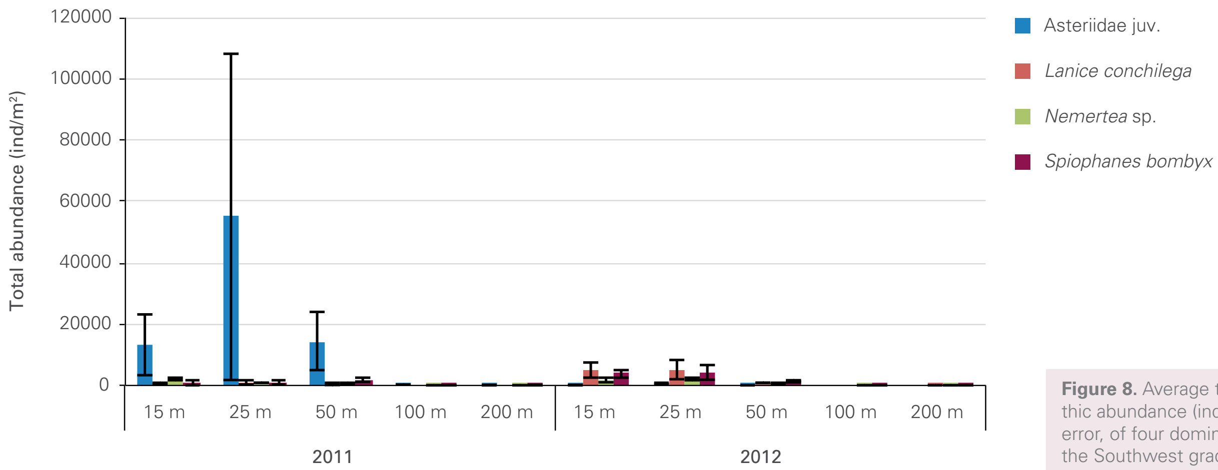


Figure 8. Average total macrobenthic abundance (ind/m^2) ± Standard error, of four dominant species on the Southwest gradient from 15 to 200 meters in 2011 and 2012.

Disregarding the juvenile starfish, the maximum and minimum macrobenthic densities for both years were situated on the Southwest gradient at approximately 15 and 200 m distance. A significant decrease in average density with increasing distance from the foundation was found on the Southwest but also the Northwest gradient. Average densities ranged from 9339 ind/m² to 1673 ind/m² in 2011 and from 18583 ind/m² to 1390 ind/m² in 2012. (Figure 9).

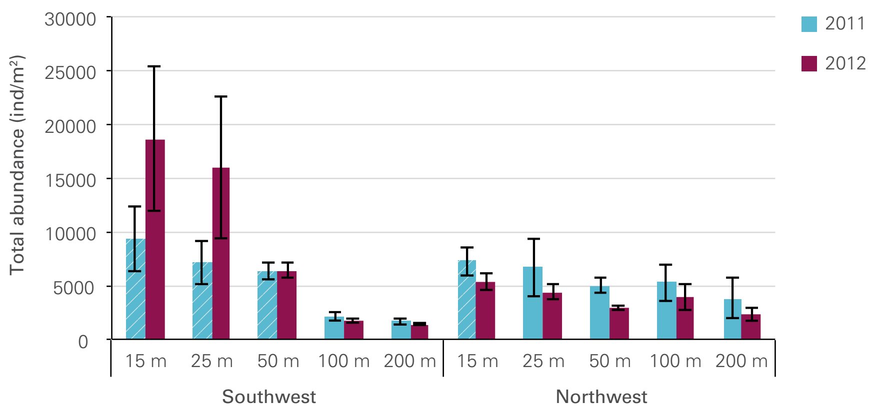
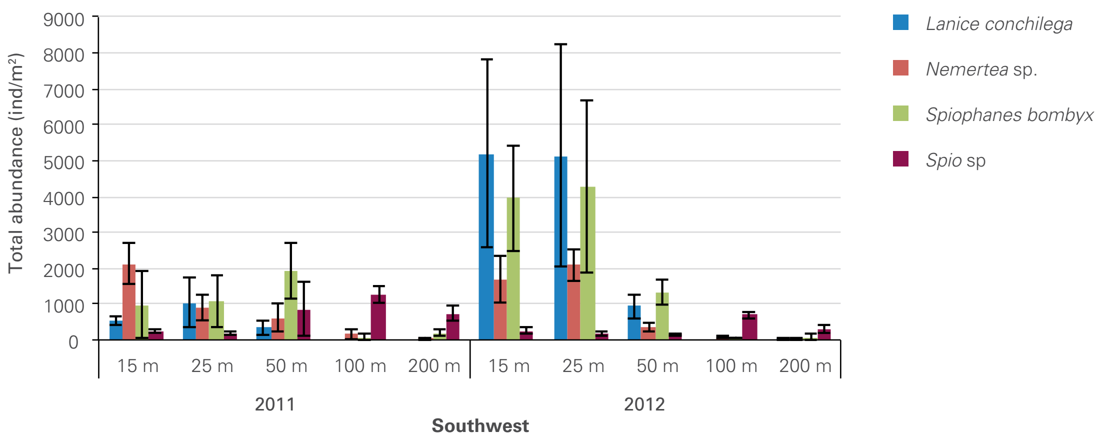


Figure 9. Average total macrobenthic abundance (ind/m²) ± standard error, from 15 to 200 m along the four gradients in 2011 and 2012. Striped bar indicates significantly higher values ($p<0.05$) compared to 200 m within gradients by pairwise comparisons (PERMANOVA).

The higher densities measured in 2012 on the Southwest gradient at 15 and 25 m could be due to a decline in juvenile starfish recruitment, providing the opportunity for other macrobenthic species to increase in density. Following the observations at 1 and 7 m in 2010, two bristle worms (*L. conchilega* and *S. bombyx*) showed an increase in average density close to the foundation in 2012. The maximum average density of *L. conchilega* was 5182 ind/m² at 15 m and 4291 ind/m² at 25 m for *S. bombyx* compared to 1025 ind/m² and 1066 ind/m² both at 25 m in 2011 (Figure 10, upper panel). A third dominant species belonging to the Nemertean group showed a maximum average density of 1700 ind/m² at 25 m in 2012.

On the Northwest gradient, a low recruitment of juvenile starfish was present in 2011 allowing other macrobenthic species to occupy the area. In both years however, the polychaete worm *S. bombyx* showed a clear decrease in density with increasing distance from the foundation. Maximum densities were measured at 15m with 1929 ind/m² in 2011 and 1377 ind/m² in 2012. Furthermore, the entire Northwest gradient was dominated by the bristle worm *Spio* sp. in 2011 with a maximum of 3725 ind/m² at 100 m. This pattern was not detected in 2012 (Figure 10, lower panel).



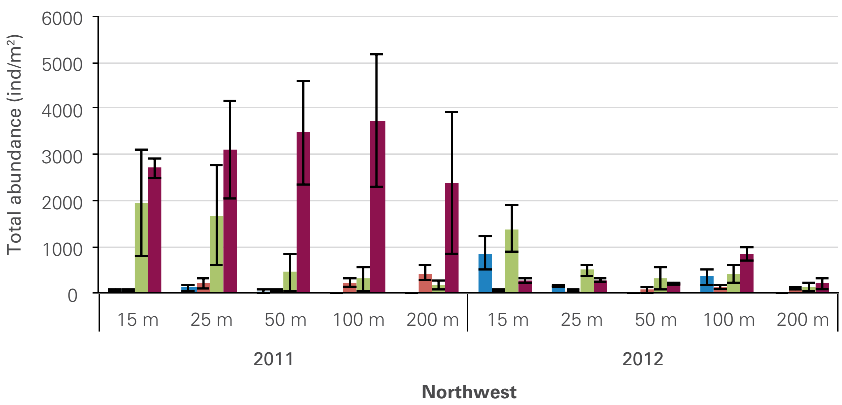


Figure 10. Average total macrobenthic abundance (ind/m²) ± standard error of the four most dominant species along the Southwest (upper panel) and Northwest (lower panel) gradients from 15 to 200 meters in 2011 and 2012.

Why would the recruitment of macrobenthic species mainly increase on the Southwest gradient? With a base diameter of 23.5 meters and a crest diameter of 55.5 meters for the filter layer of the scour protection system (Brabant and Jacques, 2010), the tidal current flow along the Southwest and Northeast gradients will decrease considerably. In the wake of the gravity based foundation, larval settlement will increase, enhancing the recruitment of macrobenthic species such as the tube forming bristle worms *L. conchilega* and *S. bombyx* but also hard substrate species such as the common starfish *A. rubens*. Enhancing this process, sand pits are present on the Southwest gradient due to dredging works in preparation of construction (Van den Eynde et al., 2010), most likely decreasing the current velocities and trapping larvae. The changes observed also correlate with the environmental variables as a finer grain size was measured on the Southwest gradient, closer to the foundation (Van Hoey et al., 2004).
As samples between 15 and 50 m were missing on the Northeast gradient, a clear evolution cannot be assessed for this gradient. However, samples taken at 1 and 7 m did also suggest an importance of the gradient with an increase in the abundance of the previously mentioned species.
The changing community detected in samples at 1 and 7 m from the foundation in 2010, has already extended up to a 50 m distance on two gradients. However, from 15 m onwards a lower influence of mobile hard substrate species such as the amphipods *M. acherusicum* and *J. herdmani* is measured.

Asterias rubens attached to a hard substrate

CONCLUSIONS

After three years of small-scale monitoring, a substantial change has been recorded in the soft sediment surrounding the D5 gravity based foundation on the Thorntonbank. The macrobenthic community has evolved away from the original (*Nephtys cirrosa*) community (Coates et al., 2011; Coates et al., 2012; De Maersschalck et al., 2006). At 1 and 7 m from the foundation, high densities were measured for the juvenile phase of the common starfish (*Asterias rubens*) and two hard substrate amphipods (*Monocorophium acherusicum* and *Jassa herdmani*), highlighting the direct effect of the presence of the wind turbine. Alongside these hard substrate species, two polychaete worms (*Lanice conchilega* and *Spiophanes bombyx*), common to the soft substrate, dominated the community but in much higher abundances than would be expected. The strong annual variability of the macrofaunal densities between gradients and years suggests an unstable young community which has not reached equilibrium thus far. Until now, the effects have been detected up to a 50 m distance from the foundation on the Southwest and Northwest gradients. Changes in sedimentological characteristics, current flows and organic enrichment due to sinking detritus and faeces are most likely the main drivers in enhancing the recruitment of certain macrobenthic species and changing the community. Our results show a strong similarity to a study carried out around a Danish offshore wind turbine where the biomass and abundance of fauna also enriched along one gradient due to the depositional flow of the Blue mussel (*Mytilus edulis*) which encompassed 97-99% of the hard substrate epifauna (Maar et al., 2009). The Blue mussel only dominates in the infralittoral zone of the GBF (see Chapter 12) but with a rich subtidal community (Kerckhof et al., 2009; Kerckhof et al., 2012) a similar flux of organic matter can be expected on the surrounding seabed.

This research focused on one of six gravity based foundations constructed on the Thorntonbank. Since 2013, this wind farm expanded with an additional 48 turbines (jacket foundations). Together with six other companies constructing or developing in this area, these results suggest a viable prediction of effects to the marine seabed at a larger scale for the future. Up scaling these results to the whole wind farm zone, with an expansion of macrofaunal densities further than 50 m around every turbine and initially in the direction of the currents, could lead to an overall change in the macrobenthic community throughout the whole wind farm zone (Figure 11).

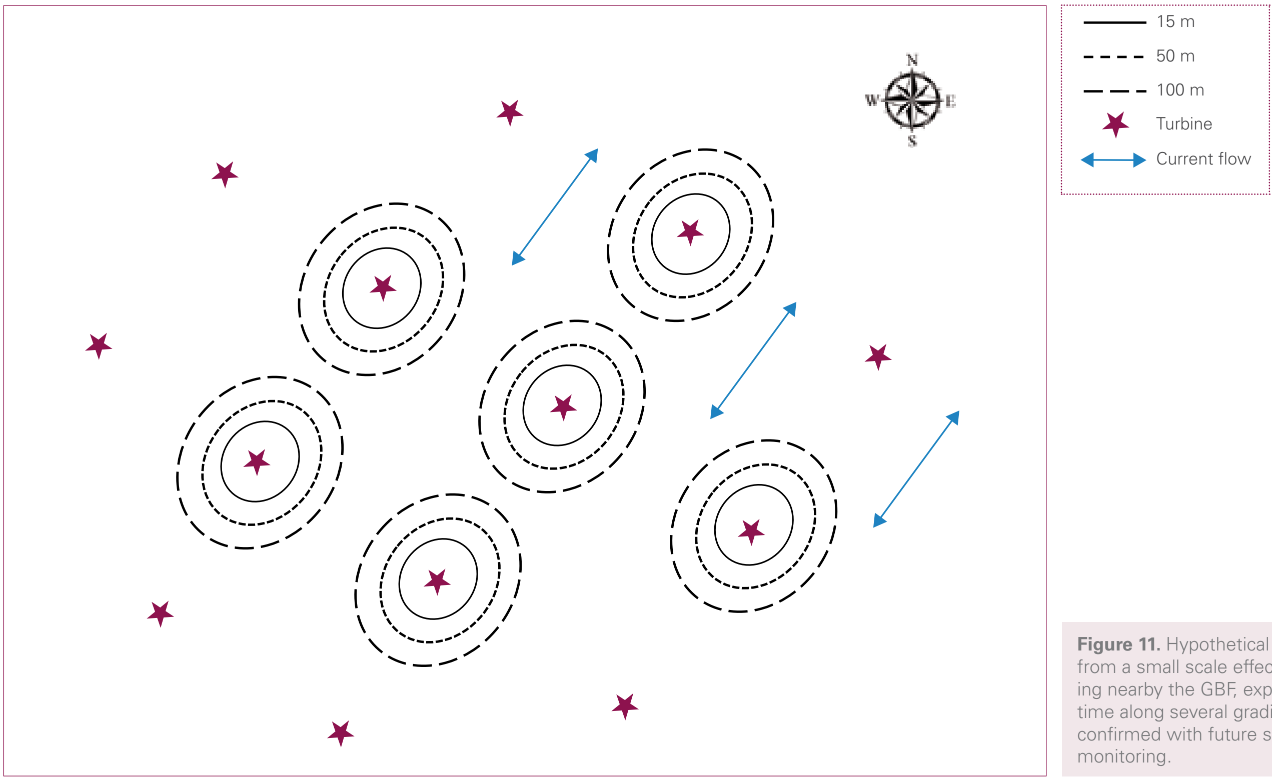


Figure 11. Hypothetical up scaling from a small scale effect, originating nearby the GBF, expanding with time along several gradients. To be confirmed with future small-scale monitoring.

FUTURE MONITORING

The small-scale, short term monitoring has proven to be essential in monitoring the effects of offshore wind farms on the soft sediment macrobenthic communities. During the coming years, gradients showing main changes in sedimentological characteristics and macrofaunal communities should be closely followed up. Furthermore, two other foundation types (monopiles and jacket foundations) have been installed in nearby areas within the Belgian offshore wind farm zone, possibly affecting the soft substrate and its macrobenthic organisms in a different way. It is advisable to carry out a pilot study around these foundations to determine whether similar changes are occurring influencing the large scale impact considerably.


CHAPTER
14

Offshore wind farms as productive sites for fishes?

Sofie Vandendriessche*, Jan Reubens*, Jozefien Derweduwen, Steven Degraer and Magda Vincx

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Artificial hard substrates in the marine environment have an influence on the local fish community. The new environment may induce some costs or benefits for the fish populations. Since the local evolution of fish stocks and the value of wind farms as management tools completely depend on the extent of the artificial reef effects at the wind farms, it is essential to identify the processes at work. Consequently, community structure, reef ecology and behavioural ecology were investigated for a number of fish species present at the offshore wind farms. The results obtained were integrated and a viewpoint on attraction/production was formulated.

INTRODUCTION

After the construction or deployment of an artificial reef, fish densities at the reef location tend to increase rapidly (Bohnsack, 1989). Two opposing, yet not mutually exclusive models have been proposed to explain these increased abundances. The attraction hypothesis suggests that fish move from the surrounding environment towards the reef. They aggregate at the reef, but there is no net increase in the local population. The fish are solely concentrated into a smaller area. The second hypothesis, the production hypothesis, assumes that the carrying capacity of the environment increases as a result of the new habitat. More fish are able to settle, survive, grow and contribute to the local population, resulting in net production (in terms of biomass and/or abundance) (Brickhill et al., 2005; Lindberg, 1997; Pickering and Whitmarsh, 1997). In the attraction-production issue, the condition of the initial fish stock present might either improve or remain as it was. There is however a third issue, more precisely the issue of the ecological trap. In this scenario, fish are attracted to, and settle preferably in a habitat with suboptimal conditions relative to other available habitats, resulting in a deterioration of the fish stock (see chapter 17).

After the construction of an artificial reef, in this case offshore wind farms (OWFs), three theoretical outcomes are possible (Figure 1). In the case of attraction, fish' growth, reproduction and mortality in the system observed will be comparable to the reference situation. The carrying capacity of the system does not change. However, spatial dispersion of the fish changes, with aggregation in some places and reduced number in others. If an ecological trap occurs, growth is reduced and/or survival rate is lower compared to the reference situation. Although better alternative habitats are available, the suboptimal habitat is preferably chosen, resulting in reduced carrying capacity of the system. In the case of production, fish have an enhanced growth, a higher survival rate or some combination of both compared to the reference situation as a result of increased carrying capacity of the system.

Figure 1. Conceptual representation of the 'attraction- ecological trap-production issue). In a reference situation (upper panel) fish grow and reproduce and mortality occurs. If attraction takes place (upper panel), the outcome matches the reference situation, but spatial dispersion differs. In the case of an ecological trap (middle panel), fish have a reduced growth, a lower survival rate or a combination of both compared to the reference situation. If production occurs (lower panel), fish have an enhanced growth, a higher survival rate or a combination of both compared to the reference situation. For reasons of simplicity immigration and emigration were left out of the model.

RESEARCH STRATEGY

Since the local evolution of fish stocks and the value of wind farms as management tools completely depend on whether attraction, production or an ecological trap occur at the wind farms, it is essential to identify the processes at work. To do so for fish, we developed a research strategy based on four major questions (Figure 2): 1) does attraction of fish occur? 2) Which age groups are attracted? 3) What mechanisms are playing? 4) How do attracted fish behave? To answer each of these questions, specific data were gathered on fish densities, length (at age), feeding habits and fish movement. In a final step, all results were integrated and a viewpoint on attraction/production was formulated. For an analysis concerning the issue of ecological trap, we refer to chapter 17 of this report.
In this chapter two groups of fish are analysed: demersal fish and benthopelagic fish (i.e. Atlantic cod and pouting).

1. **Does attraction of fish occur?**
   To determine attraction of demersal fish to the wind farms, we examined densities of different species according to the (BA)CI (Before After Control Impact) design (see chapter 10, Box 2). Densities in the wind farms were compared with densities in control areas, before and after construction activities at the two examined wind farms (i.e. concessions at the Thorntonbank and Bligh bank). All data were derived from trawl catches and were standardized to numbers of fish per 1000m² of seafloor.For the benthopelagic fish, density data were derived from line fishing at the wind farm on the Thorntonbank. A catch per unit effort (CPUE) was quantified and catches were standardized to number of fish caught in one hour by one fisherman.

2. **Which age groups are attracted?**
   Length-frequency distributions were built to investigate the age composition in the population as it gives clear information concerning the cohorts present and their length distributions.

3. **Which mechanism play?**
   To investigate the trophic relationships between fish species and resident organisms on the wind farm's hard substrates, the diet of soft substrate demersal fishes (focus on dab) and reef fishes (focus on pouting) were analysed. The contribution of potential prey species was estimated through stomach content analysis and their importance in the diet was assessed through several indices (see box fish stomach analysis).

4. **Behavioural ecology**
   In situ observations of behaviour and movements may provide valuable insights in the ecology of fish. However, directly observing the behaviour of marine fish in the wild is logistically very difficult. As a result, other methods are needed to infer fish behaviour. We used acoustic telemetry to investigate residency at the wind farm and to empirically quantify movement behaviour of Atlantic cod. We tracked 22 Atlantic cod (year class 1) equipped with an acoustic transmitter (coded V9-1L tag, Vemco Ltd.). The tagged Atlantic cod were tracked with automated acoustic receivers (VR2W, VEMCO Ltd.). The receivers were placed around two wind turbines at the Thorntonbank and recorded the presence of any acoustic transmitter within their detection range (i.e. 250 to 500 m). The study ran from May 2011 until July 2012. The detection information obtained was used to determine spatio-temporal patterns in presence.

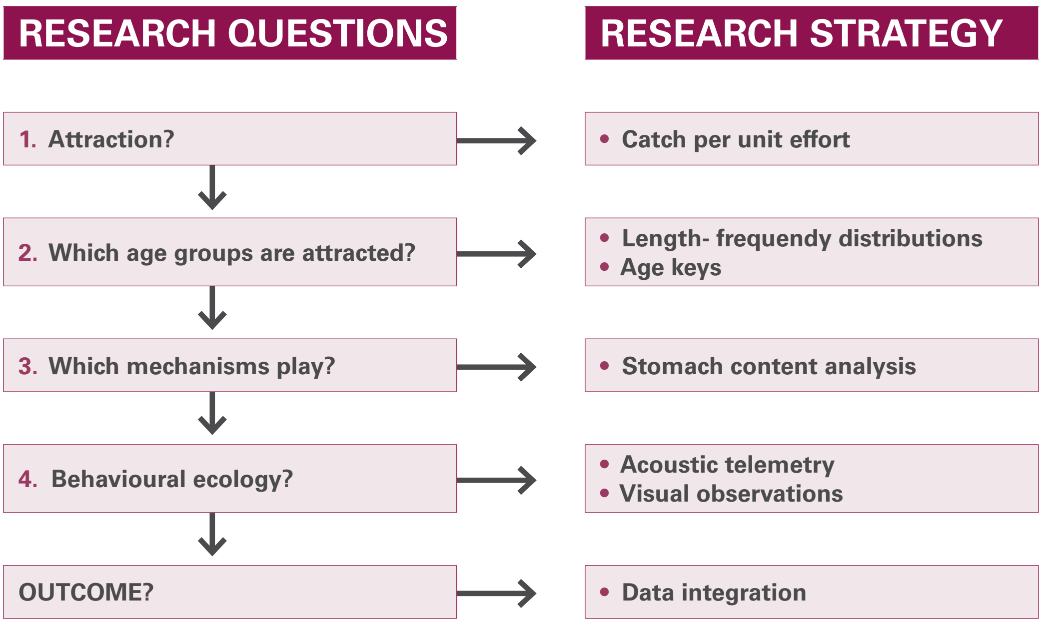


Figure 2. Schematic overview of the holistic approach to unravel the attraction-ecological trap-production issue. In the column on the left the methods used for data analysis are enumerated, on the right an outline of the research questions is given.

DATA OVERVIEW

1. **Does attraction of fish occur?**
In the case of attraction, a persistent increase in densities within the wind farms and a decrease in the surrounding areas is expected. In the samples taken between the turbine rows (at a distance of at least 180 m from the turbines), increases were not observed for any of the analyzed demersal species (see chapter 10). Only for sole (*Solea solea*) in spring, significant increases were observed at the impact stations of the Bligh Bank top, but the resulting densities were still very low (0.2 individuals per 1000 m²) and the persistence of this trend needs to be confirmed by extending the time series. The studies of Bergström et al (2012, 2013) and of Wilhemsson et al (2006) indicated that increased densities were limited to a radius of 20-160 m from swedish turbines, depending on species and that smaller scale studies may be needed to document increases. For the Belgian case study, this may mean that increases between the turbine rows will remain very limited or that it will take a lot of time for the reef effects to expand into the space between turbine rows (>180 m).
Both Atlantic cod and pouting (benthopelagic fish) were clearly attracted towards the wind farm in summer and autumn. In this habitat, the catches were up to more than a 100 times higher compared to sandy reference areas. For more details on the methodology and results we refer to chapter 11.

2. **Which age groups are attracted?**
Analysis of the length-frequency data of all demersal species from trawl catches did not yield any clues of increased recruitment or growth within the wind farms. On the contrary, dab (*Limanda limanda*) seems to move away from the space between turbine rows: in 2011 very few individuals of the year 1 class were seen, but there were still new recruits. In 2012, even the new recruits were gone from the wind farm samples, while individuals of both year classes were still abundant at the reference stations. This can either mean that dab is moving away from the wind farm, or that dab moves closer to the turbines (< 180 m). Observations of dab close to the turbines during diving or angling, however, were rare (Jan Reubens, pers. comm.), so the first hypothesis is probably the right one. For plaice (*Pleuronectes platessa*), length-frequency data showed the presence of a number of larger individuals within the Bligh Bank wind farm, especially in autumn 2011, resulting in an average length increase of 6 cm compared to the reference stations at that time. This is probably the result of a refugium effect due to the absence of fisheries (even though the fishing pressure at the Bligh Bank is rather low compared to areas closer to shore, see chapter 8), rather than an effect of attraction.The length-frequency data revealed that specific age groups of Atlantic cod were present in the Thorntonbank wind farm. Year class 1 and 2 were observed, but the presence of the latter was restricted to winter and spring. Age class 1 was present throughout the year. For pouting, year class 0 and 1 were encountered in the wind farm. The new recruits (year class 0) arrived at the OWF in August/September. For more details on the methodology and results we refer to chapter 11.

3. **Which mechanisms play?**
In wind farms, fish attraction depends on four major mechanisms: (1) food availability and feeding efficiency, (2) the provision of shelter from predators and currents, (3) the presence of a suitable habitat for settlers and immigrants, and (4) stress resulting from wind farm noise and predation pressure (Figure 3). So far, we mainly focused on the mechanism of food availability and feeding efficiency. Artificial hard substrates introduced in wind farms are covered by hard substratum fauna (Petersen and Malm, 2006), that constitute a new source of prey for predatory fish. In the North Hoyle wind farm (GB) for example, large schools of juvenile whiting (*Merlangius merlangus*) were observed while feeding on the tube building amphipod *Jassa falcata*, which was dominantly present on the turbines (May, 2005). Similarly, we expected demersal and benthopelagic fish species to forage on hard substrate prey species in the vicinity of the Belgian wind farms. To investigate the trophic relationships between fish species and resident organisms on the wind farm's hard substrates, we analyzed stomach contents of soft substrate demersal fishes (focus on dab) and reef fishes (focus on pouting).

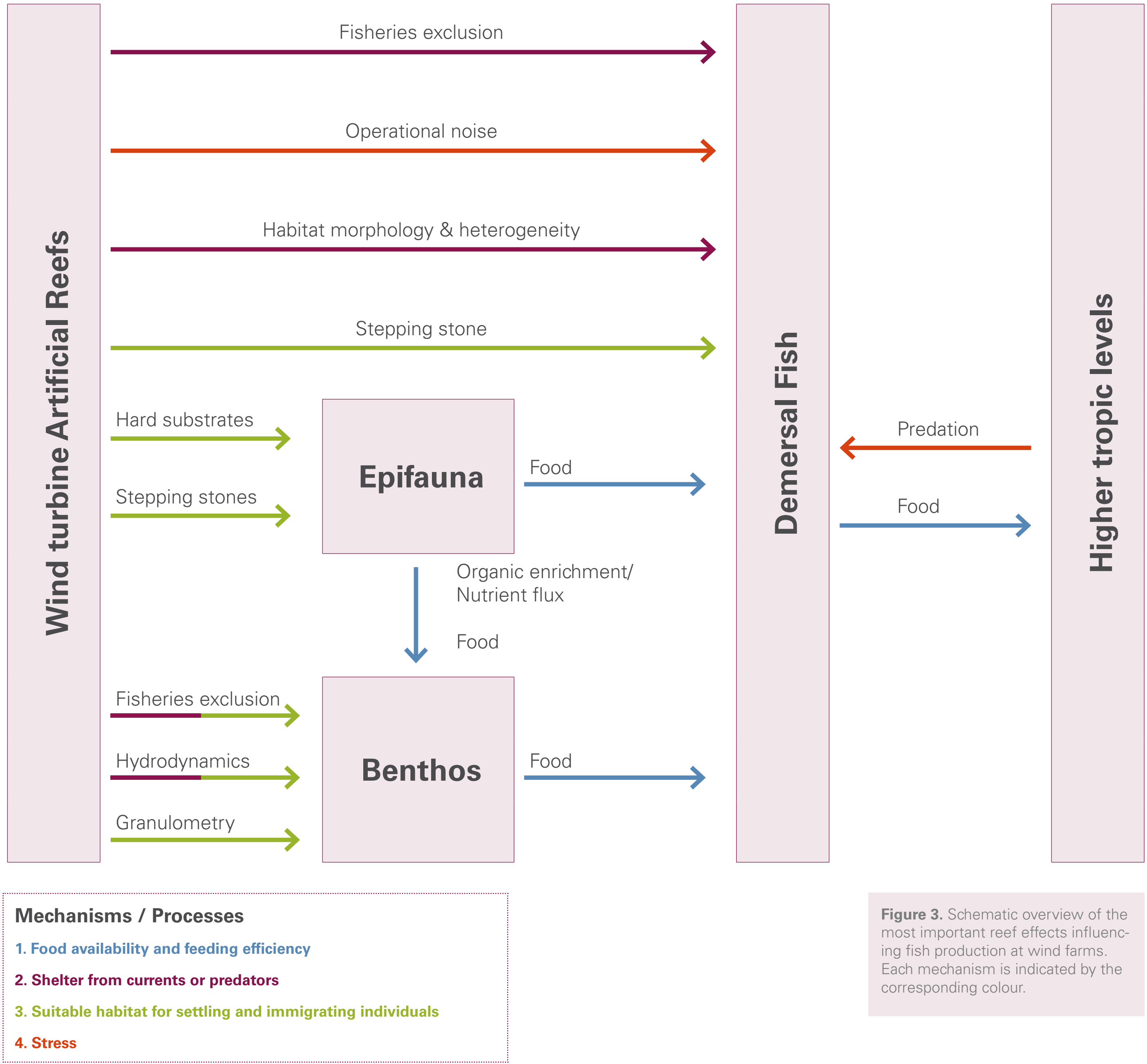


Figure 3. Schematic overview of the most important reef effects influencing fish production at wind farms. Each mechanism is indicated by the corresponding colour.

The stomach content data of dab originated from a small-scale pilot study at the Thorntonbank wind farm in autumn 2010 (Derweduwen et al, 2012). Data from the wind farm (> 180 m of the GBF's), and outside the wind farm (Thorntonbank reference station) showed little differences. The diet of dab generally consisted of amphipods, decapods, mysids and polychaetes (table 1). The dwarf swimming crab *Liocarcinus pusillus* - which likes coarser sediments- and the hard substratum amphipod *Phtisica marina* were only found in the stomachs of dab originating from the wind farm. However, the most abundant hard substratum species *Jassa herdmani* and *Pisidia longicornis* present on the turbines (Kerckhof et al., 2010a; Reubens et al., 2011) could not be found in the stomachs of dab. This probably can be linked to the small sampling size (limited number of individuals from only two stations), to the sampling distance (>180 m from the nearest turbine) or to different prey preferences of dab. Dab did generally have fuller stomachs within the wind farm (mean Fullness Index 0.15) than outside (mean FI 0.05). This might be an indication of a higher food availability for dab around the wind turbines. For Danish wind farms, Leonhard and Pederson (2006) estimated that the availability of food for fish around the turbine sites directly increased by a factor of approximately 50 after the introduction of hard substrates, in comparison with the former sandy area. Taking into account that few hard substrate fauna were found in the stomachs but that the stomachs were fuller (due to more sandy substrate prey) at the Thorntonbank, and that density data indicate that dab is moving away from the Bligh Bank wind farm, we believe that food availability is not a driver for attraction in dab.

	% N		% FO	
	Reference	OWF	Reference	OWF
Amphipoda	0	66	0	44
Bryozoa	0	*	0	11
Copepoda	10	8	10	33
Cumacea	0	1	0	11
Decapoda	25	23	30	56
Gastropoda	0	3	0	22
Mysidacea	55	0	20	0
Polychaeta	10	0	30	0
Pisces	*	0	40	0

Table 1. The numerical contribution (% N) and frequency of occurrence (%FO) of prey groups present in the stomachs of dab (Limanda limanda) from a reference station (n=14) and an offshore wind farm station (OWF, n=15) at the Thorntonbank. The asterisks indicate that individuals could not be discerned (bryozoan colonies, body parts of fish but no head counts).

For pouting, the diet was compared for fish caught at the wind turbines of the Thorntonbank and at a sandy bottom reference site (Gootebank). Stomach content differed significantly between the two sites. Amphipods and crabs dominated the diet of fish at the wind turbines, while the fish at the Gootebank were characterized by more diverse diets with fish, crabs, anemones and amphipods as the most important prey groups (Table 2). A more detailed analysis of the individual prey species showed that pouting at the wind farms mainly fed upon hard substrate associated prey species (i.e. *Jassa herdmani, Pisidia* longicornis) while at the sandy area they fed both on hard and soft substrate associated prey species (i.e. *Callionymus* sp., Actiniaria sp., polychaeta sp. and *Liocarcinus holsatus*). The diet of the fish caught at the wind turbines was quite similar (average similarity 59 %), while the ones from the Gootebank had a more diverse prey composition (average similarity 37 %). In addition, pouting at the wind turbines generally had fuller stomachs compared to the Gootebank (mean Fullness Index of 1.5 ± 1.4 and 0.6 ± 0.8 respectively).

Table 2. Overview data from stomach content analysis of pouting (Trisopterus luscus) from the Gootebank (sand) and the offshore wind farm (OWF). The gravimetric contribution (% G) and frequency of occurrence (%FO) of prey groups present in the stomachs of pouting are listed in the left column. In the right column the 5 most important prey species (in terms of weight) are listed.

	% G		%FO		% G			
	Sand	OWF	Sand	OWF		Sand		OWF
Amphipoda	8.1	66.8	64.7	94.1	***Callionymus* sp.**	43.14	***Jassa herdmani***	61.97
Anthozoa	9.7	0.0	5.9	0.0	**Pisces spec.**	9.82	***Pisidia longicornis***	10.22
Detritus	0.1	0.3	5.9	5.9	**Actiniaria sp.**	9.69	**Pisces sp.**	8.42
Echinodermata	0.1	0.0	5.9	0.0	**Polychaeta sp.**	4.72	***Liocarcinus holsatus***	5.45
Mollusca	0.1	0.0	17.6	5.9	***Liocarcinus holsatus***	4.28	***Necora puber***	3.05
Mysidacea	1.4	0.0	11.8	5.9				
Natantia	4.4	0.3	29.4	2.9				
Pisces	53.0	8.4	23.5	5.9				
Reptantia	15.8	22.9	76.5	79.4				
Rest	7.4	1.2	76.5	55.9				

BOX 1: stomach analyses of fish

From trawl samples (dab) or angling samples (pouting), all fish were measured and where possible weighed. Depending on the number of fish and weather conditions, fish were either dissected on board or were injected with formaldehyde and stored for laboratory analysis. On board or in the lab, intact stomachs were removed by cutting above the oesophagus and below the large intestine. An incision was made along the longitudinal axis and the contents were emptied onto a Petri dish with a few drops of deionised water. All prey items encountered in the stomachs were counted and identified to the lowest possible taxonomic level. After identification, the stomach contents were dried and incinerated to obtain dry weight and ash free dry weight.

Specifications on the fish (length, weight) and prey items (species, number, weight) were used to calculate a number of indexes that give information on the amount of food in the stomach and the importance of the different prey items (Hyslop, 1980; Pinkas 1971, Hureau 1970):

- Fulness Index: the ratio of the weight of the stomach content versus the weight of the fish
- Frequency of occurrence: the percentage of the total number of stomachs in which the specific prey species occurs
- Numerical percentage: the ratio of the number of individuals of a certain prey item to the total number of prey items
- Gravimetrical percentage: the ratio of the weight of an individual prey item to the total weight of prey items
- Index of relative importance: an index to assist in evaluating the relationship of various food items. Takes frequency of occurrence and numerical and gravimetrical percentages into account
- Feeding coefficient: the product of the gravimetrical and numerical percentage. It shows the relative importance of the different prey items in the diet.

Total length measurement on board of the RV Belgica.

Fish stomach

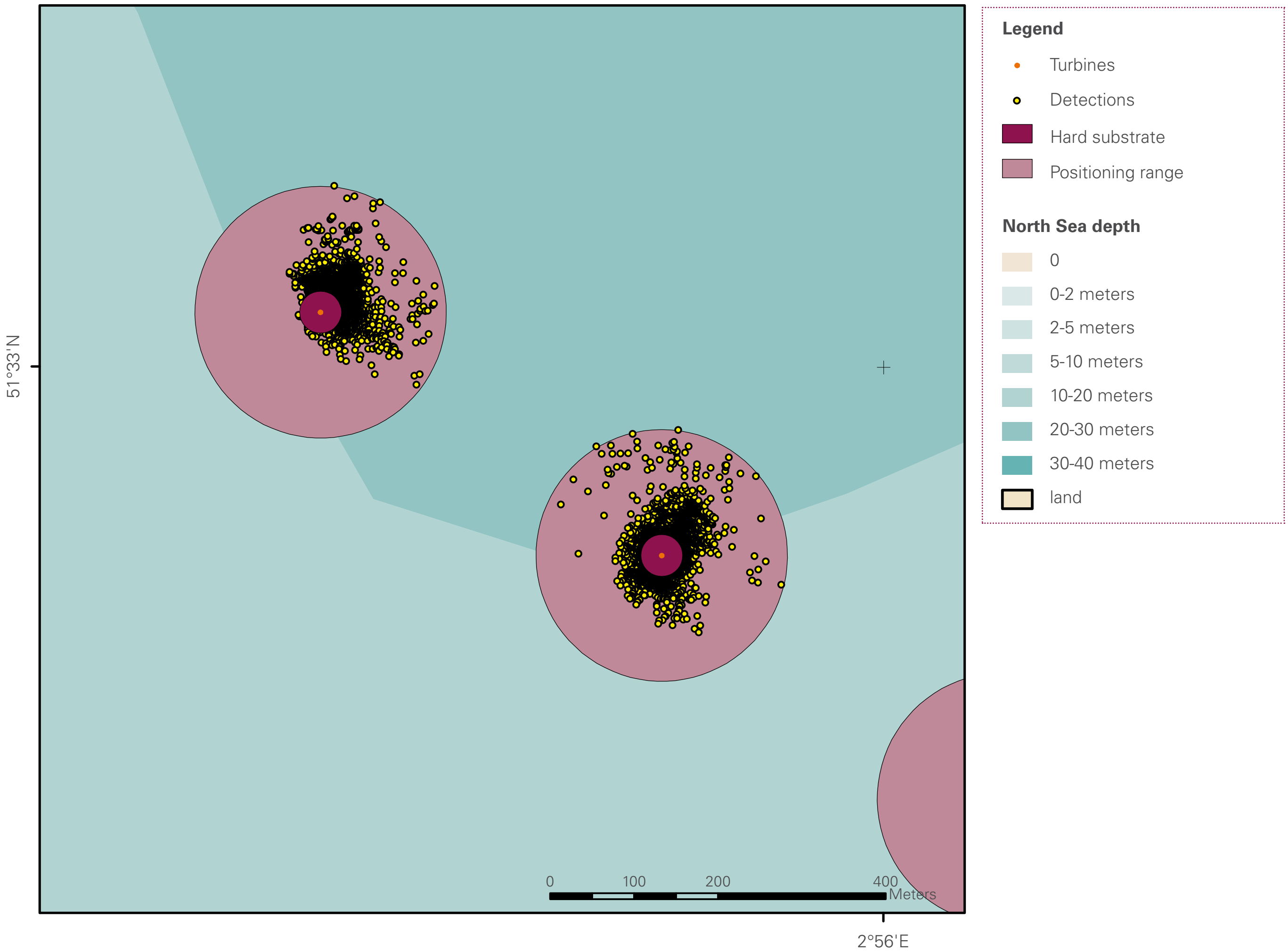
4. Behavioural ecology

Acoustic telemetry revealed a strong seasonal variation in occurrence of Atlantic cod within the wind farm. During summer and autumn fish were present for an extended period of time. By the end of December however, most fish were no longer detected and throughout the winter months (December-March) few detections were encountered. In spring some fish reappeared, although most were not detected anymore in the study area (see box telemetry).

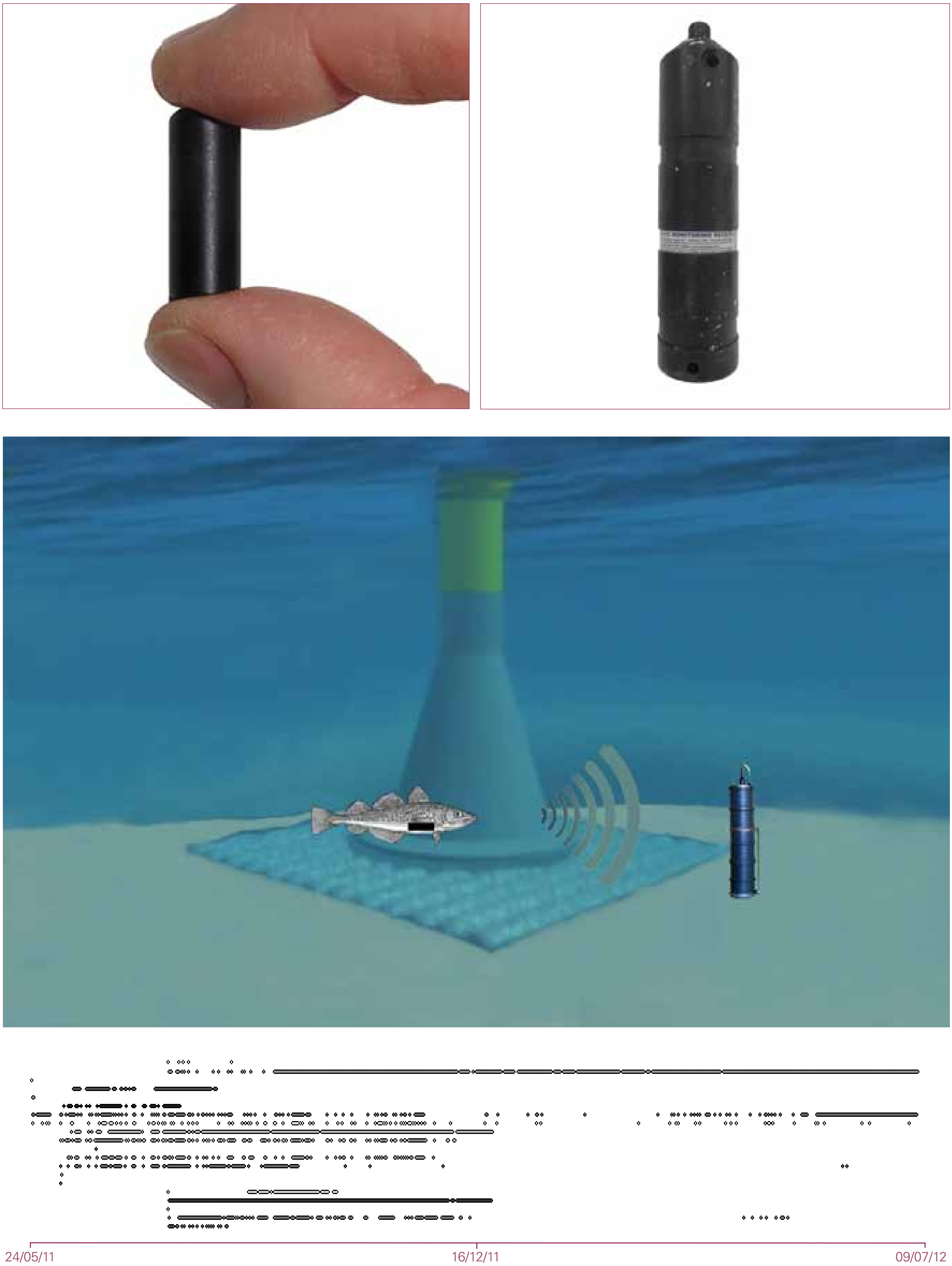
During summer and autumn, many of the tagged fish were encountered (almost) daily at the OWF throughout a long period of time, indicating strong residency (see box on acoustic telemetry). More detailed detection data revealed even that many fish were present at the wind farm for more than 75% of the time. They resided in a small area without making extensive migrations (Reubens et al., 2013b).

Further, the telemetry study revealed that the tagged Atlantic cod were strongly attracted towards the wind turbine artificial reefs. Although the wind farm concession area is dominated by soft-bottom sediments and only small patches of hard substrates are available, most of the detections were encountered on the hard substrates of wind turbines or in their close vicinity (Figure 4). About 90 % of the calculated positions (relative measure) were within a 40 m range from a wind turbine (note that the hard substrates extent to approximately 25 m from the wind turbine.

Figure 4. Positions of tagged Atlantic cod at the wind turbines. The pink circle represents the area in which position calculation can be performed. The purple circle represents the hard substrate and the yellow dots show the exact positions of the fish.



BOX 2: Acoustic Telemetry



An acoustic transmitter (upper left) is implanted in Atlantic cod and the signals emitted are recorded by a receiver (upper right and middle). In this way, long term monitoring of fish presence can be performed. The graph shows the presence of 20 tagged Atlantic cod in the period May 2011- July 2012.

CONCLUSIONS

Bohnsack (1989) stated that production enhancement at artificial reefs is most likely for demersal fish species, since they are ecologically more closely tied to the benthos. At the Belgian wind farms however, no persistent and statistically significant signs of attraction could be derived from density data for demersal fish, and diet analysis does not indicate an intense use of the food sources present at the vicinity of the turbines. Still, these conclusions are based on data from trawl samples taken during a short period of post-construction processes and at a relatively large distance from the turbines (>180 m). Since it takes around three to five years before stable faunal communities are established after deployment of artificial hard structures (Jensen, 2002; Gray, 2006; Petersen and Malm, 2006), and since it takes time for the local (turbine level) effects to expand into the sandy substrate between the turbine rows (20 – 160 m as in Bergström et al (2012), or even further), we expect a different picture to form within the next few years of wind farm construction and exploitation.

Based on the presented results (see also chapters 11 and 17), we can conclude that pouting and Atlantic cod are strongly attracted towards the wind farm. On a local scale and in terms of extra biomass, we can assume that there is production.

Specific age groups are attracted towards the wind farm artificial reefs (WARs). They show high residency and feed upon the dominant epifaunal prey species present (see chapter 12). Growth is observed throughout the period the fishes are present. In addition, the fish are certainly not caught in an ecological trap in terms of habitat quality (see chapter 17).
On a regional scale however, the situation might be different. So far, no changes in production of Atlantic cod or pouting were observed (Reubens et al, 2013c). Inter-annual variations in catch rates are present, but could not be linked to effects of the OWFs. A multitude of factors; such as environmental conditions, food availability, larval predation, spawning stock structure (Köster et al., 2003; Vallin et al., 1999); influence fish stocks, impeding the assignment of causal relations. Even though no effects of the OWFs are observed on a regional scale yet, this does not necessarily imply that they are not present. In some cases, the first signs of increased production are observed soon after deployment, while in others it may take many years before changes can be observed or measured (Gell and Roberts, 2003). The time frame within which changes are expected to be measurable depends upon the species investigated, their life-history behaviour and their turnover rate (Pérez-Ruzafa et al., 2008).

Surgical implantation of acoustic transmitter

FUTURE MONITORING

- Fish attraction towards wind farms depends on several mechanisms. In this study we focused on food availability and feeding efficiency. In future research however, the other main mechanisms (i.e. shelter, suitability of habitat for settling and stress) should be integrated in the research objectives as well. The impact (stress) of noise during construction of wind turbines on fish larvae is currently being investigated (E. Debusschere, unpublished data).

- Currently, the attraction-ecological trap-production issue is investigated for some demersal and benthopelagic fish species. The number of fish species investigated should be expanded to be able to assess the impact on the ecosystem level instead of on individual level.

- Stomach content analyses give valuable information concerning the fish diet, however they do not render any information on the quality of the prey. Therefore energy profiling and fatty acids profiling (of both fish and prey items) should be performed to estimate the energy transfer from prey to consumer on the long term. De Troch et al. (in prep.) did a first assessment for Atlantic cod and pouting (caught at a wind farm) and some of their dominant prey species.

CHAPTER 15

Attraction of seabirds

Nicolas Vanermen, Eric Stienen, Wouter Courtens,
Marc Van de walle and Hilbran Verstraete

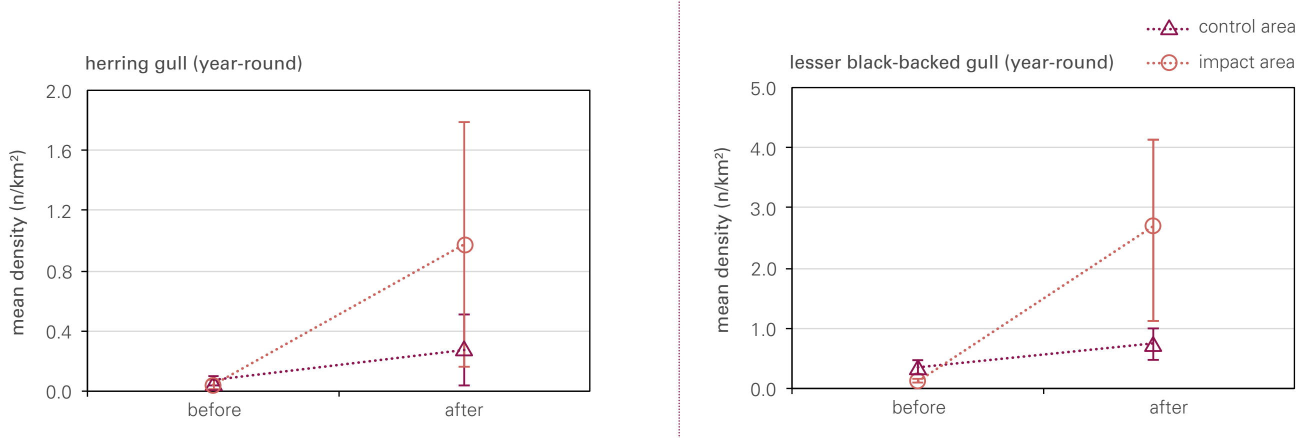
Several gull species were shown to be attracted to the offshore wind farms at the Belgian part of the North Sea, which is hypothesised to result from increased roosting possibilities or enhanced feeding conditions. Birds inside the wind farms were mainly observed resting on the water or the turbine foundations, but there is also few but increasing evidence that seabirds indeed started profiting from an improved food availability. In order to unravel the hypothesised link between the increased underwater biodiversity and seabird presence, future monitoring should further focus on the (foraging) behaviour of seabirds occurring inside the wind farms, and start up a research program on pelagic fish communities.

SEABIRD ATTRACTION TO OFFSHORE WIND FARMS AT THE BELGIAN PART OF THE NORTH SEA

Monitoring seabird displacement effects (Chapter 5) showed that seabirds are not necessarily scared away by rotating turbines. On the contrary, several species occur in higher numbers than before. Figure 1 illustrates the strong increase in numbers of lesser black-backed and herring gull (*Larus fuscus, Larus argentatus*) inside the Bligh Bank wind farm, opposed to the moderate upward trend in the control area. Other seabird species were found to occur in lower numbers than before, but were nevertheless regularly observed entering the wind farms (for example auks). These birds' avoidance behaviour is thus far from total, and it is not unthinkable that in time they will habituate to the presence of wind turbines. With the introduction of new artificial habitat one can indeed expect the unexpected, which is nicely illustrated by the recent observations of shag *Phalacrocorax aristotelis*, a seabird species favouring cliffs and rocky shores. While shags were only very rarely observed staging at the BPNS before the construction of the first turbines (4 observations of 5 staging individuals in the course of 20 years of seabird monitoring), there were already 5 observations of 6 staging individuals since the beginning of 2012, all within the wind farm boundaries.

RV Belgica approaching the Bligh Bank wind farm during a seabird monitoring survey.

Figure1. Densities of herring and lesser black-backed gull at the Bligh Bank study area before and after wind farm construction.



Shag on a turbine base at the Thorntonbank.

ATTRACTION / PRODUCTION HYPOTHESIS

The most extreme case in which seabirds would fit in the attraction-production hypothesis (see Chapter 14) would be the colonisation of the offshore turbines and/or transformer platforms for breeding purposes. The idea may sound odd, but there are numerous examples of birds colonising man-made structures. Peregrine falcons (*Falco peregrinus*) learned to breed on high buildings and cathedrals 'mistaken' for cliffs, allowing them to colonise towns and industrial areas. In 1998, black-legged kittiwakes (*Rissa tridactyla*) started to breed on an offshore gas platform in the Irish Sea, followed by the colonisation of several other gas platforms in the Dutch part of the North Sea a few years later. Camphuysen & De Vreeze (2005) argue that the exact location of the Dutch platforms played a key role in their colonisation, with the nearby 'Frisian Front' offering high food availability during the crucial chick rearing period.

For now, the most plausible positive effect that offshore wind farms are likely to have on birds, is increased food availability. The introduction of hard substrate in a sandy soft-bottom ecosystem brings about a cascade of environmental changes (the so-called 'reef effect'), most notably organic enrichment and the attraction of hard-substrate fish (Degraer et al., 2011). Another important factor in this respect could be the exclusion of fishery, allowing the interlaying soft-bottom ecosystem to recover from decennia of heavy beam trawling impact.

The most important question yet to be answered is whether birds are attracted to wind farms from a sheer physical point of view, with the wind farm functioning as a stepping stone or a resting place, or whether they already learned to exploit the hypothesised increase in food availability. A good example of an offshore wind farm functioning as a stepping stone is given by Leopold et al. (2011). Large numbers of mainland breeding great cormorants *Phalacrocorax carbo* exploit the offshore OWEZ and PAWP wind farms for feeding, and use the met-mast and monopile foundations to rest. The presence of above-water structures is a critical side condition for the occurrence of great cormorants that need to dry their feathers after feeding. Without the presence of the turbines, these areas would simply be off-limit.

Initially, birds occurring inside the Belgian offshore wind farms (mainly gulls) were only observed resting on the water or on top of the transformer platforms, strongly supporting the idea that their presence was to be interpreted in the view of roosting possibilities. Since October 2012 however, flocks of black-legged kittiwakes are regularly observed foraging inside the Bligh Bank wind farm. Strikingly, the percentage of kittiwakes displaying active foraging behaviour inside the wind farm appears to be much higher than in the control area (5.9 versus 0.3%). In subzone B of the Thorntonbank wind farm (operational since the beginning of 2013), good numbers of lesser black-backed gulls were observed foraging near the jacket foundations during the surveys of April and May 2013. The fact that this behaviour is observed only now (several months/ years after turbine construction) may not be coincidental, but can be a reflection of the delayed increase in food availability to seabirds following initial reef effects. Assuming that (in time) offshore wind farms offer increased feeding possibilities, seabird attraction effects too are expected to increase. Seabirds are known to readily exploit any area with high and predictable food availability, and improved foraging conditions might also speed up the habituation process for birds that are now still reluctant to enter the wind farms.

Gulls resting on a jacket foundation during the construction of Phase 2 & 3 of the Thorntonbank wind farm.

FUTURE MONITORING

We will continue to monitor seabird presence inside the Belgian offshore wind farms, with increased attention to their behavioural and foraging-related actions. To further investigate the hypothesised link between seabird presence and food availability, it would be very interesting to conduct research on pelagic fish communities occurring in- and outside the wind farms. To what extent improved foraging conditions benefit seabirds on a population level is very hard to assess. The benefits gained however are unlikely to weigh up to the costs of additonal mortality. An increased number of flight movements inside the wind farms inevitably results in an increase of collision fatalities, potentially turning the situation into an ecological pitfall (see Chapter 17).

CHAPTER 16

Attraction of harbour porpoises to offshore wind farms: what can be expected?

Jan Haelters, Laurence Vigin and Steven Degraer

The elusive and highly mobile harbour porpoise is the most abundant cetacean in Belgian waters, seasonally reaching average densities of more than 2 animals/km². Operational wind farms may affect the porpoise habitat in various negative and positive ways, such as through the introduction of possibly deterrent noise or the introduction of artificial substrates with associated porpoise prey fish. Porpoises show concentration areas in Belgium, none of which being linked to the wind farms so far. Because of the spatial resolution being too low, aerial surveys will need to be complemented with targeted passive acoustic monitoring in the future.

INTRODUCTION

The most abundant cetacean in Belgian waters, as well as in the North Sea as a whole and in the adjacent Atlantic Ocean, is the harbour porpoise *Phocoena phocoena*. In Belgian waters it is especially common during late winter and early spring. Recent data indicate that their numbers in the southern North Sea have increased also during winter and summer/early fall of the last decade (Haelters et al., 2011a; MUMM, unpublished; SCANS II). There is a lot of speculation about possible attraction to, or expulsion from operational wind farm areas. Harbour porpoises may be attracted to the wind farms because of the high numbers of fish near wind turbine foundations (Chapter 14) or because there is less disturbance due to shipping or fishing (Scheidat et al., 2011). They may however also be scared off because of the increased underwater noise levels within and around operational wind turbines (Chapter 6). We investigated if the current monitoring could reveal attraction or expulsion phenomena.

MONITORING DESIGN

In the framework of offshore wind farm monitoring we combined two methods to study the temporal and spatial distribution and abundance of harbour porpoises: aerial line transect monitoring (Buckland et al, 2001) and passive acoustic monitoring (PAM) using autonomous, moored sensors (Figure 2).

The highly standardised aerial survey flights were carried out following predefined track lines 5 km apart (Haelters, 2009). From the results densities were estimated for 10 by 10 km blocks. These blocks were chosen to reveal broad-scale differences in density of harbour porpoises in Belgian waters between surveys carried out from 2008, when no wind turbines were present, up to 2013, when wind farms were (partly) operational at the Thornton- and Bligh Bank. Between 2008 and 2013, 20 aerial surveys were performed. A number of these were made when pile driving took place in Belgian waters, while others were incomplete. Not every season could be covered by aerial surveys: most of them were made during late winter and early spring, when harbour porpoises are known to be present in Belgian waters at highest densities. For the analysis we used only the surveys that were complete or almost complete, and that took place when no piling was taking place.

Figure 1. Aircraft used for aerial surveys (Norman Britten Islander), and a cardinal buoy with a chain at its side holding a C-PoD; the C-PoD is hanging at a depth of around 1.5m, and is contained in an open stainless steel tube.

For PAM we used C-PoDs, devices that record characteristics of noise such as frequency, duration, repetition and bandwidth. Using dedicated software (see www.chelonia.co.uk) the most probable source of the noise (dolphin, porpoise, SONAR) is attributed to every noise event. As such, PAM yields a detailed temporal indication (detection rate) of the presence or absence of harbour porpoises at the mooring location (Haelters et al., 2011b). Between 2009 and 2013 we moored C-PoDs near the edge of territorial waters in the eastern and western part of Belgian waters (respectively at the Thorntonbank or Gootebank and at the Oostdyck Bank), and a few km off Blankenberge (MOW1; Figure 2). Data collected during or shortly after piling operations were omitted in the analysis presented here, as these operations have shown to affect harbour porpoise presence, and as such detection rates, over a large area (Haelters et al, 2012a). As a measure of harbour porpoise presence we used the percentage of *detection positive 10 minutes per day* (DP10m/d): this is the fraction of 10 minute periods in a day in which harbour porpoises were detected.

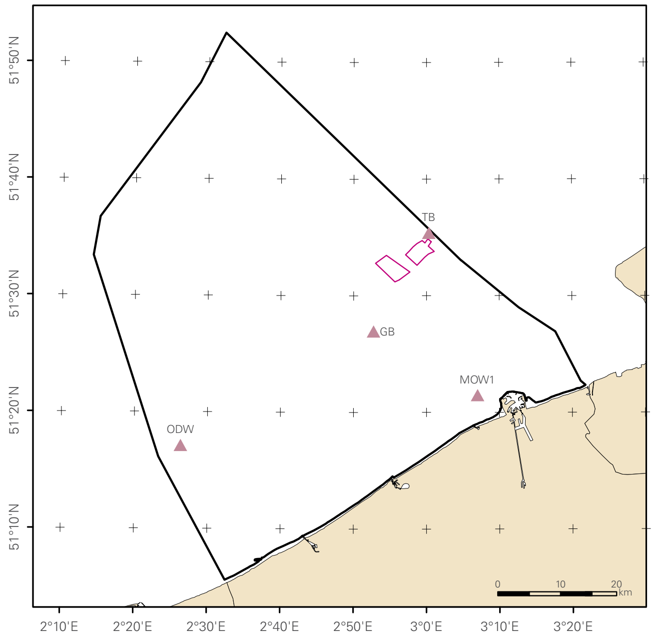


Figure 2. Location of the C-PoDs (TB: Thorntonbank; GB: Gootebank; MOW1: Meetdienst Openbare Werken 1; ODW: Oostdyck West).

Legend

- Belgian continental shelf
- C-Power Wind farm
- C-PoDs

SPATIAL AND TEMPORAL DISTRIBUTION OF HARBOUR PORPOISES

The highest average densities of harbour porpoises were mostly recorded during March and April, with up to 2.7 ind./km² in March 2011, although large inter-annual fluctuations occurred (for instance between 2008 and 2013 in May, and between 2010 and 2011 in April) and data presented wide confidence intervals (Figure 3). The lowest densities recorded were 0.05 animals/km² (August 2009) and 0.16 animals/km² (May 2009 and January 2010).

Density surface maps resulting from the aerial surveys illustrate an uneven distribution of harbour porpoises in Belgian waters in space and time (a selection is presented in figure 4). While the results of the surveys of February indicate a fairly even density, the majority of the porpoises was found in the western part during March and April. This suggests a seasonal shift in distribution between February and April from the northern and north-eastern part of Belgian waters towards the south-west and west.

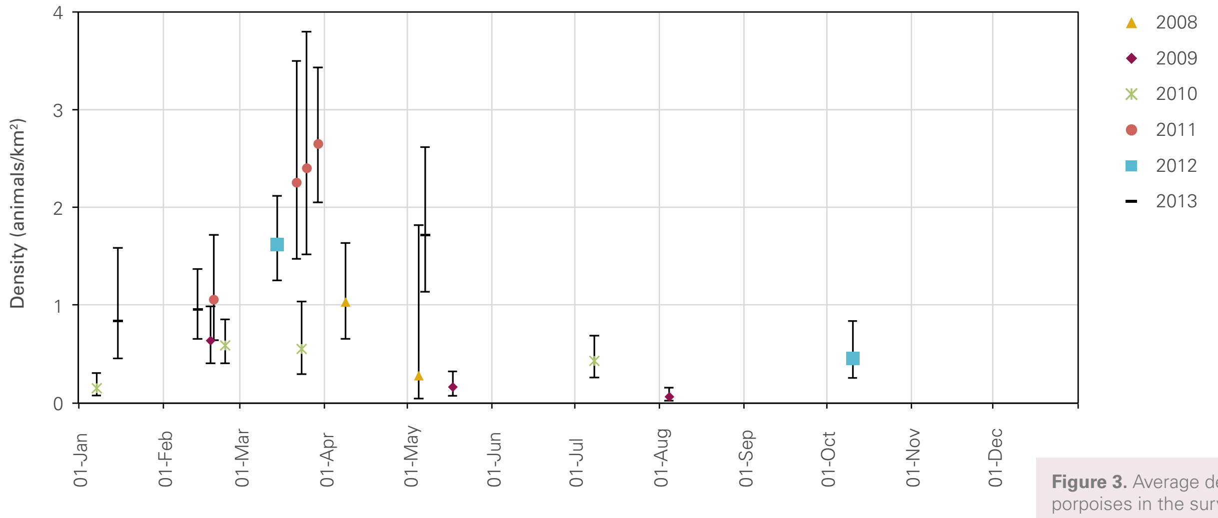


Figure 3. Average density of harbour porpoises in the survey area, estimated on the basis of aerial surveys performed between 2008 and 2013.

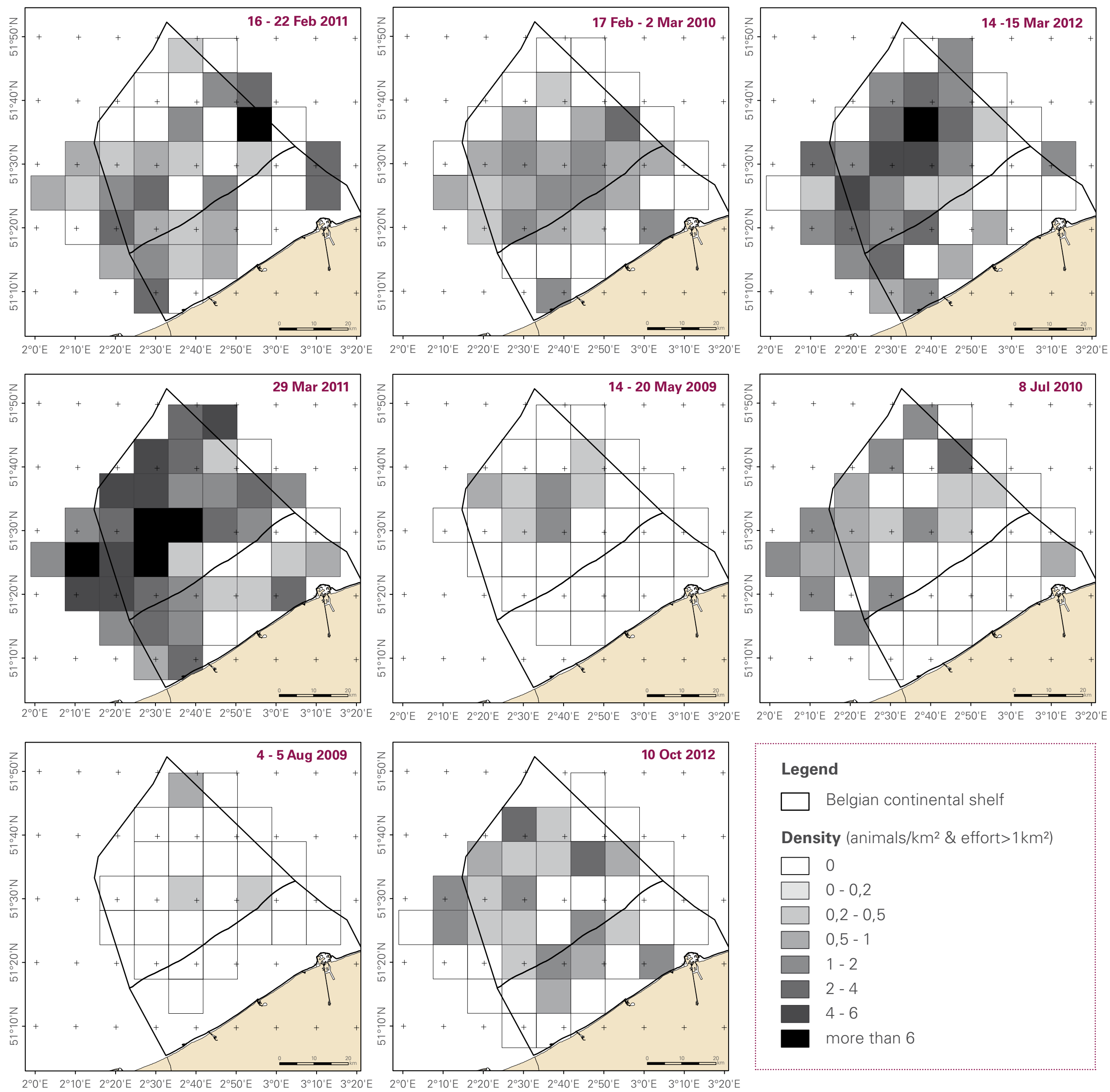


Figure 4. Selection of harbour porpoise density (n/km²) maps based on data collected during aerial surveys. Only aerial surveys performed during times when no pile driving was ongoing in Belgian waters, and with a (virtually) complete coverage are presented.

The results of PAM (Figure 5) indicate a generally low detection rate at the MOW1 location, consistent with few harbour porpoises close to shore in the eastern part of Belgian waters. The highest detection rate at this location occurred, although irregularly, during late winter – early spring. The detection rate was seasonally higher further offshore. At the Oostdyck the PAM data indicate a higher detection rate from the end of February to the end of April (2012). At the Thorntonbank the combined data from 2011 to 2013 indicate a higher detection rate between February and May.

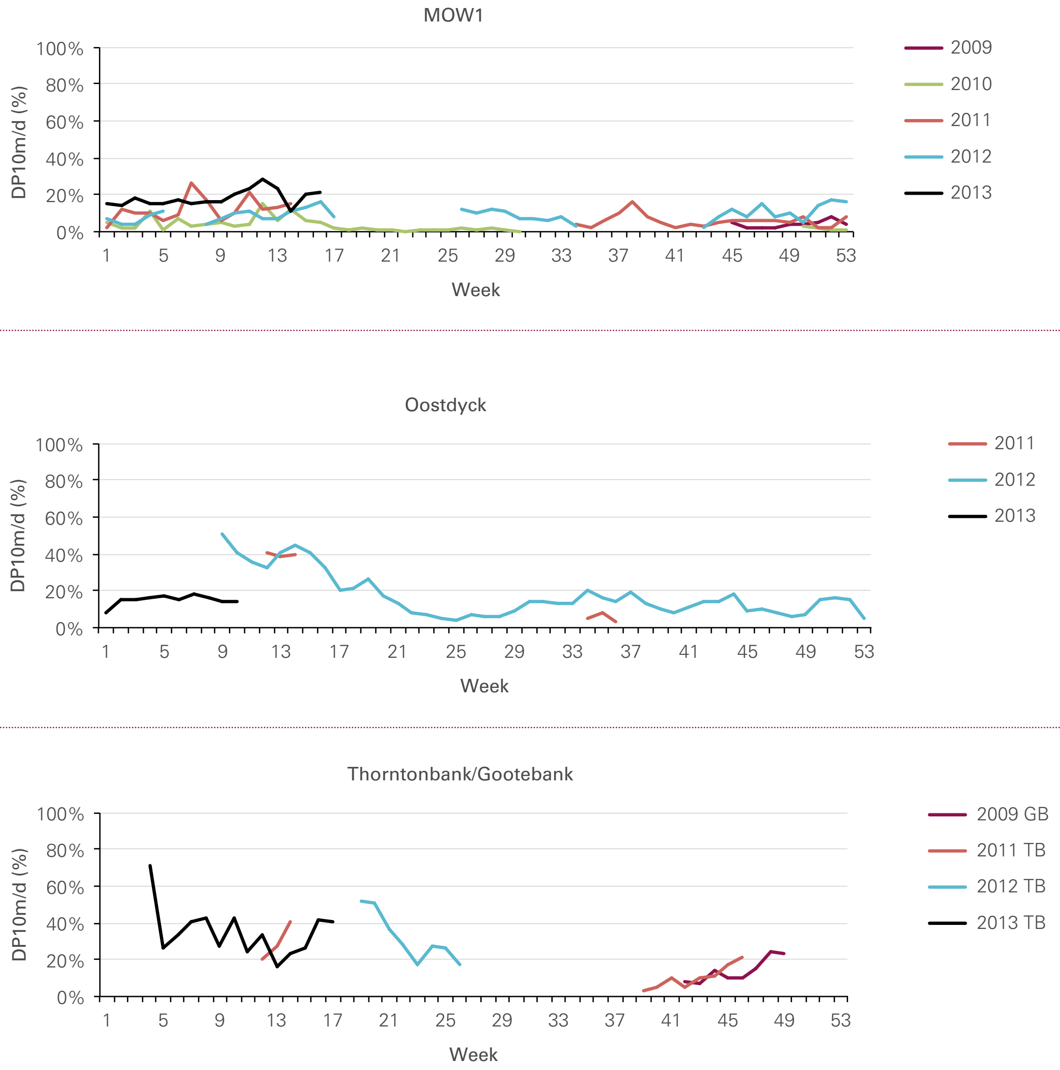


Figure 5. Weekly average detection rate (expressed as percentage of dp10m/d) at MOW1, Oostdyck and Thorntonbank/Gootebank between 2009 and 2013.

MAY WE CONCLUDE ON ATTRACTION OR (PARTIAL) EXCLUSION?

Aerial surveys suggest that harbour porpoises occur throughout Belgian waters. They seem to shift from the north towards the south-west and west in late winter-early spring. In spring they occur in the highest densities in the western part of Belgian waters. Close to shore they reach a higher density in the west than in the east. Off the central part of the Belgian coast, and up to around 30 km offshore, there is an area with a consistently lower density.

The reason for a differential distribution of harbour porpoises in Belgian waters throughout the year is related to a seasonal movement, in the first place most likely the consequence of the local food availability. Such food availability can be dependent on factors such as turbidity or water temperature. Harbour porpoises need to feed on a daily basis to stay fit. Therefore they are forced to move to the best feeding grounds or to follow mobile prey. As the offshore wind farm areas are relatively small compared to the area that can be covered in a short period of time by this highly mobile species, differences in distribution within and outside wind farms are probably inferior to seasonal variations within the southern North Sea caused by movements to find suitable prey resources. However, when all foreseen wind farms will be operational, differences in prey density within and outside them may influence the local distribution of porpoises on a relatively small temporal and spatial scale.

The data collected up to now do not allow for detecting the fine spatial scale distribution of harbour porpoises needed to evaluate the attraction to, or expulsion from operational offshore wind farms. They can be used as a background, and do give us

an idea of the natural spatio-temporal patterns and trends in harbour porpoise distribution and abundance in Belgian waters. They consist currently, however, of data not in a sufficiently high temporal (aerial surveys) nor spatial (aerial surveys, PAM) resolution to elucidate possible attraction or exclusion effects. A much finer-scale monitoring would be needed to reveal such patterns, preceded by an assessment of how cost-effective it would be: what would be its power to detect change? Continuation of the current monitoring beyond construction will enable us to ascertain population level effects in Belgian waters.
It should be noted that wind turbine foundations attract fish that consist potential prey for harbour porpoises (Haelters et al., 2012b; Chapter 14). Therefore it is likely that feeding opportunities within wind farms are better than in the areas just outside them. This would favour – on a small scale – the presence of harbour porpoises within wind farms, rather than outside them. We expect, given the noise levels generated by an operational wind farm (Tougaard et al., 2009; Norro et al., 2011) and the hearing sensitivity of harbour porpoises (Kastelein et al., 2002), that disturbance would be limited, and that therefore exclusion effects on the long term, and perhaps after some habituation, are unlikely to occur (ICES, 2010; Murphy et al., 2012). The question remains if the currently and naturally preferred feeding grounds present – on a large scale – a more favourable habitat than the wind farm area.

FUTURE MONITORING

Linking PAM and aerial survey data?

It would be useful, given the limited temporal resolution of aerial survey data, to be able to attribute an absolute density to PAM data of acoustically active animals. This is, however, problematic for several reasons. Detections may concern single animals or groups, detection gradients from the PAM devices remain unknown, detection ranges between PAM devices vary, vocalisations can be directional and the animals may exhibit diurnal rates in movement and in vocalization rate. The consequence is that it constitutes a complex and challenging mathematical problem (Kyhn et al., 2012; Thomas and Marques, 2012; Marques et al., 2013). However, there may be a more pragmatic way to try to link relative PAM with absolute densities obtained through aerial surveys, even if only a limited number of aerial surveys were performed, and the number of PAM devices deployed is low. We have compared the average density of groups of harbour porpoises estimated during aerial surveys in the most appropriate grid cells in which C-PoDs were deployed (absolute density divided by the average group size during that month) with the detection rates at this C-PoD averaged over 5 days or over the most appropriate period in case the aerial survey was not completed in one day (Figure 6).

We find a highly significant, and almost linear, relationship between detection rate and group density of harbour porpoises. Such a relationship should in fact not be expected to be a linear one, at least not over the whole range of density/detection rate, as a saturation can be expected in high density areas. However, the issue still remains a complex one, with many factors influencing both detection rate in passive acoustic monitoring and density estimates obtained through aerial surveys.

Spatio-temporal resolution of data

The best method to increase the spatio-temporal resolution of data in order to elucidate possible attraction/repulsion effects would be to deploy a relatively high number of PAM devices within and outside an operational wind farm area during a period in which no construction takes place in adjacent wind farms (Scheidat et al., 2011). Even with a relatively large number of replicates, discussion can remain on the interpretation of data.

Noise levels vs. hearing sensitivity of harbour porpoises

Although some noise measurements have been made at operational wind farms, these took place only during conditions with low sea states and limited wind speeds. Data on underwater noise is needed throughout the range of sea state conditions, which is only possible through the use of moored noise measuring equipment. There may also be important differences in both the amplitude and predominant frequencies of the noise generated by different types of turbine and foundations, and also the seascape and seafloor constitution play a role in noise generation and transmission. Harbour porpoises living in the relatively noisy southern North Sea may be more tolerant to noise than harbour porpoises living in quiet areas such as west of Scotland. Therefore underwater noise data is needed for each scenario to ultimately be compared with the hearing sensitivities of harbour porpoises and with data collected through PAM.

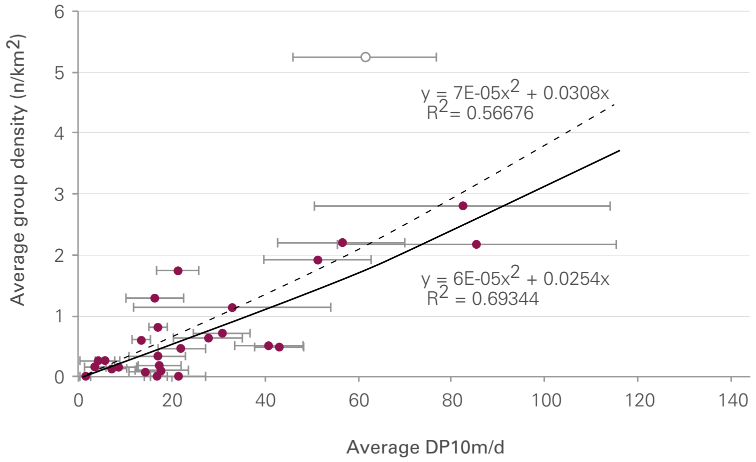
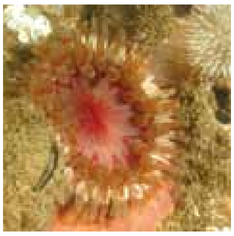


Figure 6. Results of PAM (DP10m/d averaged over 5 days or relevant period; incl. CI) vs. results of aerial surveys (groups/km² averaged over the relevant 10x10km grid cells); the dotted line includes the outlier (open data point), the full line does not take account of it in calculating the trend line.








PART IV

NUANCING EFFECT INTERPRETATION

CHAPTER 17

Not necessarily all gold that shines: appropriate ecological context setting needed!

Steven Degraer*, Francis Kerckhof*, Jan Reubens*, Nicolas Vanermen*, Ilse De Mesel, Bob Rumes, Eric W.M. Stienen, Sofie Vandendriessche and Magda Vincx.

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At present, everybody agrees that offshore wind farms do impact the natural environment. Whether or not these impacts should be valued positive or negative, or ecologically and societally acceptable, however remains an open question. While boosting local species richness, the artificial hard substrata may for example also open the door to non-indigenous and even invasive species. Some fish and seabirds are further known to be attracted to wind farms, but fish do not necessarily take profit from these structures and seabirds may suffer from an increased collision risk. The true impact will therefore be valued only if local observations are up scaled to the ecoregion level.

INTRODUCTION

One of the most frequently raised societal questions regarding the impact of offshore wind farms (OWFs) is whether or not the impact should be considered acceptable. As such, the societal relevance of our findings is much linked to a human appreciation of whether the effects are considered positive or negative. Positive or negative, or good or bad, however varies according to different societal points of view, which may not be considered a scientific exercise (Winter et al., 2012). Science may and should however aid assessing the acceptability of impacts. A first and most important step to assess acceptability comprises a scientific context setting as to assess the ecological significance of the observed effects, with the aim of proposing robust sets of criteria and standards.

A series of impacts have been identified in the Belgian OWFs, varying from seemingly negative to seemingly positive impacts as presented in the former chapters. Gannets *Morus bassanus* for example do avoid OWFs, while lesser black-backed gulls *Larus fuscus* seem to be attracted to OWFs (Chapters 4 and 15). Harbour porpoises *Phocoena phocoena* escape from excessive noise levels during piling to a distance of about 20 km, while the same species may want to take profit of the increased food resources once the OWF is fully constructed (Chapters 7 and 16). Soft sediment macrobenthos species richness and biomass seem to increase (Chapters 9 and 13) and some fish species are on average bigger in the OWF, while lesser weever fish *Echiichthys vipera* typically disappears from OWFs (Chapter 10). Hard substratum epifauna finally significantly adds to the biodiversity of the formerly soft sediment environment (Chapter 12). Given the obviously dominant increase in several assets of local biodiversity, many people now seem to have a rather positive general appreciation of the effects (Anonymous, 2012b, c; see also Chapter 18). To holistically evaluate the ecological significance of these positively appreciated effects, a proper context setting is needed. Such context indispensably comprises at least an up scaling of the effects both from effects on local individuals to the level of populations and from single wind turbine effects to Southern North Sea-wide OWF effects. Here, we focus on the potential of ecological traps (in its broadest sense), i.e. the chance of which may seem positive at first sight in fact is negative when interpreted at an appropriate ecological scale. Three examples showcase the need for nuancing effect interpretation, but also to further investigate effects at an ecosystem scale and in a cumulative perspective: (1) the possible facilitation of non-indigenous species by OWFs to further invade the Southern North Sea, (2) the attraction – production dilemma in artificial reef fish and (3) the increased risk of collision of attracted seabirds. The seemingly positive impact of increased benthic richness is tackled in Chapter 18.

CASE 1
ARTIFICIAL HARD SUBSTRATA: BIODIVERSITY HOTSPOT OR STRATEGIC POSITIONING OF INVASIVE SPECIES?

Non-indigenous species: what's in a name?

Non-indigenous species (NIS) are here defined as any species that occurs outside its natural range (past or present) and that has become established in a certain region in the wild with self-sustaining populations. As such, non-indigenous can be synonymised with non-native and allochthonous. This means that the occurrence of such species derives from an intervention by man either through deliberate/ intentional (e.g. import for aquaculture) or non-deliberate/ non-intentional (e.g. climate change, habitat creation, accidental propagule introduction) human action. We further make a distinction between introduced species and range expanding species. Introduced species are a subset of non-indigenous species that are introduced in a certain region – in this case the North Sea – by historical human intentional or unintentional activities (e.g. Carlton, 1996) across natural dispersal barriers. This means that they came from remote areas elsewhere around the globe including the Mediterranean, the Black and Caspian Sea (Wolff, 2005). Range expanding species are another subset of non-indigenous species that are spreading from adjacent regions by natural means. For the Southern North Sea, this encompasses Atlantic species with a Northeast Atlantic origin.
For a number of species, now with a cosmopolitan occurrence in harbour and coastal habitats and therefore possibly non-indigenous, it is often difficult to unravel whether or not they are native in the North Sea especially in the absence of fossil evidence. Such species of which the indigenous or non-indigenous status in a certain geographical area cannot sufficiently be proved are termed cryptogenic (Carlton, 1996).

Human interventions have a major impact on local marine biodiversity. A striking example is the ongoing hardening of the coast by the construction, in historical times, of many coastal defence works, harbours and other artificial structures. More recently, artificial hard substrata are even introduced in the offshore environment and wind farms will in the future occupy large areas of the shallow waters of the North Sea.

In Belgian waters, these new artificial structures attract hard substratum species that were formerly unable to live in the sandy environment of the Southern North Sea and they will facilitate the expansion of rocky shore species, living west of the Dover Strait, into the North Sea. Additionally, introduced species from all over the world may now find a suitable place to survive. At first sight, this increase of local species richness may seem a positive effect, that may however be countered by the fact that these non-indigenous species (NIS) may harm the (local) ecosystem when becoming invasive (Reise et al., 2006). The increased risk of invasiveness may as such be considered an ecological trap linked to the introduction of hard substrata in an originally soft sediment environment.

Here, we address the possible effects of the presence of NIS on the local biodiversity, and, on a broader scale and time frame, on the fauna of the Southern North Sea. Contrary to Chapter 12, where the subtidal colonisation process on the wind turbines is analysed, this section focuses on the intertidal zone, where a high number of NIS are currently thriving.

Patella vulgata, *Elminius modestus* and *Littorina littorea*

Megabalanus coccopoma and *Balanus perforatus*

Hemigrapsus sanguineus

The colonisation of the structures was fast (Kerckhof et al., 2012) and NIS were present shortly after turbine installation. Their presence was most striking in the intertidal zone, where we identified 17 obligate intertidal species, of which no less than one out of two species appeared to be non-indigenous (Table 1). These NIS include six introduced species, i.e. the Pacific oyster *Crassostrea gigas*, the barnacles *Elminius modestus* and *Megabalanus coccopoma*, the amphipod *Jassa marmorata*, the Asian crab *Hemigrapsus sanguineus* and the midge *Telmatogeton japonicus*, and two range expanding species, i.e. the barnacle *Balanus perforatus* and the limpet *Patella vulgata*. Except for *M. coccopoma*, the presence of NIS seems permanent and juveniles of all species considered have been found during subsequent years. Most of these species were already detected in the vicinity of the wind farms, particularly on buoys (Kerckhof et al., 2007; F. Kerckhof, unpublished data). These buoys form a somewhat comparable habitat, but lack a real intertidal zone as they move up and down with the tides. As such, only the uppermost and lowermost intertidal zones, i.e. splash zone and infralittoral fringe, are present on buoys. Only *P. vulgata* was not yet discovered on buoys.

Most NIS colonised the wind turbines during the first two years after installation and are common both on the monopile turbines at the Bligh Bank and the concrete gravity based wind turbines (GBFs) at the Thorntonbank. *Patella vulgata, H. sanguineus* and *C. gigas* however only arrived after three to four years and are currently restricted to the GBFs. The larger, more massive concrete GBF's can indeed be regarded as small rocky outcrops, offering a suitable place to settle for certain rocky shore species, including NIS. We however anticipate that some of these species will also be able to colonise the smaller sized monopiles in the future. Some of these species have already been detected on navigational buoys in the region (F. Kerckhof, unpublished data).

We expect that other NIS will pop up within the wind farms, since more NIS have been observed in the area of the wind farms and also on ships operating in the area, including the research vessel Belgica (Kerckhof et al., 2007; F. Kerckhof, unpublished data). The non-indigenous barnacle *Balanus* (*Amphibalanus*) *amphitrite* for example, is common in Belgian marinas and is occasionally recorded on offshore buoys of which one close

Table 1. Overview of recorded intertidal species at the Thorntonbank and Bligh Bank offshore wind farms with indication of their abundance as indicated by the SACFOR scale, as developed by the Joint Nature Conservancy Council (JNCC) (Connor and Hiscock, 1996). S, superabundant; A, abundant; C, common; F, frequent; O, occasional; R, rare. Bold: non-indigenous species.

	Thorntonbank gravity based foundations						Bligh Bank monopiles			
	years						*years*			
	1	2	3	4	5	6	1	2	3	4
Emplectonema gracile (Johnston, 1873)			O							
Emplectonema neesii (Örsted, 1843)			O			O				
Pleioplana atomata (OF Müller, 1776)			O							
Eulalia viridis (Johnston, 1829)				O						
***Patella vulgata* Linnaeus, 1758**			F	F	F	F				
Littorina littorea (Linnaeus, 1758)			F	F	F					
***Crassostrea gigas* (Thunberg, 1793)**			O	O	O	O				
Mytilus edulis (Linneaus, 1758)	F	S	S	S	S	S	C	C	A	A
***Elminius modestus* Darwin, 1854**	A	A	A	A	A	A	C	C	C	C
Balanus crenatus Bruguiére, 1789		F					C	R		
***Balanus perforatus* Bruguiére, 1789**	S	A	A	C	C	C		C	F	F
Balanus improvisus Darwin, 1854			O				O	R		
***Megabalanus coccopoma* (Darwin, 1854)**	C						F			
Semibalanus balanoides (Linnaeus, 1758)		S	S	S	S	S	C	C	C	C
***Jassa marmorata* (Holmes, 1903)**	C	C	C	C	C	C	C	S	C	C
***Hemigrapsus sanguineus* (De Haan, 1835)**			F	F	F	F				
***Telmatogeton japonicus* Tokunaga, 1933**	S	S	S	S	S	S	S	S	S	S

to the wind farm on the Thorntonbank (Kerckhof et al., 2007; Kerckhof and Cattrijsse, 2001). *Megabalanus tintinnabulum* is common in the fouling community of ships and has been noted before on e.g. buoys (Kerckhof et al., 2007; Kerckhof and Cattrijsse, 2001). Both species should hence have the capacity to colonise the Belgian wind farms.

Successfully introduced species are often opportunists that can now be found all over the world in habitats altered or influenced by human activities. Some of them may occur in such large numbers so that they change the habitat and alter local biodiversity. They are called invasive. Such species are a threat to the native biodiversity and may even affect commercially important species. Especially shallow coastal waters, subject to a multitude of human activities including the construction of artificial hard substrata, seem vulnerable to bio-invasions (Ruiz et al., 2009; Mineur et al., 2012). Most NIS found in this study, are known from coastal habitats, but our findings illustrate that they are very well capable to live in offshore conditions, provided that suitable habitat is available. The introduced Pacific oyster *C. gigas* for example, is thriving and spreading along the coasts of the Southern North Sea (Troost, 2010). The species is competing with native biota, especially the blue mussel *Mytilus edulis*. In certain regions, such as the Wadden Sea, mussel banks have even been replaced by Crassostrea reefs (Markert et al., 2009; Kochmann et al., 2008; Diederich, 2006).

Although both species may co-exist (Diederich, 2005), it is clear that commercial exploitation becomes difficult if mussel beds are infested with *C. gigas*, without any commercial value. If *C. gigas* were able to establish (semi-)permanent offshore populations in the Southern North Sea, it would be able to further strengthen its competitive position in the Southern North Sea; this possibly to the detriment of the commercially valuable coastal mussel banks, which are already under severe pressure (OSPAR, 2010). Most probably, *C. gigas* has already firmly established populations and the species may be considered here to stay, regardless what will happen. Other species such as the non-indigenous barnacles, also compete for space and resources with indigenous species, but are of less concern since none of the indigenous species are actually outcompeted and their competitors do not have a commercial value. *Telmatogeton japonicus* finally seems to occupy an empty niche, i.e. steep vertical walls in the intertidal, a feature that is seldomly encountered naturally in the North Sea. Competition with indigenous species may as such be excluded.

In conclusion, the newly introduced hard substrata within OWFs play an important role in the establishment and the expansion of the population size of NIS and we argue that these new artificial hard substrata offer new opportunities for NIS (introduced and southern Northeast Atlantic range-expanding species) to enter the Southern North Sea, or, if already present, to expand their population size and hence strengthen their strategic position in the Southern North Sea. This is particularly important for the obligate intertidal hard substrata species, for which other offshore habitat is rare to non-existing. We however also recognise that not all species have the same capacity to truly invade a habitat, but plead for a continued monitoring of this phenomenon as OWF development continues in the Southern North Sea.

CASE 2
WIND TURBINE ARTIFICIAL REEFS AS AN ECOLOGICAL TRAP FOR POUTING?

Each habitat in the marine environment has a specific carrying capacity, influenced by environmental parameters (e.g. currents, heterogeneity, temperature, sediment type, organic enrichment, etc.). As a result, habitat selectivity will influence the fitness, survival chance and reproductive capacity of fishes. Fish aggregation devices have the potential to act both as ecological traps (Hallier and Gaertner, 2008) and as productive sites (Dempster et al., 2011), depending on the species, the ecology and the environment. Pouting *Trisopterus luscus* is known to be attracted to wind turbine artificial reefs and high catch rates are observed during summer and autumn (Reubens et al., 2013a; Reubens et al., 2011). However, whether the wind turbines are poorer (ecological trap) or richer (productive site) in habitat quality than the surrounding soft-bottom sediments remains unknown. Therefore, we investigated length-at-age, condition and diet (as proxies for fitness) of pouting at different sites in the Belgian part of the North Sea. Pouting was sampled from January 2009 until December 2012 at a GBF wind turbine and at two sandy reference areas (i.e. the Gootebank and the Belgian part of the North Sea, BPNS). At the OWF and the Gootebank pouting were collected by standardised line fishing. At the BPNS, fish were caught with an 8-metre beam trawl with a fine-meshed shrimp net and a bolder-chain.

At the OWF, 0-group pouting were significantly larger compared to the Gootebank and the BPNS (Figure 1). In autumn, average length was 18.8 ± 1.5 cm at the OWF, while it was 15.6 ± 2.3 cm and 17.6 ± 1.7 at the BPNS and Gootebank respectively. Comparison between the OWF and the BPNS confirmed this pattern, with average lengths of 18.8 ± 1.5 cm at the OWF compared to 15.6 ± 2.3 cm in the BPNS in autumn, and 20.5 ± 1.4 cm at the OWF compared to 17.6 ± 2.4 cm at the BPNS in winter.

The Fulton's condition index, indicative for the general condition of the fish, was calculated as $(W/TL^3)*100$, with W = total weight (g) and TL = total length (cm). No significant differences in condition index were detected between the wind turbines and the Gootebank (Figure 2), as fish had a similar condition index (1.4 ± 0.26 g/cm³ and 1.4 ± 0.16 g/cm³ for the wind turbines and Gootebank respectively) for the period September-November.

Figure 1. Comparison of average total length (cm; + standard deviation) of pouting *Trisopterus luscus* at an offshore wind farm (OWF, green bars) and Gootebank (red bars).

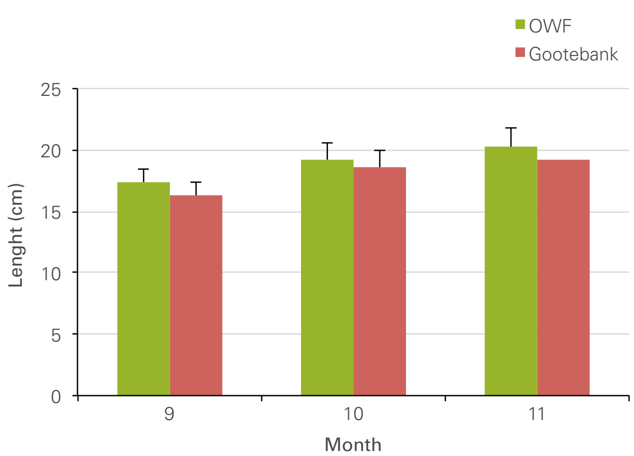
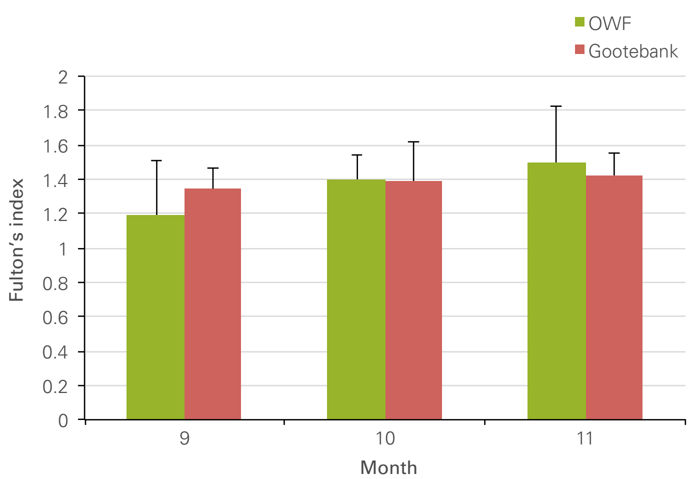


Figure 2. Average Fulton's condition index (+ standard deviation) of pouting *Trisopterus luscus* at the offshore wind farm (OWF, green bars) and the Gootebank (red bars).



Stomach content analyses revealed that large differences in diet were present between pouting from the OWF and the Gootebank (see also chapter 14). At the OWF, the diet was dominated by Amphipoda, followed by Reptantia, while the pouting at the Gootebank had more diverse diets with fish, Reptantia, Anthozoa and Amphipoda as the most dominant prey groups (Table 1). A more detailed analysis of the individual prey species showed that pouting at the OWF mainly fed upon hard substratum-associated prey species (i.e. *Jassa herdmani*, *Pisidia longicornis* and *Liocarcinus holsatus*), while at the sandy area they mainly fed both on hard and soft substratum-associated prey species (i.e. *Callionymus* sp., Actiniaria sp., *Polychaeta* sp. and *L. holsatus*). In addition, the stomach fullness (IF) was significantly higher at the OWF (1.5 ± 1.4 IF) compared to the Gootebank (0.6 ± 0.8 IF), which signifies a high food availability at the former.

Based on the information of the current study, no evidence was obtained to assume that OWFs act as an ecological trap for pouting, related to habitat quality. Length of pouting at the OWF was slightly larger compared to individuals at the sandy areas, while no significant differences in condition were observed between sites. In addition, no restrictions related to food availability were encountered at the OWF. Based on the measured proxies, fitness of pouting was even slightly better compared to the sandy areas (increased length and enhanced fullness index). This might be a first indication towards production (in terms of biomass) of pouting at the OWF. It should be noted however, that the current results do not exclude the OWF to potentially act as an ecological trap via increased fishing mortality in the future. Fish aggregations are particularly vulnerable to fishing pressure (Rose and Kulka, 1999). Concentration of both fish and fisheries activities can lead to local overfishing. If (uncontrolled) fisheries would be allowed at the OWF, which is not the case in Belgian waters, fish aggregating in this habitat would experience enhanced fishing mortality and may thus be caught in an ecological trap. Further details may be found in Reubens et al. (2013b).

Some of the most dominant prey species of pouting *Trisopterus luscus*.

CASE 3
SEABIRD ATTRACTION AND INCREASED COLLISION RISK

In January 2013, 1,662 offshore turbines were present in European waters. The European Union aims at an offshore capacity of 43 GW in the near future, which is equivalent to more than 14,000 3 MW turbines (EWEA, 2013). The number of offshore turbines still to be installed is thus enormous and their distribution will no longer be limited to the near shore zone, illustrated by the fact that at the Doggerbank in the central part of the North Sea, plans were licensed to build a 9 GW wind farm. As such, all North Sea seabirds will be confronted with the presence of offshore turbines. Considering the future large-scale exploitation, it is interesting to extrapolate the results as found at the BPNS and frame them into an international context. The numbers of estimated collision victims presented in Chapter 5, are without any doubt highly site-specific, largely reflecting the local seabird community, and the results based on this extrapolation should thus be interpreted with care.

In their research on wind farm-induced mortality in German waters, Dierschke et al. (2003) regard an increase of the existing mortality rate by less than 5% as acceptable. For Flanders, Everaert (2013) also sets the acceptable level at 5%, but with a more stringent threshold of 1% for vulnerable species and species facing population decline. When extrapolating the expected number of victims per turbine at the Bligh Bank wind farm (Table 2, see also chapter 4) to a scenario of 10,000 turbines, we exceed the 5% limit for lesser and great black-backed gull (*Larus fuscus, L. marinus*). Black-legged kittiwake (*Rissa tridactyla*) too shows a relevant increase of the existing adult mortality by 1.5%. The other three species regarded here (northern gannet *Morus bassanus*, common gull *Larus canus* and herring gull *Larus argentatus*) are at the safe side of the mortality threshold value.

Importantly, the applied threshold values are indicative, set to function as an 'early warning system', and the true critical threshold will depend on the species and its population dynamics (Dierschke et al., 2003). Nevertheless, the results presented here show that the cumulative impact of large scale wind farm development might potentially cause significant increases in bird mortality levels, putting specific seabird populations under pressure.

Table 2. Estimation of the additional mortality per 10,000 offshore turbines and a micro-avoidance of 97.6%, based on an extrapolation of the CRM results found for the Bligh Bank study area ([a] Mitchell et al., 2004; [b] Wetlands International, 2013; [c] BTO, 2013; [d] Poot et al., 2011).

Species	Biogeographical population	Population level	Yearly mortality	Number of collisions per year	Additional mortality per year
northern gannet	NE Atlantic	310,000 [a]	8.1% [c]	182	0.7%
common gull	NW and C Europe	1,640,000 [b]	14.0% [c]	545	0.2%
lesser black-backed gull	ssp. *graellsii* + *intermedius*	930,000 [b]	8.7% [c]	11,818	14.6%
herring gull	ssp. *argenteus* + *argentatus*	3,030,000 [b]	12.0% [c]	1,091	0.3%
great black-backed gull	N and W Europe	420,000 [b]	16.5% [d]	5,091	7.3%
black-legged kittiwake	NE Atlantic	6,600,000 [b]	5.9% [c]	5,818	1.5%

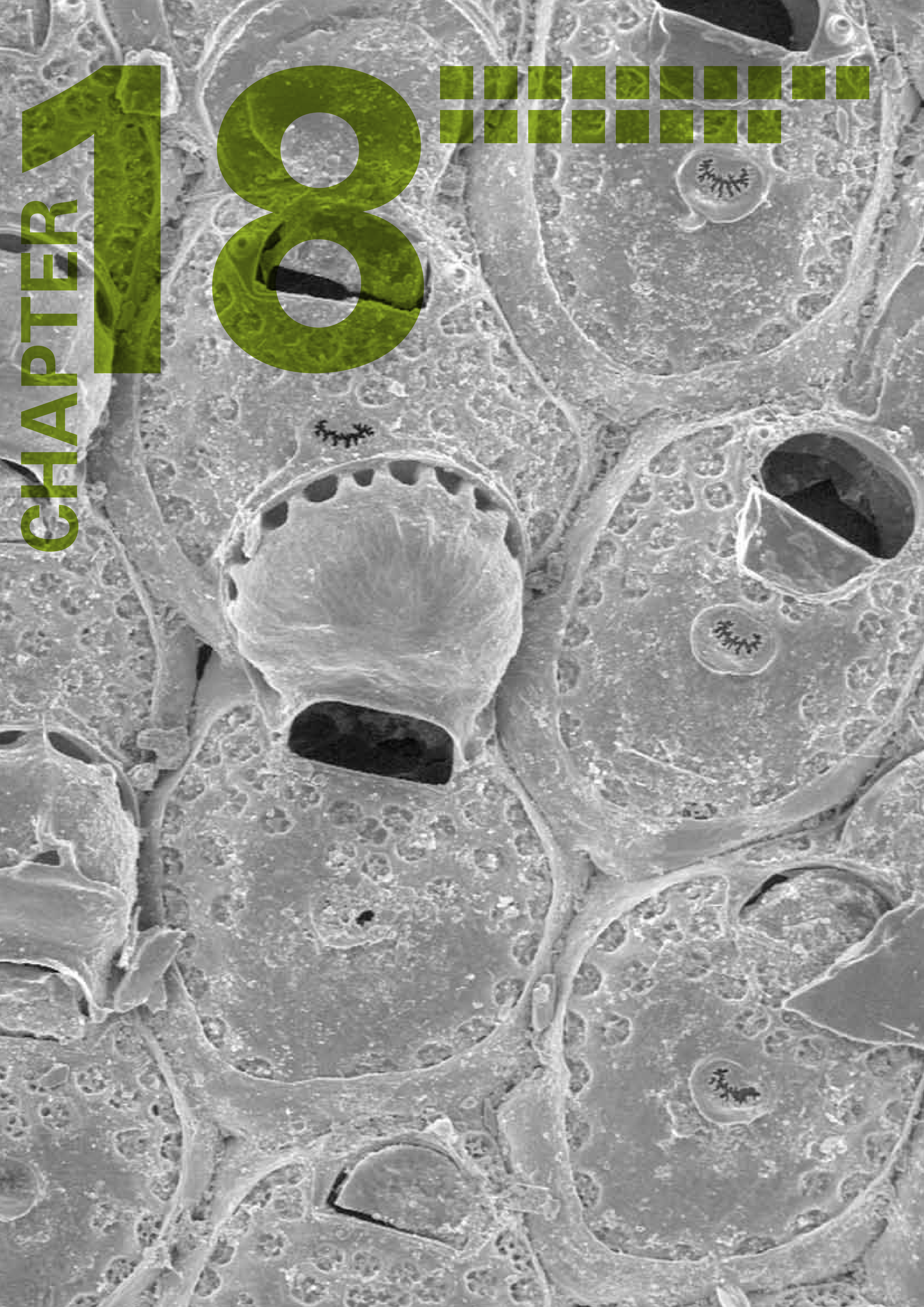
FUTURE MONITORING

All three examples demonstrate that the current data do not allow us to equivocally demonstrate ecological traps to occur at OWFs. NIS are present, but so far neither bio-invasions nor its ecological effects were detected. Fish are attracted to the OWFs, but seem to have found a suitable habitat at the OWFs. Birds may also be attracted, but only few species seem to be at risk due to potential collision with the wind turbines. The same data may however also be interpreted from a different point of view: we were only able to reject the ecological trap hypothesis for pouting, while for all other ecosystem components the question is yet to be answered. Further attention is hence needed here.

Future monitoring should take account of two considerations, i.e. the need for up scaling to species population levels and to the expansion of OWFs in the Southern North Sea. At the level of seabird populations, there is an urgent need for scientifically sound thresholds for acceptable additional mortality, which are societally accepted and politically defined, ensuring coherence at a North Sea scale. Further, while pouting seems to take profit from OWFs, we do not know whether or not this is the case for other fish species, some of which with commercial interest such as cod *Gadus morhua*. When finally the population size of e.g. NIS would become too large, bio-invasions with unwanted ecological consequences may still occur. A focus on population size rather than local densities is hence advised for future monitoring. When focusing at species population size, an up scaling of local wind turbine effects to the effects of Southern North Sea wide wind farms becomes indispensable. The extent of OWF is indeed inherently linked to habitat extent and hence population size potential. To properly deal with both aspects of up scaling a cross-wind farm and international collaboration will be needed.

Hemigrapsus sanguineus

CHAPTER 18



Does it really matter? Changes in species richness and biomass at different spatial scales

Bob Rumes, Delphine Coates, Ilse De Mesel, Jozefien Derweduwen,
Francis Kerckhof, Jan Reubens and Sofie Vandendriessche

Since the installation of the wind farm foundations and associated scour protection in an area previously characterized by soft bottom sediments, the number of hard substrate associated fish and benthic species has increased markedly. At the level of a single turbine footprint a nearly 4000-fold increase in autumn biomass was observed, whereas at the level of the entire wind farm a 14-fold increase was observed. Further development of the entire Belgian wind energy zone may increase benthic biomass by as much as 3% of the current estimated benthic biomass in the Belgian part of the North Sea.

INTRODUCTION

The artificial reef effect and the resultant attraction of fish species to wind turbine foundations are often considered the major benefits of offshore wind farm development for the marine environment. The installation of artificial hard substrate in an area previously known for soft bottom sediments will increase local biodiversity due to an influx of hard substrate associated species. In conjunction with the exclusion of commercial fishing in the area (Chapter 8), both this development of the hard substrate epifauna (Chapter 12) and the organic enrichment of the soft substratum benthos associated with the turbine foundations (Chapter 13) will increase local productivity and biomass. By combining the data collected on the various ecosystem components we determine in this chapter how species richness, as a proxy for biodiversity, and biomass, as a proxy for productivity, have changed since the installation of the first offshore wind turbines. These changes are evaluated at different scales ranging from turbine footprint (for the three foundation types present) and a single wind farm concession area to the entire Belgian wind energy zone and the Belgian part of the North Sea.

RESEARCH STRATEGY

In the concession zone of the offshore wind farm at the Thorntonbank (Chapter 2), species richness and biomass and data of the following functional groups are collected: soft sediment epibenthos, soft sediment endobenthos and epifouling macrobenthos. Species richness data are collected for demersal, benthopelagic and hard substrate associated fish and squid. Hard substrate associated fish species are those species known to live predominantly on or near natural or artificial hard substrate. For information on the manner in which these data are collected we refer to their respective previous chapters in this book and earlier reports (Degraer et al., 2010, 2011, 2012).

A comprehensive species list (see also Annex 1) is compiled taking into account those species or taxa observed in the concession area prior to the construction of the first turbine foundations (baseline monitoring: 2005-early 2008) as well as those species or taxa observed in the concession area after to the construction of the first turbine foundations (impact monitoring: autumn 2008-2012). The year of first observance was determined as well as the fact whether this species was observed at multiple occasions, the latter as an indication for continued presence in the area. Species and congeners which could not be identified to the species level had to be combined on higher taxonomic levels to achieve a homogeneous taxonomic resolution among the different functional groups.

Biomass is expressed as ash free dry weight (AFDW) in autumn 2005 (baseline) and 2012 (impact). For the fouling community, data of 2011 are used since meteorologically adverse conditions prevented the autumn 2012 sampling. The first turbine foundations in Belgian waters were colonised by an extensive epifouling community within 3.5 months after installation (Kerckhof et al., 2009). For the purpose of this study, no significant order-of-magnitude differences with the 2012 biomass are expected since the hard substrate epifauna is collected from the concrete gravity based foundations (GBF) installed in 2008 and the colonisation and succession on the structures has stabilised in the last few years (Chapter 12). For endo- and epibenthos no AFDW data of 2009-2011 are used, as the majority of the turbine foundations in the wind farm area was installed only as late as 2011, and as such the data for 2008-2011 are not be considered representative. Total biomass on the turbine foundation and scour protection was calculated by multiplying the average biomass per m² by surface area of the respective depth zone (intertidal, submerged foundation, scour protection) and summing up the values from all depth zones (excluding the splash zone). For the intertidal zone, lacking quantitative samples, biomass data from Krone et al. (2013a) was used, since a similar *Mytilus edulis* dominated epifauna was observed. At the time of writing, no biomass data are available on the autumn fouling community on the more recently installed monopile and jacket foundations and therefore biomass data of the subtidal part of the GBF is used in the extrapolation of this data to monopile foundations. For jacket foundations, where a *Mytilus edulis* dominated subtidal epifauna was observed up to autumn 2013, biomass data from Krone et al. (2013a) was used.

Each of the foundation types (Figure 1) has a different footprint area on the seabed. For a single GBF, the initial type of foundation used on the Thorntonbank, the footprint of the concrete structure comprises 177 m². In addition, there is a scour protection surrounding the GBF comprised of an armour (median diameter of the stones of 350 mm) and filter layer (median diameter of the stones of 50 mm). These add respectively another 1866 m² and 376 m² to the total footprint of the structure (Peire et al., 2009). As such the total footprint area prior to construction is 2419 m². In the absence of a scour protection the footprints of the steel jacket foundations used on the Thorntonbank amount to 357 m² per foundation. One could even argue that during the operational phase the loss of sandy sediment is limited to only the four anchoring point with a total area of ~10 m². Two types of steel monopile foundations were used on the Bligh bank and the Lodewijkbank. We calculated the footprint of the latter since more of these have been installed. A total monopile footprint of 573 m² is comprised of 20 m² footprint of the steel structure and 553 m² of the scour protection.

After construction, distinct communities of epifouling macrobenthos were observed on the foundation in the splash zone, the intertidal zone, the subtidal part of the foundations, and also on the armour layer of the scour protection (Chapter 12). The filter layer of the scour protection was rapidly covered by sand. Due to the complex 3D nature of the armour layer it provides an estimated additional 65 032 m² of artificial hard substrate[1] at the GBF foundation. Per jacket foundation a total submerged substrate surface of 1280 m² is assumed (Krone et al., 2013a). For monopile foundations, the most common type of turbine present in the Belgian part of the North Sea, we used the dimensions of the monopile foundations present on the Lodewijkbank. An overview of the available surfaces is given in table 1.

The wind farm concession area on the Thorntonbank covers 19.83 km². The wind farm consists of 55 foundations: six GBF with scour protection, 48 jacket foundations without scour protection and one jacket foundation of the OHVS with scour protection (Bolle et al., 2012). The wind farm on the Bligh bank has used 56 monopile foundations and one jacket foundation in its phase 1, with up to 55 turbines yet to be installed during phase 2. In the wind farm on the Lodewijkbank 73 monopile foundations have been installed. In addition to these already constructed wind farms, four more were licensed with up to 315 additional turbines of which the foundation types are as yet uncertain.

[1] A volume of 1306 m³ of rocks was deposited with a layer thickness of 0.7 m. The top half of the layer (653 m³) is found to be consistently above the level of siltation throughout the monitoring period and as a result is colonized by hard substrate epifauna. Using the average surface to volume ratio as based on the recovered rocks (N=14) and an average interstitial space between the rocks of 40%, an area of 65032 m² of armour layer hard substrate is calculated.

Table 1. Overview of the newly available hard substrate surface area per structure for the three foundation types present in the BPNS. For the GBF the dimensions of the D5 foundation were used, for monopile dimensions of the structures installed at the Lodewijkbank were used. n.d. means not determined.

Foundation type	**Vertical zonation**				
	splash zone	**intertidal zone**	**subtidal zone**	**scour protection**	
				armour layer	filter layer
	Surface area in m²				
GBF (CP-D5)	62	76	671	1866	376
Jacket	n.d.	51	1280	0	0
Monopile (NW)	39	58	518	471	82

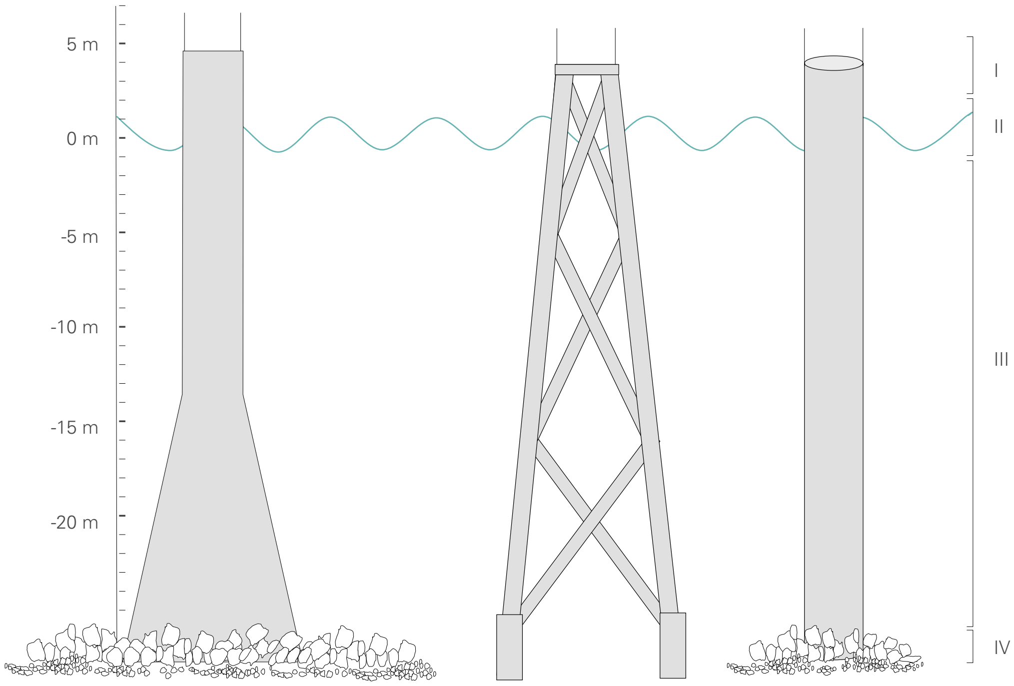


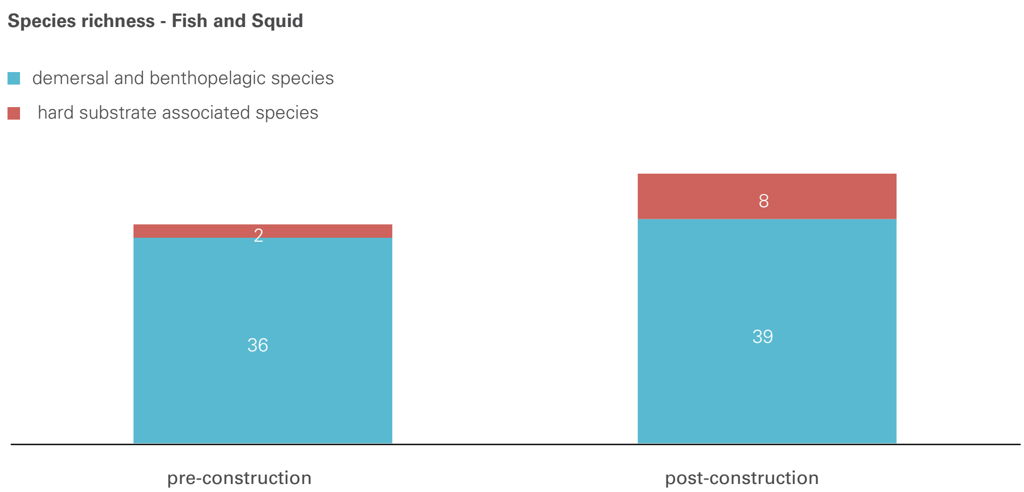
Figure1. Foundation types present in the Belgian part of the North Sea (from left to right: Gravity based, Jacket and Monopile foundation) with indication of the different fouling depth zones: I splash zone, II intertidal zone, III submerged foundation, and IV scour protection (if present).

SPECIES RICHNESS

A total of 44 fish species and four species of squid were observed in the wind farm area from 2005 to 2012 (Figure 2). Prior to the installation of the turbine foundations, 38 species were recorded including two hard substrate associated species: sea bass (*Dicentrarchus labrax*) and pouting (*Trisopterus luscus*). After the installation of the foundations the number of hard substrate associated fish species increased to eight with the addition of combtooth blennies (Blenniidae sp.), wrasses (Labridae sp.), lemon sole (*Microstomus kitt*), Atlantic pollock *(Pollachius pollachius)*, saithe (*Pollachius virens*), and black seabream (*Spondyliosoma cantharus)*.

Our results suggest that the species pool of fish and squid present in the wind farm area on the Thorntonbank has not undergone drastic changes. With a single exception (painted goby – *Pomatoschistus pictus*) all species observed prior to the installation of the turbine foundations are still present after the installation. The main difference observed is an increase in the number of hard substrate associated fish species (from 2 to 8). At Horns Rev, a Danish offshore wind farm located on a sandy seabed, a similar increase in reef habitat fish species was observed (Leonhard et al., 2013). It is unlikely that the limited increase in species richness of demersal and benthopelagic fish and squid species (from 40 to 43 species) is due to the exclusion of commercial fishing in the area since most of these species will not stay within a single wind farm concession area for longer periods (Lindeboom et al., 2011).

Figure 2. Species richness of fish and squid in the wind farm area prior and post construction of the (first) turbine foundations with distinction between demersal and benthopelagic species and hard substrate associated species.



A total of 285 benthic species were observed in the wind farm area from 2005 to 2012. Prior to the installation of the turbine foundations, 91 species were recorded, including ten hard substrate associated species (~11%). These hard substrate associated species were probably recovered from either shell fragments or coarser sediments. After the installation of the turbine foundations the number of hard substrate associated species increased to 100 out of 264 species observed in total (~38%). 83 species are recorded only once, of which respectively 21 and 62 were observed only before and after construction of the first turbine foundations.

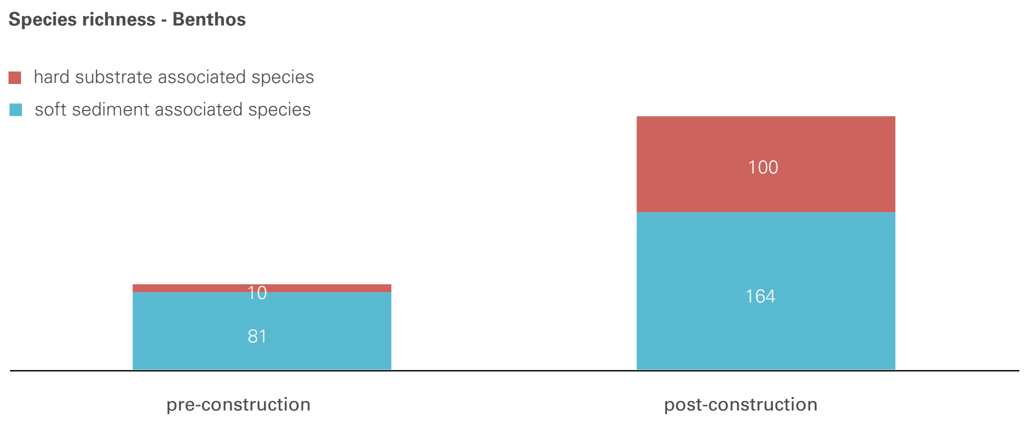
In contrast to the species of fish and squid, the number of benthic species observed in the concession area has more than doubled since the installation of the first turbine foundations (from 91 to 264, Figure 3). The number of hard substrate associated species has increased from 10 to 100. The large majority of the latter (90) were observed for the first time in the concession area after the installation of the foundations. These include both the dominant intertidal species, such as *Telmatogeton japonicus, Mytilus edulis* and, *Semibalanus balanoides,* as well as the dominant subtidal species, such as *Jassa herdmani, Tubularia* spp. and *Electra pilosa*. Prior to the installation of the turbine foundations, only shells and coarser sediments were available as substrate for such species.

Many of the species found in the area for the first time, had already been reported from elsewhere in the Belgian Part of the North Sea, for instance on shipwrecks. Both wrecks and turbine foundations provide patches of hard substrata in sea beds dominated by soft sediments. On these wrecks a total of 224 hard substrate associated species has been observed (Zintzen, 2007). As such it can be expected that the number of species typically associated with hard substrate will continue to increase in the wind farm zone in the coming years due to colonisation by additional species, a continuing increase in available habitat, expansion of this wind farm zone e.g. to include the gullies between the sand banks, and the ongoing sampling effort.

In addition to this, the number of soft sediment benthic species observed more than doubled, from 81 to 164. While the exclusion of commercial fishing in the area and the organic enrichment of the soft bottom sediments may account for part of this increase in species richness, it is likely that a post-construction increase in sampling effort plays a significant roll (number of epibenthic samples 2005-2008: 16 /2009-2012: 28, number of macrobenthic samples: 2005-2008: 60/ 2009-2012: 66). A clear shift in the benthic species composition of the soft sediments was only observed in the immediate vicinity of the foundations, where an accumulation of juvenile starfish (Asteriidae juv.) and opportunistic polychaetes such as *Spio* sp. and *Spiophanes bombyx* was observed (Coates et al., 2012). In the rest of the concession area the soft bottom benthic communities are still dominated by the same taxa as before (Chapters 9 & 10). 83 species out of a total of 285 benthic species ever registered in the area, were recorded only once. This indicates the low probability of encountering these species and may partly also be due to difference in taxonomic keys used by different reseachers. It is likely that this number will decrease as long-term monitoring continues and overall sampling effort increases.

Of the 333 taxa recorded including 44 fish and four squid species and 285 benthic species, only four were new for the Belgian part of the North Sea: *Fenestrulina delicia*, *Harmothoe antilopes, Molgula complanata* and *Polydora caulleryi* (Figure 4). All four hard substrate associated species are present in the surrounding UK, French and/or Dutch marine waters and the absence of records of these species in previous Belgian datasets may be indicative of the relatively poor knowledge of the fauna of the natural hard substrate rather than an extension of their geographical range. Additionally, four previously only once or rarely observed taxa were noted: *Thelepus setosus, Iphimedia nexa, Maja squinado* (spider crab) and *Homarus gammarus* (European lobster) (Figure 8).

Figure 3. Species richness of benthos in the wind farm area prior and post construction of the (first) turbine foundations with distinction between soft sediment and hard substrata associated benthos taxa.



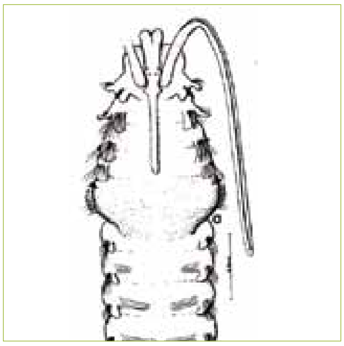
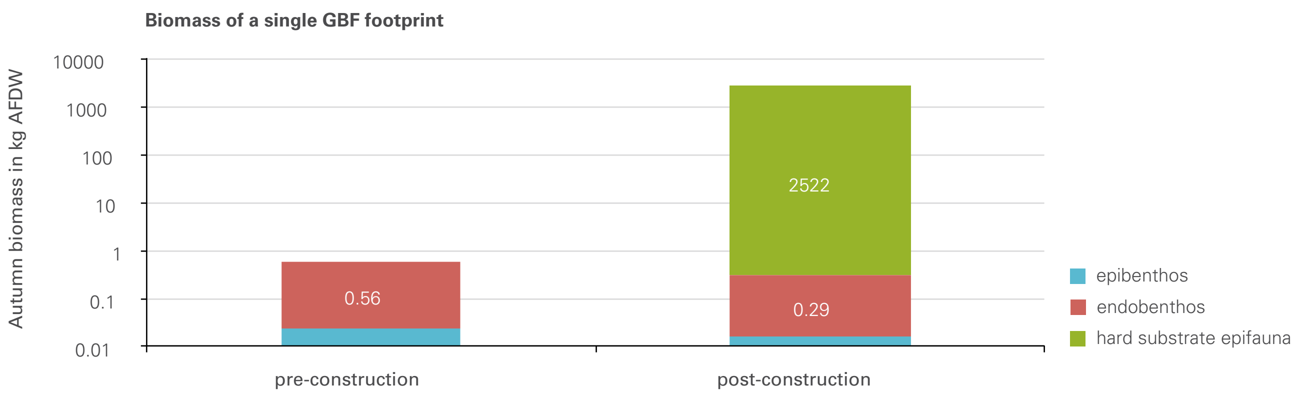


Figure 4. Species newly observed for the Belgian part of the North Sea. From left to right: the bryozoan *Fenestrulina delicia* (see also S.E.M. picture at the front of this chapter), the annelid worms *Harmothoe antilopes* and *Polydora caulleryi* (anterior end, drawing adapted from Blake, 1971) and the tunicate *Molgula complanata*

BIOMASS

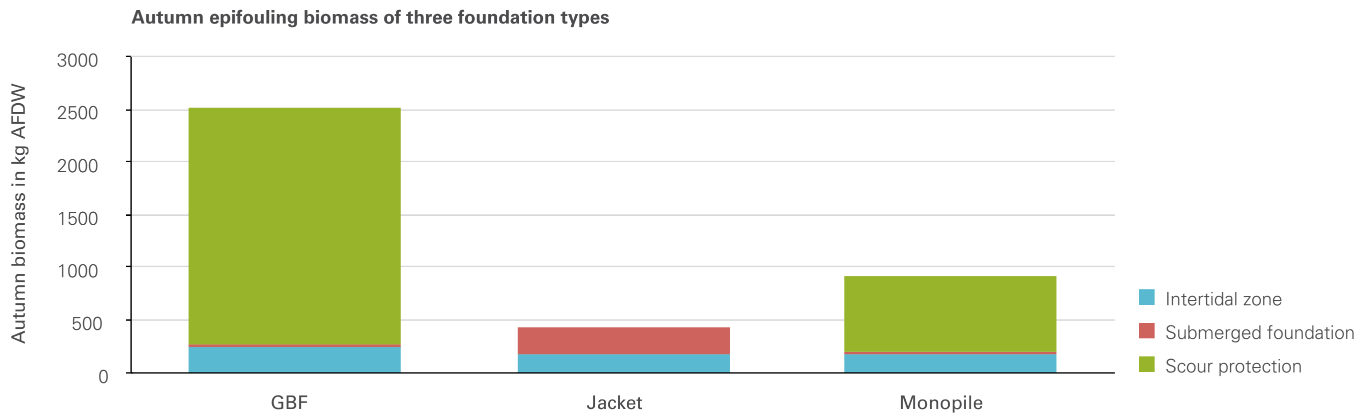
Autumn benthic biomass for a single GBF footprint increased ~4000 fold from 0.6 kg AFDW in 2005 (pre-construction) to ~2500 kg (post-construction) (Figure 5). For this particular foundation structure, the majority of the hard substrate epifaunal biomass was situated at the scour protection (89%) followed by the intertidal *Mytilus* zone (10%), with only the remaining (1%) located on the submerged part of the foundation. Epibenthos and endobenthos are assumed to have recolonized the silted filter layer (376.4 m²).

Figure 5. Autumn biomass prior (2005) and post (2012) construction of the offshore wind farm for the footprint of a single GBF.



Comparison of the calculated total autumn biomass for the three foundation types used in the BPNS shows that, despite a much higher subtidal area and a different fouling community, jacket foundations will have a lower epifouling biomass (Figure 6). The highest epifouling biomass is expected at the GBF, which has a sizable scour protection.

Figure 6. Calculated total autumn biomass (in AFDW) for a single concrete gravity based foundation (GBF), steel jacket foundation and steel monopile foundation present in the Belgian part of the North Sea.



For the entire Thorntonbank wind farm concession, with six GBF and 49 jacket foundations, the autumn biomass increased about 14 fold from 4.8 to 69.6 ton AFDW (Figure 7). Epibenthic and endobenthic biomass increased by 311 and 230% respectively. In contrast, epibenthic biomass in the reference area increased only by 1.3%. For endobenthos the increase falls within the boundaries of the inter-annual variation. In this wind farm the six GBF (with scour protection) account for a biomass comparable to that of 35 jacket foundations without scour protection (see also Figure 6).

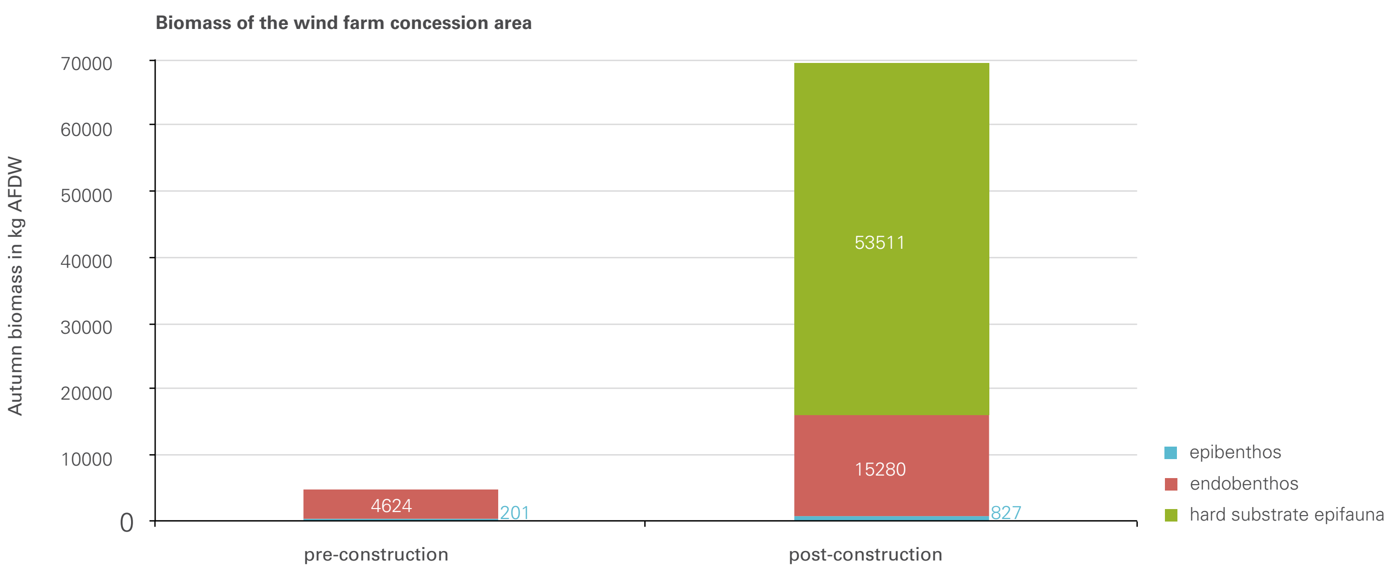
Zintzen et al. (2008b) estimated a mean epifauna biomass of 288 g AFDW m^{-2} for nine Belgian shipwrecks, with higher values for coastal sites with *Metridium senile* assemblages. In a Dutch study by Leewis et al. (2000) the average biomass of the *Metridium senile* assemblage was 1072 g AFDW m^{-2}. These values are higher than what we observed for epifauna biomass on the foundations (48 g AFDW m^{-2} for the submerged part of the GBF foundations. and 35 g AFDW m^{-2}. for the scour protection), with exception for the intertidal zone (3298 g AFDW m^{-2}). While these differences in values may in part reflect the difference in epifauna of a recently colonized offshore substrate and a coastal mature hard substrate community, we should also take into account the strong seasonal and interannual variations as we used data from autumn 2012 and both Zintzen et al. and Leewis et al used late spring to summer data.

Using the size of the seabed footprint of the different foundation types and the available surface of the respective structures, we calculated an epifauna biomass m^{-2} footprintof 1132 g AFDW m^{-2} for GBF,1230 g AFDW m^{-2} for jacket foundations, and 1603 g AFDW m^{-2} for steel monopile foundations. This is much higher than the soft sediment biomass of 0.8 g AFDW m^{-2} as measured in the concession zone. In general soft sediment macrobenthos biomass values for the southern North Sea are around 10 g AFDW m^{-2} (Duineveld et al., 1991, Heip et al., 1992), with higher values in the coastal *Abra alba* community (30-50 g AFDW m^{-2}, Prygiel et al., 1988).

Our results show that for the entire Thorntonbank wind farm concession area autumn biomass increased about 14 fold. While this biomass estimate is based on an extrapolation of a limited number of samples, and as such can be considered a very rough estimate, it remains valid to conclude that there is an order of magnitude increase in biomass for the entire concession area – as is observed in other countries (Lindeboom et al., 2011, Krone et al., 2013a, Birklund, 2006). This increased biomass serves as a food resource for the fish species and -indirectly - bird species found to aggregate or forage near the artificial hard substrate. This is illustrated by the large numbers of *Trisopterus luscus* (pouting) and *Gadus morhua* (Atlantic cod) observed near these structures both of which are known to feed on *Jassa* spp.(Reubens et al., 2011 and 2013d). Preliminary results also suggest that several bird species are attracted to the Thorntonbank area, including species with high protection status such as *Sterna sandvicensis* (Sandwich Tern), *Sterna hirundo* (Common Tern) and *Hydrocoloeus minutus* (Little Gull) (Vanermen et al., 2012, Chapter 15). As yet no attraction for marine mammals can be observed (Chapter 16) but this may be the result of ongoing construction activities in nearby concession areas, a type of disturbance that is expected to go on intermittently up to 2018.

In contrast to Dutch (Lindeboom et al., 2011), Danish (Birklund, 2006) and German (Krone et al., 2013a) offshore foundations as well as the Belgian jacket foundations, only a fairly thin portion of the GBF and monopile foundations is covered by *Mytilus edulis* (blue mussel), resulting in a lower epifaunal biomass for the submerged part of the foundation compared to the intertidal zone and scour protection. On the foundations of the Horns Rev wind farm, *Asterias rubens* (common starfish) played a role as key predator in preventing a "mussel monoculture" from developing (Leonhard & Birklund, 2006). This may also be the case here as seasonally high densities of *A. rubens* have been observed from the GBF (Kerckhof et al., 2010b) and surrounding soft sediments (Coates et al., 2012).

Figure 7. Calculated autumn biomass (in AFDW) prior (2005) and post (2012) construction for the entire Thorntonbank wind farm concession area.



FUTURE MONITORING

We expect that, due to the further development of the Belgian wind energy zone, the number of hard substrate associated species present in an area previously characterised by soft sediments will increase. Furthermore, the exclusion of fisheries activities in the area is expected to allow a number of benthic species sensitive to disturbance to recover or recolonize. However, these artificial hard substrate do not provide a long term solution for the preservation or restoration of the fauna of the threatened natural boulder fields and oyster banks since they harbour a different epifaunal community (Kerckhof et al., 2012) and have a relatively short expected lifetime (~20-30 years).

Our results demonstrate that there is a spectacular increase in biomass as a result of the development of fouling on the foundations and associated scour protection. Since the largest part of this fouling biomass is situated on the scour protection and the presence and extent of the scour protection is largely related to the type of foundation, the impact of the further development of the entire Belgian wind energy zone (with seven wind farms with a total of 446-530 turbines licensed) will be largely dependent of the foundation types chosen. Depending on the type of foundation chosen, roughly between 1078 (all new foundations GBF – total footprint 0.93 km^2) and 272 (all new foundation jacket – total footprint 0.20 km^2) ton of fouling AFDW could be added to the Belgian part of the North Sea[2] resulting in the maximal addition of circa 3% of the total biomass from the BPNS[3].In comparison, all shipwrecks on the BPNS together represent a footprint between 0.85 km^2 and 1.49 km^2 and were calculated by Zintzen (2007) to increase the soft sediment biomass of the BPNS by a maximum of 4%. Future monitoring will determine whether our assumptions with regards to the fouling biomass on the jacket and monopile foundations are valid.

If the objective is to preserve the soft sediment fauna characteristic of the area, than licensing should focus on minimising the amount of artificial hard substrate introduced to zone i.e. allowing only jacket type foundations. If, on the other hand, the objective is to combine renewable energy development with the promotion of a number of hard substrate associated commercial species such as Atlantic cod (Reubens et al., 2013a), European lobster and edible crab, than introduction of sizable artificial hard substrates may be beneficial although this will need to be confirmed by studies on their residence periods, food and shelter requirements.

[2] Simplified extrapolation taking into account the already installed foundations and assuming similar foundation dimensions and fouling development for the entire wind energy zone. While both assumptions are clearly false (see e.g. Zintzen et al., 2008b) they do allow for a rough order-of-magnitude estimate.

[3] Assuming an average value of 10 g AFDW m^{-2} for the BPNS (as in Duineveld et al., 1991; Heip et al., 1992)

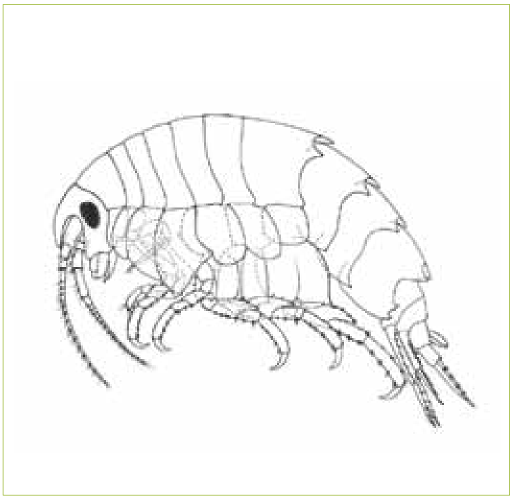
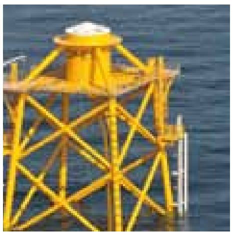


Figure 8. Species only once or rarely encountered in the Belgian part of the North Sea prior to the construction of the offshore wind farm: *Thelepus setosus*, *Iphimedia nexa*, *Maja squinado* (spider crab) and *Homarus gammarus* (European lobster).



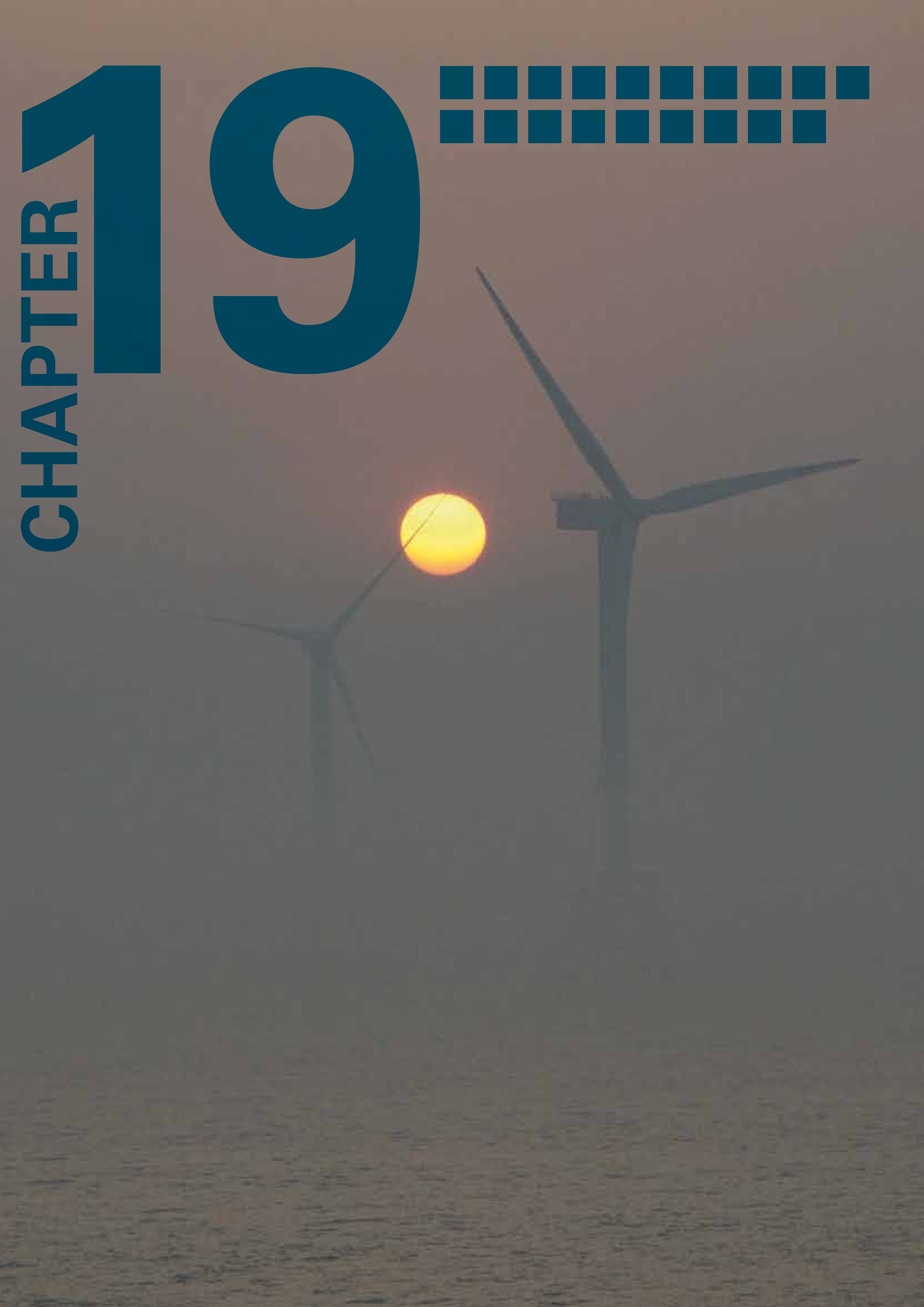



PART V

REFLECTIONS FOR AN OPTIMISATION OF FUTURE MONITORING PROGRAMMES

CHAPTER 19

CHAPTER 19



Optimising the future Belgian offshore wind farm monitoring programme

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Six years of monitoring triggered a reflection on how to best continue with the monitoring programme. The basic monitoring has to be rationalised at the level of the likelihood of impact detection, the meaningfulness of impact size and representativeness of the findings. Targeted monitoring should continue to disentangle processes behind the observed impact, for instance the overarching artificial reef effect created by wind farms. The major challenge however remains to achieve a reliable assessment of the cumulative impacts. Continuing consultation and collaboration within the Belgian offshore wind farm monitoring team and with foreign marine scientists and managers will ensure an optimisation of the future monitoring programme.

INTRODUCTION

During the first six years of monitoring, the Belgian offshore wind farm monitoring programme primarily focused on describing the main societal, physical and ecological impacts of offshore wind farms and understanding a selection of processes behind those impacts. Several ecosystem components were investigated and compared with reference conditions at the site and in control areas. This basic monitoring resulted in a comprehensive description of the major changes in the wind farm zone so far (Chapters 3-12). Based on the basic monitoring several hypotheses on the ecological processes behind the observed impacts were generated and investigated. This targeted monitoring so far focused on a local enrichment in soft sediment macrobenthos near the wind turbines, and the (possible) attraction of fish, seabirds and marine mammals as a consequence of habitat alterations (Chapters 13-16). We further started evaluating the observed impacts and the related ecological processes in a wider context (Chapters 17-18).

Arriving at the end of this first six years of offshore wind farm monitoring, we reflect on the continuation of the monitoring programme. The main questions to be answered are what programme aspects need correction or continuation, but also what aspects neglected so far deserve scientific attention in the future. This chapter is based on the prospects on monitoring as elaborated in the different chapters and sheds a light on how the future monitoring programme could and should look like to optimally make use of existing knowledge and available resources.

BASIC MONITORING

Basic monitoring focusing on the effect of human activities such as the construction and operation of offshore wind farms is the most common type of monitoring in impact studies. It allows keeping track of major and even unforeseen impacts and is therefore the ideal research strategy to have a finger firmly on the pulse of environmental impact development. It may trigger adjusting or even halting activities in case unacceptable impacts would occur. The continuation of the basic monitoring of all ecosystem components should hence be considered mandatory from a marine ecosystem management perspective, including societal acceptability. The seascape survey for example so far showed the public to generally accept the presence of offshore wind farms. This may however change once the wind farm closest to the coast is constructed, hence requiring future monitoring attention. Some reflections on what has been done so far and how to best continue are however indispensable for an optimisation of the future basic monitoring programme.

In this study, we differentiated between 'positive' and 'negative' responses to offshore wind farms. Next to the impairment of the seascape, ecological 'negative' impacts include the altered sediment characteristics, increased erosion of the natural sandy sediments around wind turbine foundations, an increase in non-indigenous species on the hard substrata, an obvious disturbance of seabirds because of avoidance and collision, and the increased sound pressure on the marine environment and its impact on marine mammals and fish. The 'positive' impacts include the enrichment of the soft and hard substratum invertebrates and fish. So far, all ecosystem components investigated in the Belgian monitoring programme have already shown some degree of response to the offshore wind farms. However, as the ecosystem at the Belgian wind farms is still developing, the patterns observed so far should be considered short term and hence most probably only reflect the initial stages of the ecological succession. Some impacts may not have been detected yet, simply because they are still not developed to the extent needed to become detectable. The enrichment of the soft sediment macrobenthos observed close to the wind turbines for instance, has been demonstrated to spatially extend through time but is likely not to have reached the spatial extent to be picked up by the basic monitoring of macrobenthos, collecting samples at more than 200 m from the turbines. A continuation of the basic monitoring of all ecosystem components is therefore recommended.

For the future basic monitoring, we should acknowledge the likelihood of impact detection being dependent on research effort, impact size and data noise. Research effort is mainly determined by the amount of observations or samples collected. Impact size is the degree of deviation from the reference conditions and data noise is natural or sampling-induced variability in the data. The low likelihood of impact detection possibly blurring impacts of offshore wind farms on seabirds, has for example been statistically underpinned by the basic monitoring for several seabird species. The current difficulties in demonstrating consistent impacts on the soft-sediment epibenthos and fish throughout the first six years of monitoring is probably related to a combination of natural and sampling-induced variability. This issue certainly needs further consideration when (re)designing the future basic monitoring programme. Here, attention for the statistical power analysis will be needed to quantify the likelihood to detect an impact of a given extent, but equally for methods on how to lower the noise in the data to be explored. For the latter issue, natural variability may be lowered for instance by focusing data collection on one season and as such excluding

seasonality. Sampling-induced variability in its turn may be lowered by increasing the sample size. A higher number of passive acoustic monitoring devices inside and outside wind farms for example, could facilitate investigating possible harbour porpoise *Phocoena phocoena* attraction to offshore wind farms. Moored equipment (available since mid-2013) will allow recording long time series of underwater noise, during a broad range of weather conditions and various wind farm development stages, and will hence increase the representativeness of underwater noise results. Within a Before-After Control-Impact (BACI) design, an appropriate balance in number of samples per group needs to be targeted. Finally, the relevance of the impact size needs discussion, as we have to accept a certain degree of human-induced impacts on the marine environment, but these impacts should not exceed thresholds of sustainability. Current exercises in the context of the European Habitats- and Birds Directives (Nature 2000), and the Marine Strategy Framework Directive (MSFD) to determine what is acceptable from a nature conservation point of view (Nature 2000: Favourable Conservation Status and Conservation Objectives) or from a sustainability perspective (MSFD: Good Environmental Status and Environmental Targets), will help setting the scene for selecting a meaningful impact limit.

Representativeness of the basic monitoring findings is a major issue to be considered in the future monitoring programme. The research so far mainly focused on two wind farms, which may not be representative for other wind farms by default. Other wind farms are present, are being built or will be constructed, each of these taking a specific position along the onshore-offshore gradient from turbid coastal waters to clear English Channel water, and along the bathymetric gradient from gullies to sandbank tops. These gradients influence the hydrodynamics and water characteristics, which in turn affect underwater life. Also the occurrence of bird species shows an onshore-offshore gradient. When planning the future basic monitoring, the spatial distribution of the sampling effort along natural environmental gradients will therefore have to be well considered. Additionally, the type of foundations differs between and even within wind farms. Steel monopile and jacket foundations, the latter generally without erosion protection layer, are most common in Belgian waters, while most of the reef effect monitoring, especially concerning fish attraction, has been performed near the concrete gravity based foundations with an extended erosion protection layer. Preliminary comparisons already demonstrated a difference in ecology between the different foundation types. To allow for a solid onshore-offshore comparison and to exclude foundation-related variability, the future monitoring programme should focus on one type of foundation. On the other hand, foundation type-effects should be investigated in a naturally homogeneous environment. Because available resources for monitoring are limited, a well-considered focus and associated sampling effort and allocation is needed.

All of above mentioned considerations, i.e. likelihood of impact detection, acceptable threshold of impact size and representativeness of the monitoring results, will be subject of a workshop on the rationalisation of the Belgian basic offshore wind farm monitoring programme in 2014. This workshop will lead to strategic decisions for a scientifically-sound and feasible basic monitoring programme at the level of research effort and allocation, data noise reduction, and impact size. The fine-tuned programme will come into force from 2015 onwards.

TARGETED MONITORING

Monitoring results that can be used to steer the design of future industrial projects, offer a significant added value to monitoring programmes. For this purpose, a proper understanding of the cause-effects relationships is needed. The targeted monitoring of the Belgian programme aims to understand the ecological processes behind the observed impacts and hence allows extrapolating its results for a better design of future wind farms. Targeted monitoring will continue to be an important aspect of the Belgian offshore wind farm monitoring programme.

The hypothesised cause-effect relationships behind offshore wind farm impacts are plentiful. The Working Group on Marine Benthos and Renewable Energy Developments (WGMBRED) of the International Council for the Exploration of the Sea (ICES) reviewed the cause-effect relationships between offshore renewable energy installations, mainly offshore wind farms, and marine benthos (ICES, 2013)[1]. They discovered a wide variety of (possible) causal relationships, all framed in a context of the marine environment as a biogeochemical reactor, as a source of biodiversity and food resources for higher trophic levels. The biogeochemical reactor context alone for example already revealed no less than 17 cause-effect relationships. From their analysis, it becomes obvious that a well-considered selection of priority relationships will be needed to ensure feasible monitoring programmes.

Several cause-effect relationships have already been tackled during the first six years of monitoring. The local enrichment of organic matter in the soft sediment close to wind turbines was found to cause an increase in macrobenthic species richness and density. Some fish and seabird species were found to be attracted to the wind turbines as a consequence of habitat alterations, such as improved feeding conditions. Stomach analysis of cod *Gadus morhua* and pouting *Trisopterus luscus* proved for example that these species primarily predate on the hard substratum epifauna. All chapters on targeted monitoring (Chapter 13-16) present recommendations for future monitoring. For a detailed justification of these recommendations, one is referred to the individual chapters. This section merely aims at highlighting a selected set of hypothesis-driven pathways for further consideration in the future Belgian targeted monitoring programme, taking into account the knowledge obtained during the monitoring so far, ecological and societal relevance, as well as feasibility.

The artificial reef effect will undoubtedly play a key role in the future targeted monitoring. It already received a lot of attention, but various cause-effect relationships remain yet to be tackled. The attraction-production hypothesis in artificial reefs has been investigated in detail for cod and pouting, but several invertebrate (e.g. edible crab *Cancer pagurus* and European lobster *Homarus gammarus*) and fish species common in Belgian offshore wind farms, were so far left unstudied. Investigations of their habitat use for example would shed a light on the key habitat features that are essential to maintain a sustained local population of these species. Also the hard substratum epifouling community, comprising important prey species for the above mentioned predatory megafauna, needs further targeted attention. Biomass estimates of these prey species may be used to extrapolate food availability to the total footprint of a wind turbine and the whole wind farm artificial reef. Energy and fatty acids profiling of both predators and prey can open the door to energy transfer estimates and hence elucidate trophic interactions within offshore wind farms. Also the soft sediment macrobenthos in the vicinity of wind turbines may be suitable for this purpose, as the increasing abundance may start playing an important role in the artificial reef food web. The artificial reef effect may further explain the attraction of some bird species (e.g. common tern *Sterna hirundo*) to the wind farms as it is hypothesised that these species benefit from a yet unexplored increased availability of pelagic fish. Whether or not pelagic prey fish also attract marine mammals such as harbour porpoises remains yet to be resolved. Attention to the pelagic fish community in the future monitoring programme is hence of utmost importance. The anticipated positive artificial reef effect may however be partially neutralised by the underwater noise generated during the construction (short term) and exploitation (long term) of offshore wind farms. More hypothesis-driven research on the impact of underwater noise on marine mammals and (the development of) fish is needed to get a full grip on the effect of underwater noise on the marine ecosystem.

While the Belgian targeted monitoring programme anticipates tackling the above mentioned cause-effect relationships, such research should ideally be dealt with in an international setting. The same or at least similar cause-effect relationships are expected in offshore wind farms abroad. This certainly holds true for the southern North Sea, where numerous wind farms are (planned to be) constructed. Given the fact that cause-effect oriented research by definition allows extrapolation outside the area under investigation, there is no need to tackle the same hypothesises in every single wind farm. A well-considered international collaboration as aimed for by initiatives such as WGMBRED, will avoid unneeded repetition of research and would significantly contribute to an optimal use of resources available for wind farm monitoring.

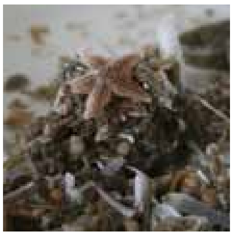
[1] ICES. 2013. Report of the Working Group on Marine Benthal and Renewable Energy Developments (WGMBRED), 19-22 March 2013, Caen, France. ICES CM 2013/SSGEF:17. 23 pp.

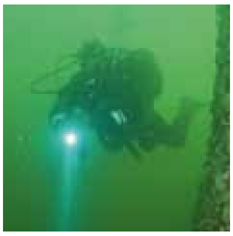
CUMULATIVE AND LARGE SCALE IMPACTS

A major challenge for the future Belgian monitoring programme – and by extension all offshore renewable energy environmental monitoring programmes – will be to assess cumulative impacts and to upscale locally observed impacts to the larger scale at which ecological processes take place. The offshore wind farm industry is expanding rapidly and new wind farms are arising fast, not only in Belgium but at several other places in the North Sea and beyond. Current monitoring efforts however mainly focus on the environmental impact of a single wind farm. Because the species that are affected are part of populations extending over larger areas, the focus of the impact investigation should be widened to the population level of those species. For example, for seabirds attracted to the wind farms, there is an increased risk of collision with the wind turbine blades. Whether or not the number of collisions may actually put the sustainability of certain bird populations at risk can however only be reliably assessed when taking account of the multitude of wind farms throughout the range of their populations' spatial distribution. Similarly, the effect on the population of harbour porpoises avoiding areas of pile driving, can also only be assessed in a cumulative offshore wind farm context throughout their distributional range. Furthermore, effects anticipated to be positive from a local perspective, such as the improved feeding condition for cod attracted to the wind turbines, are yet to be evaluated at the population level before final conclusions on the attraction-production hypothesis can be drawn. There is hence an urgent need for scientifically sound thresholds for acceptable overall mortality or habitat loss, which should be investigated at the spatial scale relevant to the population of each species under consideration.

Offshore wind farms are only one of the many human activities in the marine environment. This is yet another aspect relevant to cumulative impact assessment. Assessing the combined effect of all these activities or merely framing the observed impact of wind farms in a broader setting, demands a holistic approach and is of major importance for the future management of the marine ecosystem. While this issue is not new to environmental impact assessment, clear research designs to appropriately tackle the issue are largely lacking. Innovative strategies are needed here.

The monitoring of both types of cumulative effects is very ambitious and cannot satisfactorily be dealt with by a single country or research team. It requires a close collaboration between scientists and administrators, preferably across country borders, to assemble and comprehensively analyse all information that is needed. The complexity is illustrated by the analysis of the fishing effort in the Belgian part of the North Sea, for which realistic distribution maps can only be drafted when VMS data, logbook data and metadata of all Belgian and foreign vessels that operate in the area are compiled, an opportunity that is still missing. The future Belgian monitoring programme will further strive to upscale its findings in a cumulative context, and will search for international collaboration to develop the analytical strategies needed.



PART VI

CITED LITERATURE

ANNEX

PHOTO CREDITS

ACKNOWLEDGEMENTS

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Annex

Overview of the taxa observed in the wind farm concession areas on the Thorntonbank and Bligh Bank with indication of their presence before and/or after the start of the construction of the wind farms at these locations. Studied groups: birds, marine mammals, fish* and macro invertebrates*.

* Groups discussed in chapter 18.

Phylum	Class	Species	Common name in Dutch	Common name in English	Observed prior to construction	Observed since start construction
Annelida	Polychaeta	*Aonides oxycephala*	-	-	x	x
		Aonides paucibranchiata	-	-	x	x
		Aphelochaeta filiformis	-	-		x
		Aphelochaeta marioni	-	-		x
		Aricidea catherinae	-	-		x
		Aricidea (Aricidea) minuta	-	-		x
		Aricidea (Acmira) simonae	-	-		x
		Aricidea (Strelzovia) suecica	-	-		x
		Autolytinae	-	-		x
		Boccardiella ligerica	-	-		x
		Capitella capitata	slangpier	gallery worm		x
		Capitella minima	-	-		x
		Chaetopterus variopedatus	perkamentworm	parchment worm		x
		Dipolydora caulleryi	-	-		x
		Dipolydora giardi	-	-		x
		Eteone flava	-	-	x	
		Eteone longa	groengele wadworm	paddleworm	x	x
		Eulalia viridis	groene bladkieuwworm	greenleaf worm		x
		Eumida sanguinea	-	-		x
		Eunereis longissima	zager	-	x	x
		Eunoe nodosa	-	-	x	
		Eupolymnia nebulosa	-	-	x	
		Thoracophelia flabellifera	-	-		x
		Exogone hebes	-	-		x

Phylum	Class	Species	Common name in Dutch	Common name in English	Observed prior to construction	Observed since start construction
Annelida	Polychaeta	*Gattyana cirrhosa*	gekroesde zeerups	-		x
		Glycera alba	-	-	x	x
		Glycera lapidum	-	-	x	x
		Glycera unicornis	-	-	x	
		Goniadella bobretzkii	-	-	x	
		Harmothoe antilopes	-	-		x
		Harmothoe clavigera	-	-		x
		Harmothoe extenuata	-	-		x
		Harmothoe glabra	-	-		x
		Harmothoe impar	-	-	x	
		Harmothoe pachenstegeri	-	-		x
		Hesionura elongata	-	-		x
		Heteromastus filiformis	draadworm	-		x
		Kefersteinia cirrata	-	-		x
		Pectinaria (Lagis) koreni	goudkammetje	trumpet worm		x
		Lanice conchilega	schelpkokerworm	sand mason worm	x	x
		Lepidonotus squamatus	geschubde zeerups	-		x
		Magelona johnstoni	-	-	x	x
		Magelona mirabilis	-	-		x
		Malacoceros fuliginosus	-	-	x	
		Maldanidae	bamboewormen	bamboo worms		x
		Malmgreniella sp.	-	-		x
		Microphthalmus similis	-	-		x
		Myrianida edwardsi	-	-		x
		Nephtys caeca	-	-	x	x
		Nephtys cirrosa	zandzager	white catworm	x	x
		Nephtys hombergii	zandzager	catworm		x
		Nephtys kersivalensis	-	-	x	
		Nephtys longosetosa	-	-		x
		Nereis pelagica	gewone zeeduizendpoot	-		x
		Notomastus latericeus	-	-		x

Phylum	Class	Species	Common name in Dutch	Common name in English	Observed prior to construction	Observed since start construction
Annelida	Polychaeta	*Ophelia borealis*	-	-		x
		Ophelia limacina	-	-	x	x
		Ophelia rathkei	-	-		x
		Orbinia sp.	-	-	x	x
		Owenia fusiformis	-	-		x
		Paraonis fulgens	-	-		x
		Parougia eliasoni	-	-		x
		Pettibonesia furcosetosa	-	-		x
		Pholoe inornata	-	-		x
		Pholoe minuta	-	-		x
		Pholoe synophthalmica	-	-		x
		Phyllodoce laminosa	-	-		x
		Phyllodoce lineata	-	-	x	x
		Phyllodoce longipes	-	-		x
		Phyllodoce maculata	gestippelde dieseltreinworm	-	x	x
		Phyllodoce mucosa	-	-		x
		Phyllodoce rosea	-	-	x	x
		Poecilochaetus serpens	-	-		x
		Polydora (Dipolydora) caulleryi	-	-		x
		Polygordius appendiculatus	-	-	x	
		Pomatoceros (Spirobranchus) triqueter	driekantige kalkkokerworm	keelworm		x
		Protodorvillea kefersteini	-	-		x
		Pseudopolydora pulchra	-	-		x
		Sabellaria spinulosa	-	Ross worm		x
		Scolelepis bonnieri	-	-	x	x
		Scolelepis foliosa	-	-	x	
		Scolelepis squamata	gemshoornworm	-		x
		Scoloplos (Scoloplos) armiger	wapenworm	bristle worm	x	x
		Sigalion mathildae	-	-		x
		Spio filicornis	-	bristleworm		x
		Spio goniocephala	-	-		x

Phylum	Class	Species	Common name in Dutch	Common name in English	Observed prior to construction	Observed since start construction
Annelida	Polychaeta	*Spiophanes bombyx*	-	bee spionid	x	x
		Streblospio sp.	-	-		x
		Syllis gracilis	-	-	x	x
		Thelepus cincinnatus	-	-	x	
		Thelepus setosus				x
		Travisia forbesii	-	-		x
Arthropoda	Insecta	*Telmatogeton japonicus*	Japanse dansmug	marine splash midge		x
	Malacostraca	*Abludomelita obtusata*	-	-		x
		Ampeliscidae sp.	-	-		x
		Amphilochus neapolitanus	-	-		x
		Aora gracilis	-	-		x
		Apherusa ovalipes	-	-		x
		Athanas nitescens	-	hooded shrimp		x
		Atylus (Nototropis) swammerdamei	-	-	x	x
		Bathyporeia elegans	-	sand digger shrimp	x	x
		Bathyporeia guilliamsoniana	-	-	x	x
		Bathyporeia pelagica	-	-	x	x
		Bathyporeia pilosa	-	-		x
		Bathyporeia sarsi	-	-		x
		Bathyporeia tenuipes	-	-		x
		Bodotria arenosa	-	-		x
		Bodotria pulchella	-	-	x	
		Bodotria scorpioides	-	-	x	
		Callianassa (Pestarella) tyrrhena	-	sand ghost shrimp		x
		Calliopius laeviusculus	-	-		x
		Cancer pagurus	Noordzeekrab	North sea crab	x	x
		Corophium (Mono-corophium) acherusicum	-	-		x
		Corystes cassivelaunus	helmkrab	masked crab	x	x
		Crangon allmanni	groefstaartgarnaal	Almann shrimp	x	x
		Crangon crangon	grijze garnaal	brown shrimp	x	x
		Dexamine thea	-	-		x

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Arthropoda	Malacostraca	*Diastylis bradyi*	-	-		x
		Diastylis laevis	-	-	x	
		Diastylis rathkei	-	-	x	x
		Diastylis rugosa	-	-		x
		Diastyloides biplicatus	-	-		x
		Diogenes pugilator	kleine heremietkreeft	small hermit crab	x	x
		Ebalia granulosa	-	-		x
		Eualus sp.	-	-		x
		Eurydice spinigera	-	-	x	x
		Eusirus longipes	-	-		x
		Gastrosaccus spinifer	-	-	x	x
		Hemigrapsus sanguineus	blaasjeskrab	Asian shore crab		x
		Hippolyte varians	veranderlijke steurgarnaal	chamaeleon prawn		x
		Homarus gammarus	Europese zeekreeft	European lobster		x
		Hyperia galba	kwalvlo	big-eye amphipod		x
		Iphimedia nexa	-	-		x
		Jassa herdmani	-	-		x
		Jassa marmorata	-	-		x
		Leptomysis gracilis	-	-		x
		Leucothoe incisa	-	-	x	x
		Leucothoe lilljeborgi	-	-		x
		Leucothoe spinicarpa	-	-		x
		Liocarcinus depurator	blauwpootzwemkrab	harbour crab	x	x
		Liocarcinus holsatus	gewone zwemkrab	flying crab	x	x
		Liocarcinus marmoreus	gemarmerde zwemkrab	marbled swimming crab	x	x
		Liocarcinus navigator	gewimperde zwemkrab	arch-fronted swimming crab		x
		Macropodia parva	kleine hooiwagenkrab			x
		Macropodia rostrata	gewone hooiwagenkrab	long legged spider crab	x	x
		Maerella tenuimana	-	-		x
		Megaluropus agilis	-	-	x	x
		Melita dentata	-	-		x

Phylum	Class	Species	Common name in Dutch	Common name in English	Observed prior to construction	Observed since start construction
Arthropoda	Malacostraca	*Melita hergensis*	-	-		x
		Mesopodopsis slabberi	steeloog-aasgarnaal	-		x
		Corophium (Monocorophium) sextonae	Sexton's slijkgarnaal	-		x
		Mysida sp.	aasgarnalen	mysid shrimp		x
		Nannonyx spinimanus	-	-	x	
		Nebalia bipes	-	-		x
		Necora puber	fluwelen zwemkrab	velvet swimming crab	x	x
		Neomysis integer	gewone aasgarnaal	opossum shrimp		x
		Atylus (Nototropis) falcatus			x	x
		Oedicerotidae sp.	-	-		x
		Orchomenella nana	-	-		x
		Pagurus bernhardus	heremietkreeft	hermit crab	x	x
		Pagurus forbesii	-	-		x
		Pagurus pubescens	-	-		x
		Palaemon serratus	steurgarnaal	common prawn	x	x
		Pandalus montagui	ringsprietgarnaal	Aesop shrimp	x	
		Paramysis arenosa	-	-		x
		Pariambus typicus	hongerlijder	-	x	x
		Perioculodes longimanus	-	-	x	x
		Pestarella tyrrhena	-	sand ghost shrimp		x
		Philocheras trispinosus	driepuntsgarnaaltje	-	x	x
		Phtisica marina	teringlijder	-		x
		Pilumnus hirtellus	ruig krabbetje	bristly crab		x
		Pinnotheres pisum	erwtenkrabbetje	pea crab		x
		Pisidia longicornis	gewoon porseleinkrabbetje	long-clawed porcelain crab		x
		Pontocrates altamarinus	-	-	x	x
		Pontocrates arenarius	-	-	x	x
		Processa modica	kortpotige knikgarnaal	-		x
		Pseudocuma (Monopseudocuma) gilsoni	-	-		x
		Pseudocuma (Pseudocuma) longicorne	-	-	x	x
		Pseudocuma (Pseudocuma) simile	-	-	x	x

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Arthropoda	Malacostraca	*Sophrosyne robertsoni*	-	-		x
		Stegocephaloides sp.	-	-		x
		Stenothoe marina	-	-		x
		Stenothoe monoculoides	-	-		x
		Stenothoe valida	-	-		x
		Synchelidium haplocheles	-	-		x
		Synchelidium maculatum	-	-		x
		Thia scutellata	teennagel	thumbnail crab	x	x
		Upogebia deltaura	harige molkreeft	-	x	x
		Urothoe brevicornis	bulldozerkreeftje	-	x	x
		Urothoe elegans	-	-		x
		Urothoe poseidonis	bulldozerkreeftje	-	x	
		Urothoe pulchella	-	-		x
	Maxillopoda	*Balanus crenatus*	gekartelde zeepok	-		x
		Balanus (Amphibalanus) improvisus	brakwaterpok	bay barnacle		x
		Balanus perforatus	vulkaantje	-		x
		Copepoda	roeipootkreeften	copepods	x	x
		Elminius modestus	Nieuw-Zeelandse zeepok	Australasian barnacle		x
		Megabalanus coccopoma	grote roze zeepok	titan acorn barnacle		x
		Semibalanus balanoides	gewone zeepok	acorn barnacle		x
		Verruca stroemia	ritspok	-		x
	Pycnogonida	Pycnogonida sp.	zeespinnen	sea spiders		x
Bryozoa	Gymnolaemata	*Aspidelectra melolontha*	-	-		x
		Callopora dumerilii	-	-		x
		Conopeum reticulum	zeekantwerk	-		x
		Electra pilosa	harig mosdiertje	hairy sea-mat		x
		Fenestrulina delicia	-	-		x
Chordata	Actinopterygii	*Agonus cataphractus*	harnasmannetje	hooknose	x	x
		Alosa fallax	fint	twaite shad	x	x
		Ammodytes tobianus	zandspiering	sandeel	x	x
		Arnoglossus laterna	schurftvis	scaldfish	x	x

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Chordata	Actinopterygii	*Belone belone*	geep	garfish		x
		Blenniidae sp.	slijmvissen	blenny		x
		Buglossidium luteum	dwergtong	solenette	x	x
		Callionymus lyra	pitvis	dragonet	x	x
		Callionymus reticulatus	rasterpitvis	reticulated dragonet	x	x
		Ciliata mustela	5-dradige meun	5 bearded rockling	x	x
		Clupea harengus	haring	herring	x	x
		Dicentrarchus labrax	zeebaars	sea bass	x	x
		Echiichthys vipera	kleine pieterman	lesser weever	x	x
		Engraulis encrasicolus	ansjovis	anchovy	x	x
		Entelurus aequoreus	adderzeenaald	snake pipefish		x
		Eutrigla gurnardus	grauwe poon	grey gurnard	x	x
		Gadus morhua	kabeljauw	cod	x	x
		Gaidropsarus vulgaris	3-dradige meun	3 bearded rockling	x	x
		Hyperoplus lanceolatus	smelt	great sandeel	x	x
		Labridae sp.	lipvissen	wrasse		x
		Limanda limanda	schar	dab	x	x
		Merlangius merlangus	wijting	whiting	x	x
		Microstomus kitt	tongschar	lemon sole		x
		Mullus surmuletus	mul	mullet	x	x
		Myoxocephalus scorpius	zeedonderpad	scorthorn sculpin	x	x
		Pegusa lascaris	Franse tong	Dover sole	x	x
		Platichthys flesus	bot	flounder	x	x
		Pleuronectes platessa	pladijs	plaice	x	x
		Pollachius pollachius	pollak	pollack		x
		Pollachius virens	koolvis	saithe		x
		Pomatoschistus lozanoi	Lozano's grondel	Lozano's goby	x	x
		Pomatoschistus minutus	dikkopje	sand goby	x	x
		Pomatoschistus pictus	kleurige grondel	painted goby	x	
		Psetta maxima	tarbot	turbot	x	x
		Scomber scombrus	makreel	mackerel		x

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Chordata	Actinopterygii	*Solea solea*	tong	sole	x	x
		Spondyliosoma cantharus	zeekarper	black seabream		x
		Sprattus sprattus	sprot	sprat	x	x
		Syngnathus acus	grote zeenaald	greater pipefish	x	x
		Syngnathus rostellatus	kleine zeenaald	Nilsson's pipefish		x
		Trachurus trachurus	horsmakreel	horse mackerel	x	x
		Trigla lucerna	rode poon	tub gurnard	x	x
		Trisopterus luscus	steenbolk	bib / pouting	x	x
		Trisopterus minutus	dwergbolk	poor cod	x	x
	Aves	*Alauda arvensis*	veldleeuwerik	Sky Lark	x	x
		Alca torda	alk	Razorbill	x	x
		Anas crecca	wintertaling	Eurasian Teal	x	
		Anas penelope	smient	Eurasian Wigeon	x	
		Anser/Branta spec.	onbekende gans	unidentified goose		x
		Anthus pratensis	graspieper	Meadow Pipit	x	x
		Apus apus	gierzwaluw	Common Swift	x	x
		Ardea cinerea	blauwe reiger	Grey Heron		x
		Branta bernicla	rotgans	Brent Goose	x	x
		Calidris alpina	bonte strandloper	Dunlin	x	
		Calidris canutus	kanoet	Red Knot	x	
		Circus aeruginosus	bruine kiekendief	Eurasian Marsh Harrier	x	
		Columba oenas	holenduif	Stock Pigeon	x	
		Fratercula arctica	papegaaiduiker	Atlantic Puffin		x
		Fringilla coelebs	vink / boekvink	Chaffinch		x
		Fringilla montifringilla	keep	Brambling	x	
		Fulmarus glacialis	Noordse stormvogel	Northern Fulmar	x	x
		Gavia arctica	parelduiker	Black-throated Diver	x	
		Gavia stellata	roodkeelduiker	Red-throated Diver	x	x
		Hirundo rustica	boerenzwaluw	Barn Swallow		x
		Hydrocoloeus minutus	dwergmeeuw	Little Gull	x	x
		Larus argentatus	zilvermeeuw	Herring Gull	x	x

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Chordata	Aves	*Larus canus*	stormmeeuw	Common Gull	x	x
		Larus fuscus	kleine mantelmeeuw	Lesser Black-backed Gull	x	x
		Larus marinus	grote mantelmeeuw	Great Black-backed Gull	x	x
		Larus melanocephalus	zwartkopmeeuw	Mediterranean Gull		x
		Larus michahellis	geelpootmeeuw	Yellow-legged Gull		x
		Larus ridibundus	kokmeeuw	Black-headed Gull	x	x
		Melanitta nigra	zwarte zee-eend	Black Scoter	x	x
		Morus bassanus	Jan-van-gent	Northern Gannet	x	x
		Motacilla alba alba	witte kwikstaart	White Wagtail	x	x
		Motacilla alba yarrellii	rouwkwikstaart	Pied Wagtail		x
		Numenius arquata	wulp	Eurasian Curlew		x
		Numenius phaeopus	regenwulp	Whimbrel	x	x
		Phalacrocorax aristotelis	kuifaalscholver	European Shag		x
		Phalacrocorax carbo	aalscholver	Great Cormorant	x	x
		Phoenicurus ochruros	zwarte roodstaart	Black Redstart		x
		Pluvialis apricaria	goudplevier	European Golden Plover		x
		Podiceps cristatus	fuut	Great Crested Grebe		x
		Podiceps grisegena	roodhalsfuut	Red-necked Grebe		x
		Puffinus puffinus	Noordse pijlstormvogel	Manx Shearwater	x	x
		Regulus regulus	goudhaan	Goldcrest		x
		Rissa tridactyla	drieteenmeeuw	Black-legged Kittiwake	x	x
		Stercorarius parasiticus	kleine jager	Arctic Skua	x	x
		Stercorarius skua	grote jager	Great Skua	x	x
		Sterna hirundo	visdief	Common Tern	x	x
		Sterna paradisaea	Noordse stern	Arctic Tern	x	
		Sterna sandvicensis	grote stern	Sandwich Tern	x	x
		Sturnus vulgaris	spreeuw	Common Starling	x	x
		Sylvia atricapilla	zwartkop	Blackcap	x	
		Tadorna tadorna	bergeend	Common Shelduck	x	
		Tringa totanus	tureluur	Common Redshank		x
		Turdus iliacus	koperwiek	Redwing	x	x

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Chordata	Aves	*Turdus merula*	merel	Common Blackbird	x	x
		Turdus philomelos	zanglijster	Song Thrush	x	x
		Turdus pilaris	kramsvogel	Fieldfare	x	
		Uria aalge	zeekoet	Common Guillemot	x	x
	Leptocardii	*Branchiostoma lanceolatum*	lancetvisje	lancelet	x	x
	Mammalia	Chiroptera indet.	onbekende vleermuis	unidentified bat		x
		Lagenorhynchus albirostris	witsnuitdolfijn	white-beaked dolphin	x	x
		Halichoerus grypus	grijze zeehond / kegelrob	grey seal	x	x
		Megaptera novaeangliae	bultrug	humpback whale		x
		Phoca vitulina	gewone zeehond	harbour seal / common seal	x	x
		Phocoena phocoena	bruinvis / zeevarken	harbour porpoise	x	x
Cnidaria	Anthozoa	Actiniaria sp.	zeeanemonen	sea anemones	x	x
		Alcyonium digitatum	dodemansduim	dead man's fingers		x
		Edwardsia sp.	-	-		x
		Edwardsiella sp.	-	-		x
		Sagartia troglodytes	slibanemoon	-		x
		Metridium senile	zeeanjelier	-		x
		Urticina felina	zeedahlia	dahlia anemone		x
	Ascidiacea	*Botrylloides violaceus*	gewone slingerzakpijp	a colonial sea squirt		x
		Diplosoma listerianum	grijze korstzakpijp	a compound sea squirt		x
		Molgula complanata	-	sea grapes		x
		Polyclinidae sp.	-	-		x
	Hydrozoa	Campanulariidae sp.	-	-		x
		Capitata sp.	-	-		x
		Clytia hemisphaerica	kleine klokpoliep	-		x
		Hydractinia echinata	ruwe zeerasp	rough hydroid		x
		Laomedea flexuosa	-	-		x
		Sarsia tubulosa	klepelklokje	clapper medusa		x
		Tubularia indivisa	penneschaft	oaten pipes hydroid		x
		Tubularia (Ectopleura) larynx	orgelpijppoliep	flower head polyp		x
Echinodermata	Asteroidae	*Asterias rubens*	gewone zeester	common starfish	x	x
	Echinoidea	*Echinocardium cordatum*	zeeklit	sea-potato	x	x

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Echinodermata	Echinoidea	*Echinocyamus pusillus*	zeeboontje	-	x	x
		Psammechinus miliaris	gewone zeeëgel	green sea urchin	x	x
	Ophiuroidae	*Amphipholis squamata*	levendbarende slangster	dwarf brittle star		x
		Ophiothrix fragilis	brokkelster	common brittlestar		x
		Ophiura albida	kleine slangster	lesser brittle star	x	x
		Ophiura ophiura	gewone slangster	common brittle star	x	x
Entoprocta		*Pedicellina nutans*	-	-		x
Mollusca	Cephalopoda	*Alloteuthis subulata*	dwergpijlinktvis	European common squid	x	x
		Loligo vulgaris	gewone pijlinktvis	Cape Hope squid	x	x
		Sepia officinalis	zeekat	common cuttlefish	x	x
		Sepiola atlantica	dwerginktvis	Atlantic bobtail	x	x
	Bivalvia	*Abra alba*	witte dunschaal	white furrow shell		x
		Aequipecten opercularis	wijde mantel	queen scallop		x
		Angulus fabula	rechtsgestreepte platschelp	bean-like tellin		x
		Angulus pygmaeus	kleine platschelp	little tellin		x
		Angulus tenuis	tere platschelp	thin tellin	x	x
		Striarca lactea	melkwitte arkschelp	milky ark	x	
		Crassostrea gigas	Japanse oester	pacific cupped oyster		x
		Donax vittatus	zaagje	banded wedge-shell	x	x
		Ensis directus	Amerikaanse zwaardschede	Atlantic jack knife clam	x	x
		Ensis arcuatus (Ensis magnus)	grote zwaardschede	sword razor		x
		Heteranomia squamula	schilferige dekschelp	jingle shell		x
		Lutraria lutraria	otterschelp	common otter shell	x	
		Macoma balthica	gewoon nonnetje	Baltic tellina		x
		Modiolarca subpictus	gemarmerde streepschelp	marbled crenella		x
		Mysella (Kurtiella) bidentata	dwergmosseltje	-		x
		Mytilus edulis	mossel	blue mussel		x
		Petricolaria pholadiformis	Amerikaanse boormossel	false angelwing	x	
		Phaxas pellucidus	sabelschede	razor shell	x	
		Sphenia binghami	kleine gaper	-		x
		Spisula elliptica	ovale strandschelp	elliptic trough shell	x	x

Phylum	Class	Species	Common name in Dutch	Common name in English	Observed prior to construction	Observed since start construction
Mollusca	Bivalvia	*Spisula solida*	stevige strandschelp	thick trough shell	x	x
		Spisula subtruncata	halfgeknotte strandschelp	cut trough shell	x	x
		Tellimya ferruginosa	ovale zeeklitschelp	-		x
		Venerupis corrugata	gewone tapijtschelp	pullet carpet shell		x
	Gastropoda	*Crepidula fornicata*	muiltje	common slipper limpet	x	x
		Cuthona gymnota	gorgelpijp-knotsslak	orange-tipped eolis		x
		Epitonium clathratulum	wit wenteltrapje	-		x
		Epitonium clathrus	gewoon wenteltrapje	common wentletrap		x
		Euspira catena	gewone tepelhoorn	necklace shell		x
		Euspira nitida	glanzende tepelhoorn	Alder's necklace shell		x
		Facelina bostoniensis	brede ringsprietslak	facelina		x
		Littorina littorea	alikruik	common periwinkle		x
		Nassarius incrassatus	verdikte fuikhoren	thick-lipped dog whelk		x
		Nassarius reticulatus	fuikhoorn	netted dogwhelk	x	x
		Odostomia turrita	spitse tandhoren	-		x
		Onchidoris bilamellata	rosse sterslak	barnacle-eating onchidoris		x
		Onchidoris muricata	wrattige sterslak	-		x
		Patella vulgata	gewone schaalhoren	common limpet		x
		Risoa (Pusillina) inconspicua	dwergdrijfhorentje	-		x
		Tritonia plebeia	kleine tritonia	-		x
		Trivia monacha	gevlekt koffieboontje	spotted cowrie		x
Nematoda		Nematoda *sp.*	rondwormen	nematodes	x	x
Nemertea	Anopla	Heteronemertea sp.	-	-		x
	Enopla	*Emplectonema gracile*	-	-		x
		Emplectonema neesii	-	-		x
		Oerstedia dorsalis	-	-		x
Platy-helminthes	Rhabditophora	*Leptoplana tremellaris*	-	-		x
Porifera	Calcarea	*Leucosolenia complicata*	vertakte buisjesspons	-		x
		Sycon ciliatum	gewone zakspons	ciliated sponge		x
	Demospongiae	*Dysidea fragilis*	-	goosebump sponge		x
Sipuncula		Sipuncula sp.	spuitwormen	peanut worms	x	x

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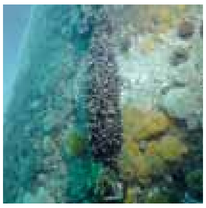
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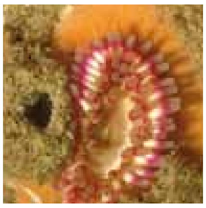
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p. 4


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p. 6


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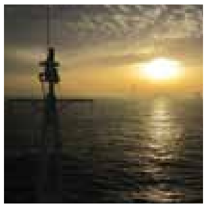
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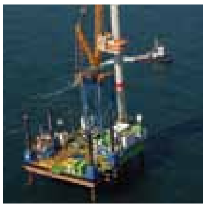
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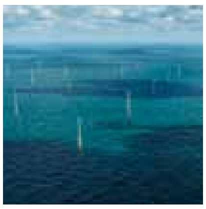
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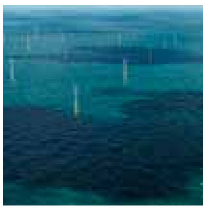
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CHAPTER 5
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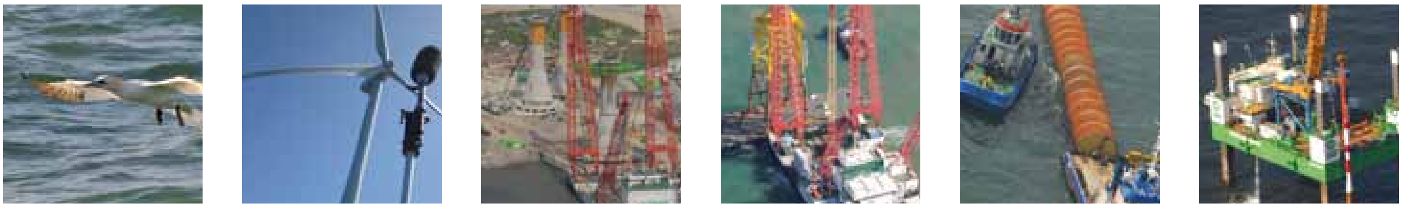
p. 58



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p. 61

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p. 66

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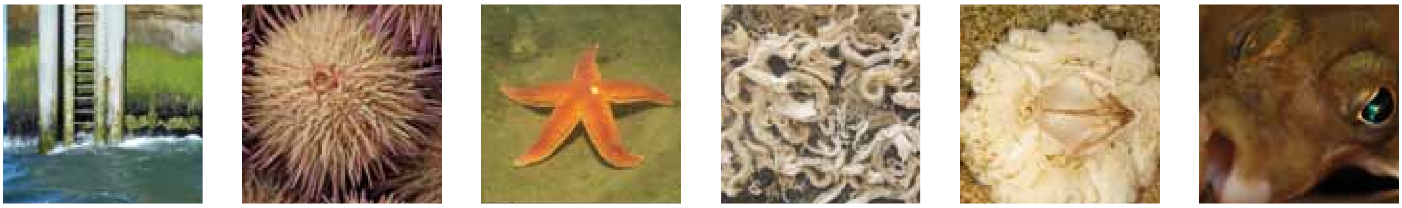

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p.100

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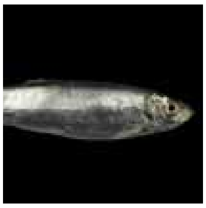
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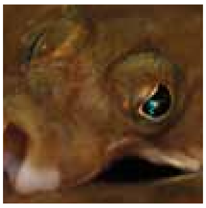
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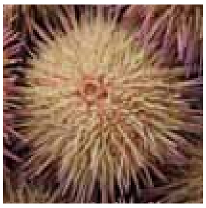
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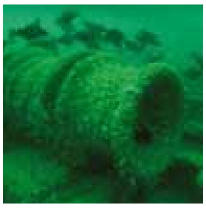
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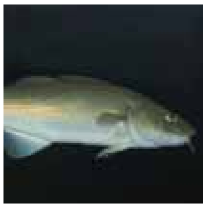
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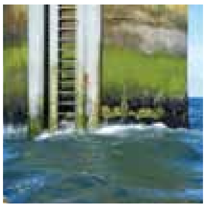
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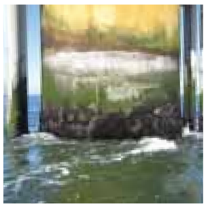
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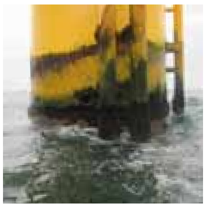
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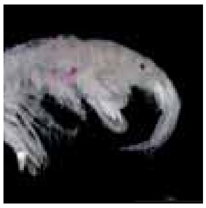
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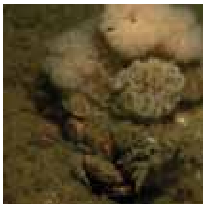
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p.136


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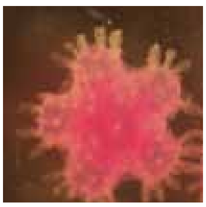
p.137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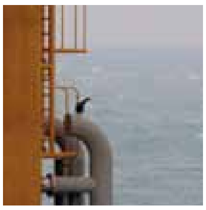
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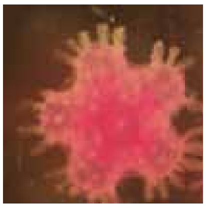
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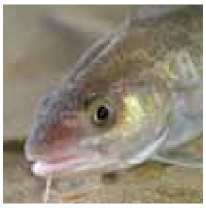
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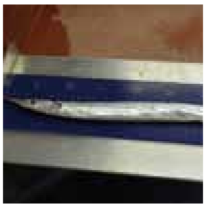
p.150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p. 162


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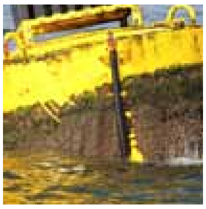
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p. 168


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p.172


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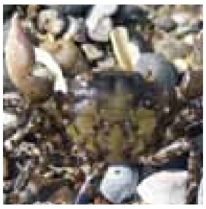
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p. 174, 176


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p. 176


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p. 176


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p. 179


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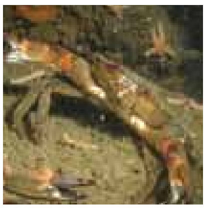
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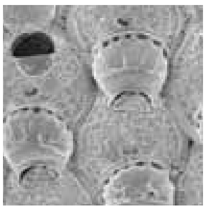
p. 181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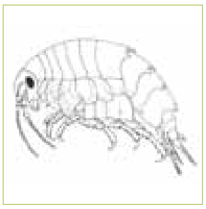
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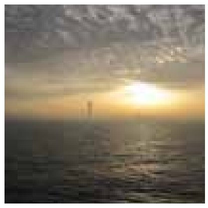
p.192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