CHAPTER 2

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

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Abstract

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

1. Introduction

The harbour porpoise (*Phocoena phocoena)* is by far the most common marine mammal in the BPNS, after several years of virtual absence (Haelters *et al*. 2011). The estimation of the harbour porpoise density ranges from 0.05 to 1.03 individuals per km², leading to an abundance of 186 to 3697 animals (Haelters *et al*. 2011). The animals show a distinct spatial and temporal distribution in Belgian waters with relatively high densities from January to April and lower numbers from May to August, plus they tend to stay in more northerly and offshore waters (Haelters *et al*. 2011, 2016). In the Greater North Sea, the harbour porpoise is considered vulnerable because of high bycatch levels (Kaschner 2003) and its exposure to increasing levels of noise pollution ranging from continuous shipping noise (Wisniewska *et al*. 2018) to impulsive noise from, e.g., pile driving (Brandt *et al*. 2018), and seismic surveys (Van Beest *et al*. 2018). Nonetheless, the species is protected by both national (Belgian Government 2001) and EU law (EU 1992), and consequently deliberate actions of killing, disturbing, injuring, and habitat deterioration are prohibited throughout its range. In the absence of mitigating measures, the high levels of impulsive underwater sound generated during pile driving can potentially kill, injure or disturb marine mammals depending on their distances from the source (see, e.g., Carstensen *et al*. 2006; Bailey *et al*. 2010). Some studies have even indicated potential negative cumulative impacts on the harbour porpoise population of wind farm development over the next decade in the North Sea (de Jong *et al*. 2019). Concerns over the possible impact of high intensity impulsive sound generated during the construction of offshore wind farms on harbour porpoise have been a driving force in determining national impulsive noise regulations in North Sea countries with Germany, the Netherlands and Belgium all formulating different, but similar, underwater sound thresholds (see Rumes *et al*. 2016 for a comparison). In Belgium, concern over the high levels of underwater noise being generated during pile driving operations for the building of the first offshore wind farms (Norro *et al*. 2010, 2013) and the observed large-scale avoidance of the construction zone by porpoises (Haelters *et al*. 2011) led to the formulation of a threshold for impulsive underwater sound in the BNS at 185 dB re 1 µPa (Sound Pressure Level, zero to peak) at 750 m from the source (Anonymous 2012). Offshore wind farm developers in the BPNS have applied several noise mitigation systems with incremental progress in complying with this threshold (Rumes & Degraer 2020). In this chapter, we aim to determine whether the reduced levels of impulsive underwater sound during construction are likely to have influenced the observed spatial and temporal extent of harbour porpoise avoidance.

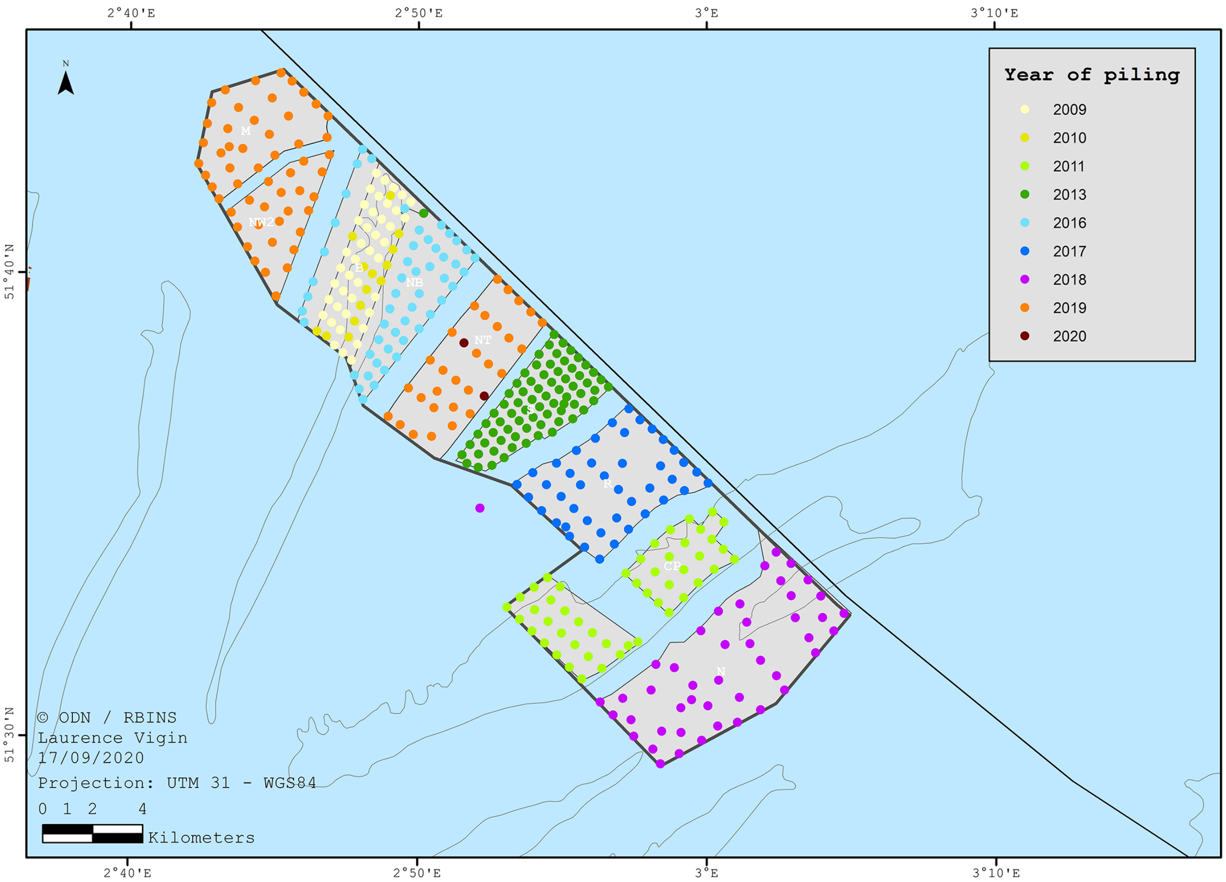

Figure 1. Timing and location of pile driving events in the Belgian part of the North Sea (period 2009-2020, data RBINS). From 2013 onwards, a seasonal pile driving ban from January 1st to April 30th was enforced. From 2017 onwards developers were obliged to use noise mitigation measures that limit the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

2. Material and methods

2.1. Study area

The Southern bight of the North Sea includes the Belgian continental shelf or BPNS with a surface of approximately 3457 km². The BPNS only covers 0.5% of the entire area of the North Sea. The Belgian continental shelf is characterized by shallow waters with a maximum depth of 45 m and a complex system of sandbanks. In the western part of the BPNS, a 238 km² zone has been designated for renewable energy. Between 2009 and 2020, nine projects have constructed wind farms in this part of the BPNS (Fig. 1).

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

For this study we focused on three wind farms: Nobelwind, Northwester 2 and SeaMade. At Nobelwind, pile driving without the use of noise mitigation measures took place in 2016. Both Northwester 2 and SeaMade used a similar noise mitigation set up in 2019, namely a double big bubble curtain (DBBC) albeit with differing levels of success. A DBBC consists of two rings of perforated pipes positioned on the sea floor around the foundation to be piled. Compressors located on the construction vessel or on a separate platform feed air into the pipes. The air passes into the water column by regularly arranged holes. Freely rising bubbles form a large curtain around the entire structure, even during running tides, thus shielding the environment from the noise source (Koschinski & Lüdemann 2013). Northwester 2 was the only project to successfully use noise mitigation measures that limit the transmission of noise pollution to the marine environment to the extent that the in-situ measured sound level (SPLz-p) remained below the national threshold (Norro 2020).

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

The second wind farm, NV Northwester 2, is located at 51 km off the coast of Zeebrugge to the northwest of Nobelwind, was granted an environmental permit on 18 December 2015. The total capacity of this wind farm of 219 MW is provided by 23 turbines, each with a capacity of 9.5 MW. Pile driving for the Northwester 2 wind farm comprised 24 piling events (23 turbines and one offshore high voltage station) from July 29th up to November 13th 2019. Pile diameter ranged from 7.4 to 8.0 m, penetration depth lay between 29 to 39 m and total piling time varied between 1 h 36 min and 3 h 40 min. All piles were installed using an S-3000 Hydraulic Hammer (maximum energy per pile 1942±406 kJ). The contractor was legally obliged to turn on an acoustic deterrent device 30 minutes before the start of piling. Construction logs show that on average the acoustic deterrent device was started 60 minutes before the start of piling (Rumes & Degraer 2020).

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

2.2. Study set up

Echolocation is likely the most important sensory perception for harbour porpoises and they have been shown to use their echolocation system almost continuously (Akamatsu *et al*. 2007; Wisniewska *et al*. 2016). This allows correlation between detection rates of porpoise clicks by passive acoustic monitoring devices and porpoise density in a marine area. Passive acoustic monitoring of porpoises was conducted using the Continuous Porpoise Detector (C-PoD, further indicated as PoD). PoDs consist of a hydrophone, a processor, batteries and a digital timing and logging system. They continuously monitor sounds between 20 kHz and 160 kHz, and can detect all odontocetes except sperm whales (*Physeter macrocephalus*). A PoD does not record sound itself, but compresses data, generating a raw file with for each click characteristics such as time of occurrence, duration, dominant frequency, bandwidth and sound pressure level. Using dedicated software (CPOD.exe; Tregenza 2014), the raw file can be objectively analysed to find click trains and to classify these into trains produced by odontocetes and trains that originate from other sources such as boat SONAR. Distinction can be made between harbour porpoises, a species producing narrow-band, high frequency clicks, and dolphins, producing more broadband clicks with a lower frequency. The maximum detection range for porpoises is approximately 400 metres. PoDs have autonomy of up to 200 days (www.chelonia.co.uk). As porpoise click sounds are emitted in frontal direction with a beam angle of 16.5° maximum (Au *et al*. 1999), PoDs are only able to detect porpoises if they are facing towards the hydrophone.

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

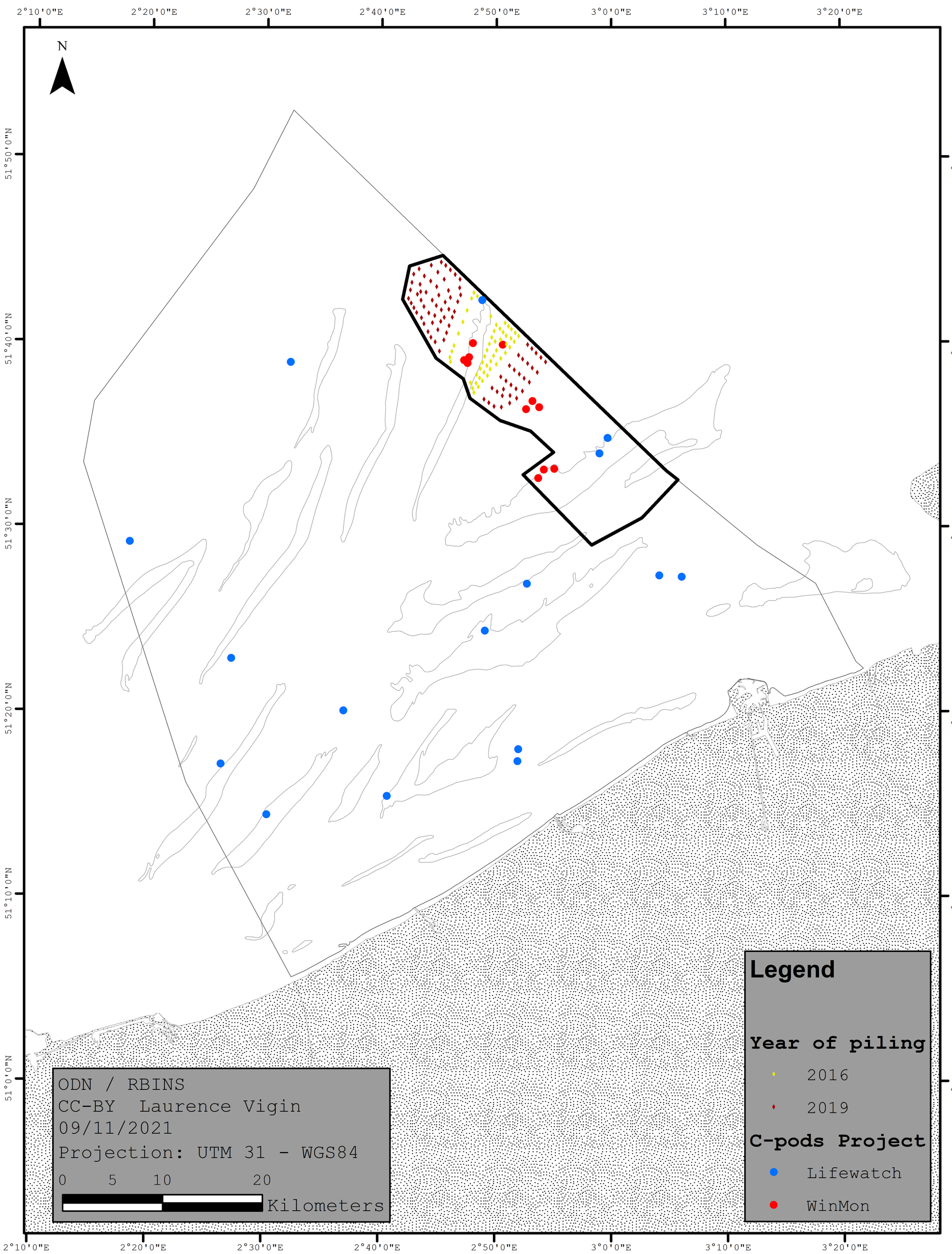

Figure 2. Location of selected porpoise detectors and pile driving events.

2.3. Data selection and dataset preparation

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

At least 30 minutes before pile driving an ADD is to be activated in order to deter porpoises from the immediate vicinity of the construction site and to protect them from the acute effects of construction noise. However, due to operational uncertainties, the actual interval between ADD activation and the start of pile driving is quite variable (Rumes & Degraer 2020) and for these analyses, the start of pile driving was provided by the developers in daily reports on piling activities. Here, the start the activation of the ADD was considered the onset of acoustic disturbance, with the end of pile driving being considered as the end of acoustic disturbance. To align the (per hour) DPH information on detections with the (per minute) information on acoustic disturbance, the latter was rounded to the nearest hour, and for each hour the following information was generated: time since acoustic disturbance in hours and location of the most recent disturbance. We calculated the minimum time since acoustic disturbance (in hours) per PoD station and per hour and combined it with the information on the distance to the individual piling events.

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

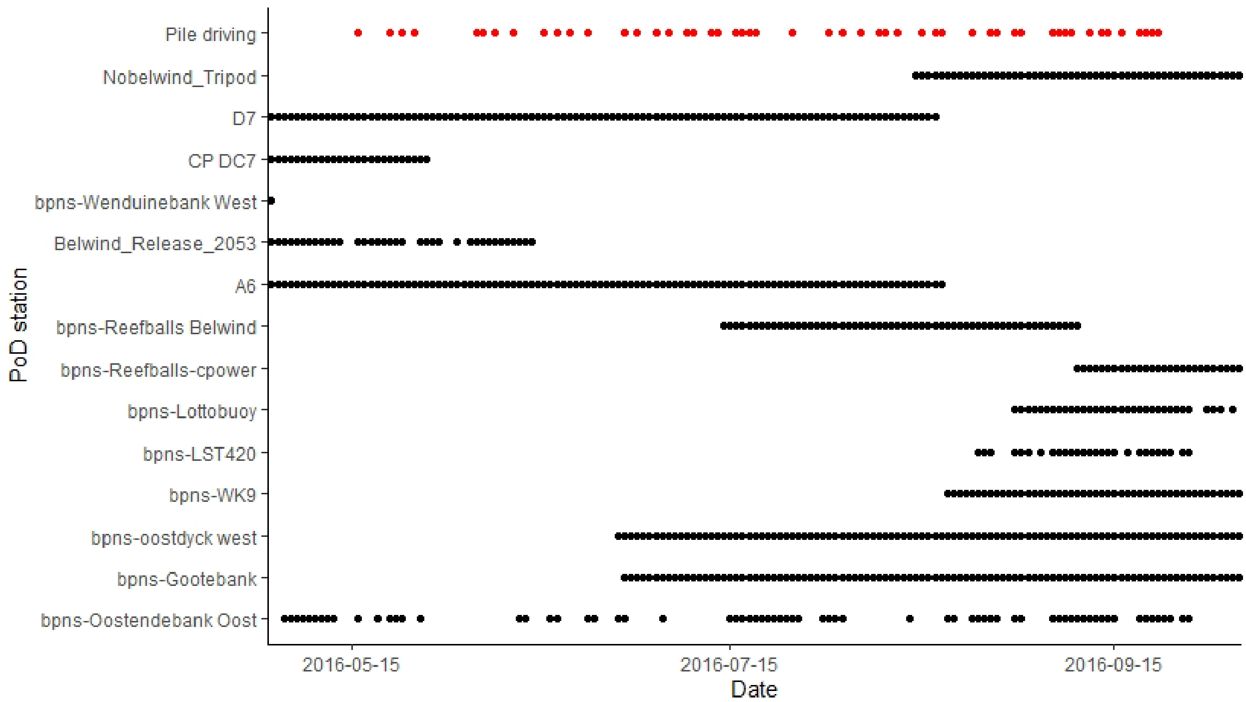

Figure 3. Location of selected porpoise detectors and timing of pile driving events in 2016.

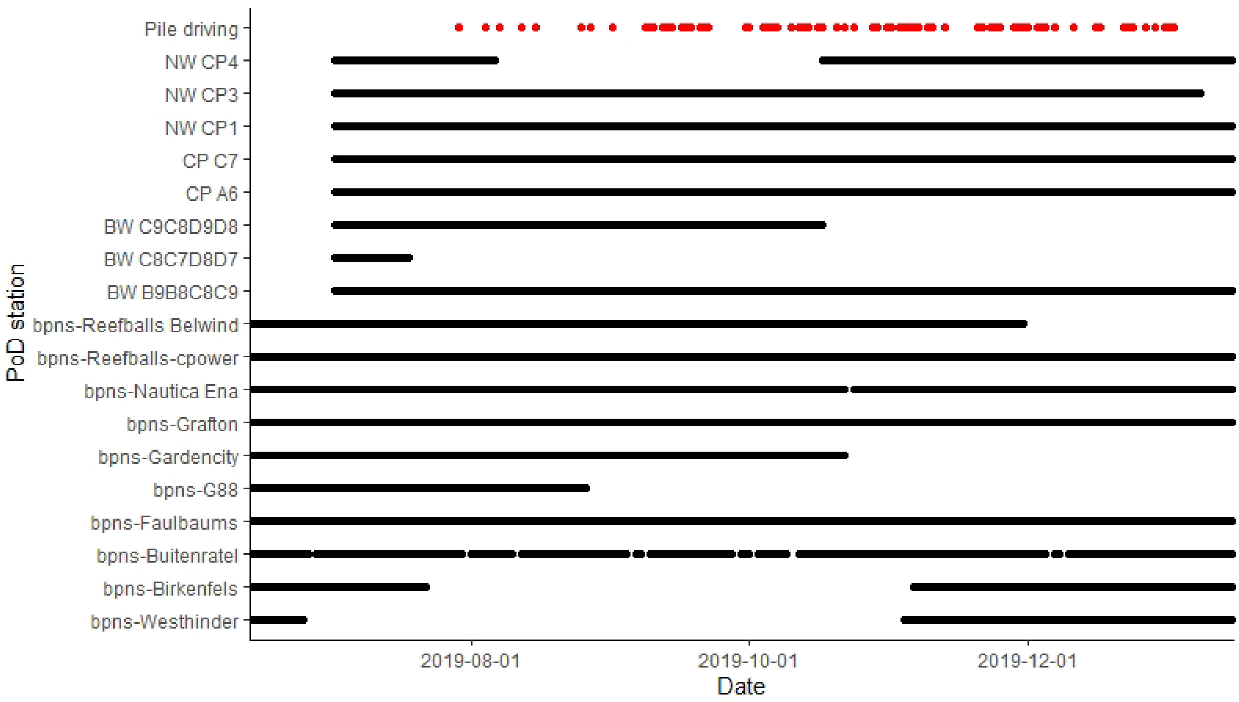

Figure 4. Location of selected porpoise detectors and timing of pile driving events in 2019.

2.4. Exploratory statistical analysis

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

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

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

3. Results

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

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

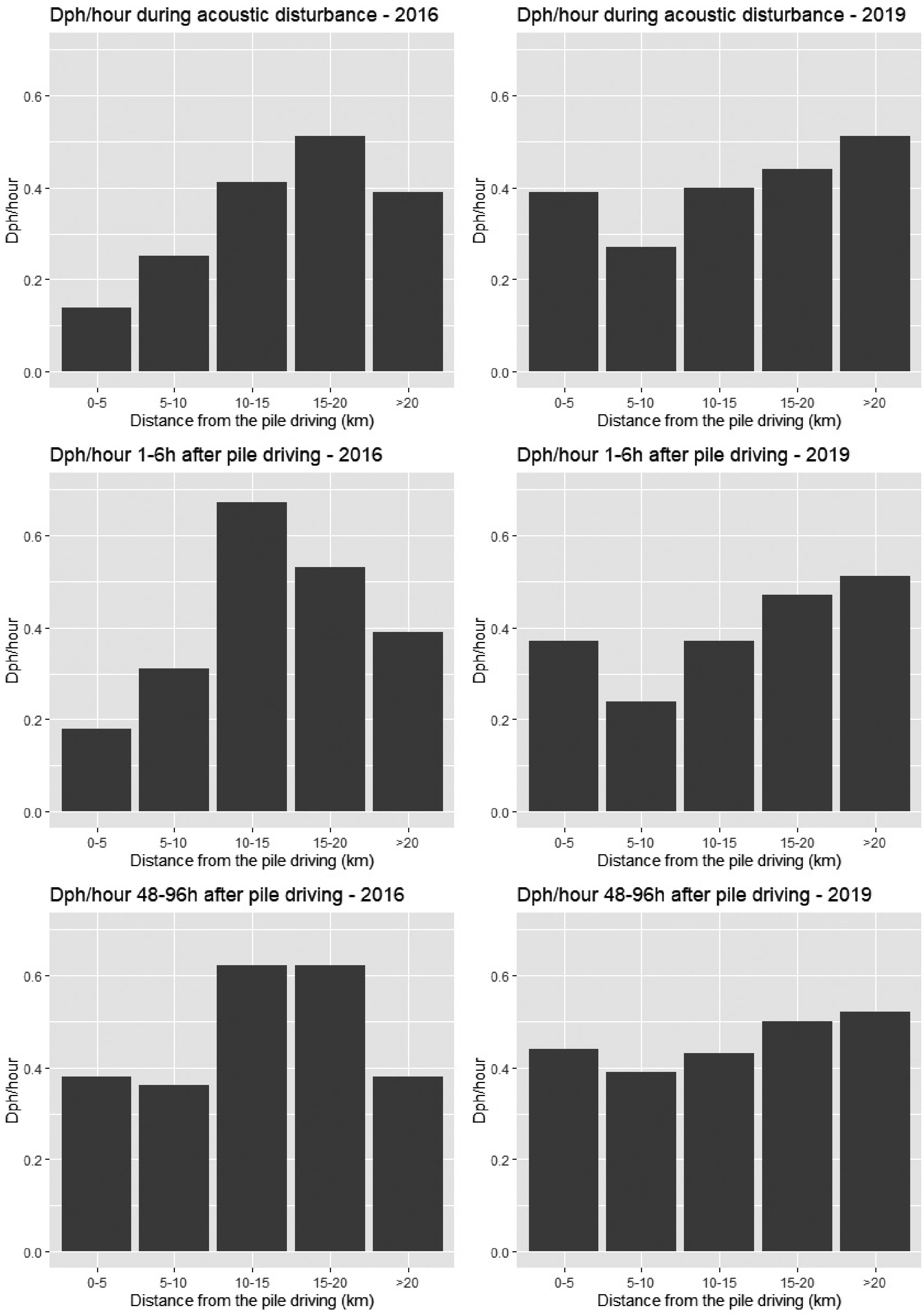

Figure 5. Mean detection-positive hours/hour (ø dph/h) for three phases of a pile driving event (Impact – top, Aftermath - middle, and Recovery - bottom) by distance to the construction site (0-5 km, 5-10 km, 10-15 km, 15-20 km and > 20 km) for pile driving without (2016) and with effective noise mitigation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

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

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

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

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

4. Discussion

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

To meet the EU objective of reaching net-zero greenhouse gas emissions by 2050, offshore wind capacity in the North Sea should increase to a total installed capacity of at least 150 GW in the next thirty years (North Seas Energy Cooperation 2020). In Belgian waters, the installed capacity of offshore wind farms is expected to triple in the next ten years which will require the installation of hundreds of turbines with a construction period likely lasting multiple years. Mitigation measures are formulated to reduce the impact of offshore wind farms construction on marine mammals (and other marine life), but these are considered onerous by developers as they increase project cost both directly (i.e., the cost of the mitigation measures) and indirectly (by increasing construction time) (Koschinski & Lüdemann 2013). In this chapter, we explored how the use of these noise mitigation systems, which results in reduced levels of impulsive underwater sound during construction, influenced the spatial and temporal extent of harbour porpoise avoidance of the construction sites.

Our results show a relative reduction in avoidance of porpoise at short to middle distances to the pile driving, both during the acoustic disturbance (use of acoustic deterrent devices and pile driving) and in the immediate aftermath thereof. Without noise mitigation, mean detection rates of porpoises reduced in all intervals up to 15-20 km from the pile driving, confirming what was previously observed using aerial survey data, where decreased porpoise densities were observed up to 20 km from the piling event (Haelters *et al.* 2013). With noise mitigation however, mean detection rates of porpoises reduced to a lesser extent and this reduction mainly took place at 0-10 km from the pile driving. This is in line with a study in German waters which found the effects of unmitigated pile driving on porpoise to reach much farther (26 km [s.e.: 22-30 km]) than those of mitigated pile driving (11 km [s.e.: 10-12 km]) (Rose *et al.* 2019). However, the same study also indicated a lower limit to the effectiveness of noise mitigation stating that, all other aspects remaining equal, further improvements in noise mitigation did not result in a further decrease in the displacement range and duration for porpoises due to piling noise. This may be due to (a combination of) a stereotypical escape distance, the displacement effect of the acoustic deterrent devices, other construction-related noise, cumulative effects due to increasingly tight piling sequences, and local habitat characteristics at different offshore wind farm areas influencing porpoises' tolerance of disturbance (Rose *et al*. 2019). Nonetheless, current noise mitigation efforts have reduced the number of harbour porpoises responding to pile driving noise by ~75% (Rose *et al*. 2019; this study), demonstrating the role that noise mitigation can have in decreasing the likelihood of offshore wind farm development in the North Sea causing negative cumulative impacts at the porpopise population scale (de Jong *et al*. 2019).

4.2. Effects of exposure to elevated levels of underwater sound

Elevated levels of underwater sound can affect harbour porpoises in several ways ranging from injury and death to discomfort and the masking of communication. Harbour porpoises are considered particularly sensitive to underwater noise (Tougaard *et al*. 2015) and will temporarily vacate too noisy areas even if these are otherwise suitable (Culik *et al*. 2000). The fact that no porpoises were observed during the obligatory marine mammal surveys prior to pile driving may lead one to suspect that they completely avoid the construction zone during the construction work (Rumes & Degraer 2020). However, as noted previously (Rumes *et al*. 2017), even during pile driving, harbour porpoises are not completely absent from sites in the vicinity of pile driving. Lacking information on the movement on individual porpoises, the amount of underwater sound these animals are exposed to remains unclear. Detections in the vicinity of the construction zone can be due to both the continued presence of animals which tolerate higher levels of underwater sound and animals which are moving away from the sound source. A future comparison of the proportion of feeding buzzes to total porpoise click trains (*sensu* Nuuttila 2013; Zein *et al*. 2019) during and after acoustic disturbance can provide more information on their behavior during acoustic disturbance.

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References

Anonymous, 2012. *Omschrijving van Goede Milieutoestand en vaststelling van Milieudoelen voor de Belgische mariene wateren. Kaderrichtlijn Mariene Strategie – Art 9 & 10*. BMM, Federale Overheidsdienst Volksgezondheid, Veiligheid van de Voedselketen en Leefmilieu, Brussel, België. 34 pp.

Au, W.W.L., Kastelein, R.A., Rippe, T. & Schooneman, N.M. 1999. Transmission beam pattern and echolocation signals of a harbor porpoise (*Phocoena phocoena*). *The Journal of the Acoustical Society of America* 106 (6): 3699-3705.

Akamatsu, T., Teilmann, J., Miller, L.A., Tougaard, J., Dietz, R., Wang, D., Wang, K., Siebert, U. & Naito, Y. 2007. Comparison of echolocation behaviour between coastal and riverine porpoises. *Deep Sea Research Part II: Topical studies in Oceanography* 54 (3): 290-297. https://doi.org/10.1109/UT.2007.370755

Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G. & Thompson, P.M. 2010. Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. *Marine Pollution Bulletin* 60: 888-897. https://doi.org/10.1016/j.marpolbul.2010.01.003

Brandt, M., Dragon, A., Diederichs, A., Schubert, A., Kosarev, V., Nehls, G., Wahl, V., Michalik, A., Braasch, A., Hinz, C., Ketzer, C., Todeskino, D., Gauger, M., Laczny, M. & Piper, W. 2016. *Effects of Offshore Pile Driving on Harbour Porpoise Abundance in the German Bight: Assessment of Noise Effects*. Report by BioConsult SH, IBL Umweltplanung GmbH, and Institute of Applied Ecology (IfAO). pp. 262.

Brandt, M.J., Dragon, A.C., Diederichs, A., Bellmann, M.A., Wahl, V., Piper, W., Nabe-Nielsen, J. & Nehls, G. 2018. Disturbance of harbour porpoises during construction of the first seven offshore wind farms in Germany. *Marine Ecology Progress Series* 596 213-232. https://doi.org/10.3354/meps12560

Belgian Government. 2001. Koninklijk besluit van 21 december 2001 betreffende de soortenbescherming in de zeegebieden onder de rechtsbevoegdheid van België. *Belgisch Staatsblad*. 14.02.2002, Ed. 3: 5568-5577.

Carstensen, J., Henriksen, O.D. & Teilmann, J. 2006. Impacts on harbour porpoises from offshore wind farm construction: acoustic monitoring of echolocation activity using porpoise detectors (T-PODs). *Marine Ecology Progress Series* 321 295-308. https://doi.org/10.3354/MEPS321295

Culik, B.M., Koschinski, S., Tregenza, N. & Ellis, G. 2000. Reactions of harbour porpoises (*Phocoena phocoena*) and herring (*Clupea harengus*) to acoustic alarms. *Marine Ecology Progress Series* 211: 255-260. https://doi.org/10.3354/meps211255

de Jong, C.A.F., Heinis, F., von Benda-Beckmann, A.M. & Binnerts, B. 2019. *Testing CEAF in SEANSE case studies - Impact of piling for wind farms on North Sea harbour porpoise population*. TNO, Den Haag. 36 pp.

European Union. 1992. Council Directive 92/43/EEC of 21 May 1992. Official Journal of the European Communities 35: 7-51

Flanders Marine Institute (VLIZ) 2021. *LifeWatch observatory data: permanent Cetacean passive acoustic sensor network in the Belgian part of the North Sea*. Marine Data Archive. https://doi.org/10.14284/447

Haelters, J., Kerckhof, F., Vigin, L. & Degraer, S. 2011. Offshore wind farm impact assessment: monitoring of marine mammals during 2010. *Offshore Wind Farms in the Belgian Part of the North Sea: Selected Findings from the Baseline and Targeted Monitoring*: 131-146.

Haelters, J., Debusschere, E., Botteldooren, D., Duliére, V., Hostens, K., Norro, A., Vandendriessche, S., Vigin, L., Vincx, M. & Degraer, S. 2013. The effects of pile driving on marine mammals and fish in belgian waters. *In*: Degraer, S., Brabant, R. & Rumes B. (eds) *Environmental Impacts of Offshore Wind Farms in the Belgian Part of The North Sea*: 71-77. Royal Belgian Institute of Natural Sciences, Brussels.

Haelters, J., Rumes, B., Vanaverbeke, J. & Degraer, S. 2016. Seasonal and interannual patterns in the presence of harbour porpoises (*Phocoena phocoena*) in Belgian waters from 2010 to 2015 as derived from passive acoustic monitoring. *In*: Degraer, S. *et al*. (ed.) *Environmental Impacts of Offshore Wind Farms in the Belgian Part of The North Sea: Environmental impact monitoring reloaded*: 249-267.

Hijmans, R.J. 2019. Geosphere: Spherical Trigonometry. R package version 1.5-10. https://CRAN.R-project.org/package=geosphere

Kaschner, K. 2003. Review of small cetacean bycatch in the ASCOBANS area and adjacent waters – current status and suggested future actions. *North* 122.

Koschinski, S. & Lüdemann K. 2013. *Development of noise mitigation measures in offshore wind farm construction*. Federal Agency for Nature Conservation.

Norro, A. 2020. An evaluation of the noise mitigation achieved by using double big bubble curtains in offshore pile driving in the southern North Sea. *In*: Degraer, S. *et al*. (eds) Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Empirical Evidence Inspiring Priority Monitoring, Research and Management. *Memoirs on the Marine Environment*: 19-27.

Norro, A., Haelters, J., Rumes, B. & Degraer, S. 2010. Underwater noise produced by the piling activities during the construction of the Belwind Offshore Wind Farm (Bligh Bank, Belgian Marine Waters). *In*: *Offshore Wind Farms in the Belgian Part of the North Sea: Heading for an Understanding of Environmental Impacts*: 37-51. Royal Belgian Institute of Natural Sciences, Brussels.

Norro, A., Rumes, B. & Degraer, S. 2013. Differentiating between underwater construction sound of monopile and jacket foundations for offshore Wind turbines: A case study from the Belgian part of the North Sea. *The Scientific Journal* 2013: 897624. https://doi.org/10.1155/2013/897624

North Seas Energy Cooperation. 2020. Joint Statement of North Seas Countries and the European Commission – 6 July 2020. Accessed from https://ec.europa.eu/info/news/progress-north-seas-energy-cooperation-2020-jul-06_en

Nuuttila, H. 2013. Identifying foraging behaviour of wild bottlenose dolphins (*Tursiops truncatus*) and harbour porpoises (*Phocoena phocoena*) with static acoustic dataloggers. *Aquatic Mammals* 39 (2): 147-161. https://doi.org/10.1578/am.39.2.2013.147

R Core Team. 2019. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna. Available from https://www.R-project.org/.

Rose, A., Brandt, M., Vilela, R., Diederichs, A., Schubert, A., Kosarev, V., Nehls, G., Volkenandt, M., Wahl, V., Michalik, A., Wendeln, H., Freund, A., Ketzer, C., Limmer, B., Laczny, M. & Piper, W. 2019. *Effects of Noise-Mitigated Offshore Pile Driving on Harbour Porpoise Abundance in the German Bight 2014-2016 (Gescha 2)*. IBL Umweltplanung GmbH.

Rumes, B. & Degraer, S. 2020. Fit for porpoise? Assessing the effectiveness of underwater sound mitigation measures. *In*: Degraer, S. *et al*. (eds) Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Empirical Evidence Inspiring Priority Monitoring, Research and Management. *Memoirs on the Marine Environment*: 29-41.

Rumes, B., Erkman, A. & Haelters, J. 2016. Evaluating underwater noise regulations for piling noise in Belgium and the Netherlands. *In*: Degraer, S., Brabant, R., Rumes, B. & Vigin L. (eds) *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea. Environmental Impact Monitoring Reloaded:* 37-50. Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management Section, Brussels.

Rumes, B., Debusschere, E., Reubens, J., Norro, A., Haelters, J., Deneudt, K. & Degraer, S. 2017. Determining the spatial and temporal extent of the influence of pile driving sound on harbour porpoises, *In:* Degraer, S. *et al*. (eds) *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: A Continued Move towards Integration and Quantification*: 129-141.

Tougaard, J., Wright, A.J. & Madsen, P.T. 2015. Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoises. *Marine Pollution Bulletin* 90: 196-208. https://doi.org/10.1016/j.marpolbul.2014.10.051

Tregenza, N. 2014. CPOD.exe: a guide for users. Available from https://www.chelonia.co.uk/cpod_downloads.htm

van Beest, F.M., Teilmann, J., Hermannsen, L., Galatius, A., Mikkelsen, L., Sveegaard, S., *et al*. 2018. Fine-scale movement responses of free-ranging harbour porpoises to capture, tagging and short-term noise pulses from a single airgun. *Royal Society Open Science* 5: 170110. https://doi.org/10.1098/rsos.170110

Wisniewska, D.M., Johnson, M., Teilmann, J., Rojano-Doñate, L., Shearer, J. Sveegazard, S., Miller, L.A., Siebert, U. & Madsen, P.T. 2016. Ultra-high foraging rates of harbor porpoises make them vulnerable to anthropogenic disturbance. *Current Biology* 26 (11): 1441-1446. https://doi.org/10.1016/j.cub.2016.03.069

Wisniewska, D.M., Johnson, M., Teilmann, J., Siebert, U., Galatius, A., Dietz, R. & Madsen, P.T. 2018. High rates of vessel noise disrupt foraging in wild harbour porpoises (*Phocoena phocoena*). *Proceedings of the Royal Society B, Biological Sciences* 285: 20172314. https://doi.org/10.1098/rspb.2017.2314

Zein, B., Woelfing, B., Dahne, M., Schaffeld, T., Ludwig, S., Rye, J.H., Baltzer, J., Ruser, A. & Siebert, U. 2019. Time and tide: seasonal, diel and tidal rhythms in Wadden Sea Harbour porpoises (*Phocoena phocoena*). *PLoS ONE* 14 (3): e0213348. https://doi.org/10.1371/journal.pone.0213348