# Cross-project evaluation of FaunaGuard operation before pile driving for German offshore wind farms

Technical report

## Part 2: Effects on harbour porpoises

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## List of abbreviations

AHD Acoustic Harassment Device (e. g. Seal Scarer, *FaunaGuard Porpoise* Module)

BBC: Big Bubble Curtain

C-POD: Cetacean Porpoise Detector (short: POD)

DPH: Detection-Positive Hours

DPM: Detection-Positive Minutes

EEZ: Exclusive Economic Zone

FG: *FaunaGuard Porpoise* Module

GAM: Generalised Additive Model

HSD: Hydro Sound Dampers

IHC: Integrated Monopile Installer (Company: *IHC*)

$L_{Peak}$: Sound Peak Level

NAS: Noise Abatement System

OWF: Offshore Wind Farm

PAM: Passive Acoustic Monitoring

PTS: Permanent Hearing Threshold Shift

SEL: Sound Exposure Level

SPL: Sound Pressure Level (= $L_{eq}$)

TTS: Temporary Hearing Threshold Shift

# 1 SUMMARY

It is mandatory that porpoises are chased away from the vicinity of offshore construction sites up to at least 750 m distance before pile driving for the installation of offshore wind turbines begins, to protect them from possible injury (permanent or temporary hearing threshold shift; PTS, TTS). To achieve this goal, until the end of 2017 a combination of pingers and a seal scarer was prescribed for mitigation purposes. A seal scarer is an acoustic harassment device (AHD) leading to decreased porpoise detection rates in much larger distances than intended. Therefore, a device specifically designed for mitigation purposes, the *FaunaGuard Porpoise* module (hereinafter referred to simply as FaunaGuard), was developed and used since then. On the one hand, it was the aim to deter all harbour porpoises from a radius of 750 m around offshore wind farm (OWF) piling sites before the start of pile driving, whereas on the other hand deterrence by this device should lead to shorter deterrence distances compared to the seal scarer, which has an impact up to 7 km. Although project-specific evaluations indicated that the FaunaGuard was highly effective, a cross-project analysis and a comparison with data from the previous procedure for piling with the operation of pingers and a seal scarer was still pending. The present report aims to fill precisely this gap and to answer the following questions through a cross-project analysis:

- *How do harbour porpoises respond to mitigation by the FaunaGuard in a short range around construction sites and at greater distances?*
- *What can be deduced from the results regarding the effectiveness of the FaunaGuard in the German Exclusive Economic Zone (EEZ) when compared to the seal scarer?*

In four offshore wind farm (OWF) projects, harbour porpoise presence was monitored acoustically: (1) continuously every minute at different distances up to 10 km from the piling, and (2) every minute at 750 m and 1,500 m distance from the piling location from a few hours before the deployment of a FaunaGuard until a few hours after the piling stopped. Stationary and mobile Cetacean Porpoise Detectors (C-PODs) were used for this purpose. The study came to the following conclusions:

1) The FaunaGuard as a specifically designed mitigation device reduced detection rates in a short range of up to 1.5 km distance slightly more effectively than deterrence by using AHDs (seal scarers), without leading deterrence through displacement lasting longer than one day. Namely, detection rates at a distance of up to 1.5 km dropped by 48 % during FaunaGuard operation, compared to on average 6.20 hours before FaunaGuard operation. Split by distance, the drop was 56 % at 750 m distance and 41 % at 1500 m distance. By this, the FaunaGuard was shown to be a highly effective mitigation system for decreasing detection rates of harbour porpoises in the vicinity of pile driving. It can be concluded that the FaunaGuard met the official demand to minimise the risk of a permanent and/or temporary hearing threshold shift (PTS, TTS) for harbour porpoises during pile-driving exercises.

2) After the first 20-25 minutes of FaunaGuard operation, harbour porpoise detection rates had nearly declined to zero in the close range of up to 1.25 km distance, meaning that harbour porpoise clicks were detected only sporadically.

3) Longer operation times led to a moderate extension of the effect range, with a maximum of 2.5 km effect range for the longest available operation times (35-40 minutes).

4) During the operation of a FaunaGuard, reduced detection rates were observed only in up to 2.5 km distance so that in contrast to the seal scarer a shorter deterrence distance was achieved. For the seal scarer, a clear effect was shown in 5-10 km distance (mean of available distances: ~ 8 km).

5) Probably due to the shorter effect range of the FaunaGuard, the combined effects of FaunaGuard/piling on harbour porpoises were not as strong as the combined effects of seal scarer/piling shown by the Gescha studies (Gescha 1: BIOCONSULT SH et al. 2016a; Gescha 2: BIOCONSULT SH et al. 2019).

The *FaunaGuard Porpoise* module is an important step forward to a less harmful piling procedure in the North and Baltic Seas. With the *FaunaGuard Porpoise* module a suitable mitigation system is available to approach this goal and it is recommended for deployment prior to pile-driving procedures that it replaces a combination of pingers and a seal scarer.

# 2 INTRODUCTION

Since the beginning of the expansion of offshore wind power in Germany, the licensing procedure for offshore windfarms stipulate that acoustic harassment devices (AHD) have to be used to scare harbour porpoises away from the danger zone where they could suffer injuries before pile driving of the foundations of wind turbines begins. For this purpose, already existing AHDs from the fishery industry, so-called seal scarers, were mainly used. These devices were developed in order to chase seals away from fish farms. Investigations into the effectiveness of these seal scarers with respect to harbour porpoises (e.g. BIOCONSULT SH 2009; BRANDT et al. 2013a; b) have shown that their impact radius extends well beyond the targeted 750 m from the sound source. Avoidance reactions of harbour porpoises were detected in distances over 7 km (BRANDT et al. 2013b). Progress in the development of noise abatement systems promoted that the German piling noise limit of 160 dB SEL at a distance of 750 m from the piling location is nowadays met or even undercut at most construction sites. On the other hand, investigations at various wind farms show that, despite keeping within the piling noise limit or even falling below, the avoidance distance of porpoises did not decrease any further (BIOCONSULT SH et al. 2019). This leads to the hypothesis that at these construction sites the response range of the animals is not only related to the impulsive sound emission during piling, but among other possible causes such as noise from vessels possibly also to the operation of the seal scarer before pile driving.

A few years ago, Ron Kastelein from *SEAMARCO B.V. (Sea Mammal Research Company Inc.)* in the Netherlands developed together with the company *Van Oord* a device to safely and temporarily deter various marine fauna species from marine construction sites by means of specialised underwater acoustics: the FaunaGuard system (VAN DER MEIJ et al. 2015). Among different marine fauna species or species groups, one target species is the harbour porpoise. The *FaunaGuard Porpoise* module, which is specifically designed to scare porpoises away, can be considered an Acoustic Harassment Device (AHD). In the following, this AHD will be referred to simply as FaunaGuard.

The FaunaGuard produces signals that are less loud and at a higher frequency range (40 kHz to 100 kHz with a source level of 149 dB SEL re 1 $\mu Pa^2 s$ at 85 kHz) than the seal scarer (13.5 to 15 kHz with a source level of approx. 189 dB re 1 $\mu Pa^2 s$), in which harbour porpoises have a better hearing ability. This means that a lower volume is required for harbour porpoise deterrence and, due to the greater propagation attenuation of the high-frequency signals, the range of the deterrence effect should be significantly smaller than that of the seal scarer. In addition, the FaunaGuard uses different complex signal sequences to minimise possible habituation effects.

Since 2018, the licensing authority, the German Federal Maritime and Hydrographic Agency (*Bundesamt für Seeschifffahrt und Hydrographie*, BSH) has changed the regulations regarding the use of AHDs before the start of pile driving from the use of a seal scarer to the use of the FaunaGuard system. Thus, for the OWFs *Borkum Riffgrund 2*, *EnBW Hohe See* and *Albatros*, *Trianel Windpark Borkum Phase 2*, *Deutsche Bucht* and *Arkona-Becken Südost*, constructed in 2017, 2018 and 2019, the FaunaGuard was used for deterrence before noise-intense piling.

Deterrence by a FaunaGuard is intended to ensure that on the one hand no harbour porpoises are harmed by the pile-driving noise, but on the other hand the marine environment is not polluted over a large area by unnecessary high and far-reaching AHD noise. In all projects, acoustic (detection) measurements of the different FaunaGuard signals were carried out. Also, in accordance with ancillary provision 14, C-POD measurements in 750 m and 1500 m distance from piling sites and at four permanent measuring positions at the edge of the respective wind farm, were used to control the efficiency of the deterrent devices. Although the project-specific evaluations in each case indicate that the FaunaGuard is highly effective in scaring away harbour porpoises, a cross-project consideration of the results with a focus on the area from 750 m to a maximum distance of 10 km from the construction site and a comparison with data from the previous procedure for pile driving is still pending.

The present report aims to fill precisely this gap and to answer the following questions through a cross-project analysis from all available data including mobile C-PODs in 750 m and 1500 m distance, as well as data from stationary C-PODs at various distances to the construction sites:

- *How do harbour porpoises respond to deterrence by the FaunaGuard in a short range around construction sites, and how is the response at greater distances?*
- *What can be deduced from the results regarding the effectiveness of the FaunaGuard in German waters when compared to the seal scarer?*

In the context of these questions, the following subtopics were investigated in detail:

1. How did the detection rates of harbour porpoises change during FaunaGuard operation at shorter distances up to 1.5 km?
2. How did the detection rates of harbour porpoises change during FaunaGuard operation at distances up to 10 km?
3. How did the detection rates of harbour porpoises change in relation to FaunaGuard duration and distance?
4. Did the effects on harbour porpoise detection rates during FaunaGuard operation differ from those during seal scarer operation?
5. Comparison with the Gescha studies (Gescha 1: BIOCONSULT SH et al. 2016a; Gescha 2: BIOCONSULT SH et al. 2019): Were the combined effects of FaunaGuard and piling different from those of seal scarer and piling?

# 3 AREA AND METHODS

This study is based on data collected at four OWFs constructed in 2018 and 2019 under operation of the FaunaGuard system as AHD in the German Bight, North Sea. For these OWFs, 207 monopiles, serving as foundations for the offshore wind turbines, were piled into the seabed (Table 3.1).

The analyses were based on two C-POD datasets of harbour porpoise detection rates:

- Data from 25 stationary C-PODs deployed during the environmental construction monitoring for the OWFs, based on the methodology described in the StUK 4 (BSH 2013).
- Data from 334 mobile C-PODs deployed to control the effectiveness of the deterrent measures before pile driving in close vicinity to construction sites, following the procedure given by ancillary provision 14 within the permission documents of the BSH for each OWF. These data were collected from a few hours before to a few hours after the end of piling at fixed distances of 750 m and 1500 m to the construction sites.

## 3.1 Research area, wind farm projects, available data

Analyses were conducted on data from the OWFs *Borkum Riffgrund 2*, *Deutsche Bucht*, *EnBW Hohe See* and *Albatros*, as well as *Trianel Windpark Borkum Phase 2* (geographic positions in Figure 3.1). A fifth OWF with FaunaGuard operation, *Arkona-Becken Südost* which was constructed in 2017, was not analysed here. Since only very few harbour porpoises were recorded in the respective project area no further improvement of conclusions to be drawn about possible effects of the FaunaGuard on the response of harbour porpoises was to be expected by including these data.

The OWF *Borkum Riffgrund 2* is located about 54 km off the coast of Lower Saxony and about 34 km off the East Frisian island Borkum (ØRSTED 2020). It was mainly built in 2018. In total, 36 wind turbines were founded by monopiles, and 20 further turbines were fixed by Suction Bucket Jackets. Only the data of the monopiles were analysed. Between March and December 2018, 9 C-POD stations and 58 mobile C-PODs were deployed. These recorded around 37,000 hours in total (Table 3.1). In 2019, the wind farm was officially commissioned and is now able to provide power for about 460,000 households.

The OWF *Deutsche Bucht* is located in the German Exclusive Economic Zone (EEZ) approximately 95 km northwest of the island of Borkum (NORTHLAND DEUTSCHE BUCHT 2020). Starting in summer 2018, 32 wind turbine foundations were driven into the seabed at water depths of around 40 m using monopiles and covering an area of 22.6 km². Two C-POD stations and 58 mobile C-PODs were deployed between April 2018 and April 2019, which recorded around 5,500 hours in total (Table 3.1). All turbines were commissioned in September 2019 and the wind farm is now able to generate electricity for about 300,000 households.

The OWFs *EnBW Hohe See* and *Albatros* are located 95 km north of Borkum and 100 km northwest of Helgoland (ENBW ENERGIE BADEN-WÜRTTEMBERG 2020). The water depth in this region is about 40 m. On an area of nearly 42 km², 71 wind turbine foundations were piled into the seafloor using monopile foundations. Between April 2018 and April 2019, a total of 7 C-POD stations and 156 mobile C-PODs collected data in this area, which in total recorded for about 38,000 hours (Table 3.1). Since October 2019, these wind farms generate electricity for about 580,000 households.

The OWF *Trianel Windpark Borkum Phase 2* is the second construction phase of the wind farm *Trianel Windpark Borkum* (TRIANEL WINDKRAFTWERK BORKUM II GMBH & CO. KG 2020). It is located about 45 km north of the East Frisian island Borkum. The first construction phase of 40 wind turbines in 2012 is not considered here. In the second construction phase from June 2018 to May 2020, a further 32 wind turbines were installed on monopile foundations which had been driven to the seabed at water depths of 27 to 33 m. At 7 C-POD stations and 62 mobile C-PODs, more than 40,000 hours were recorded between March and December 2018 (Table 3.1).

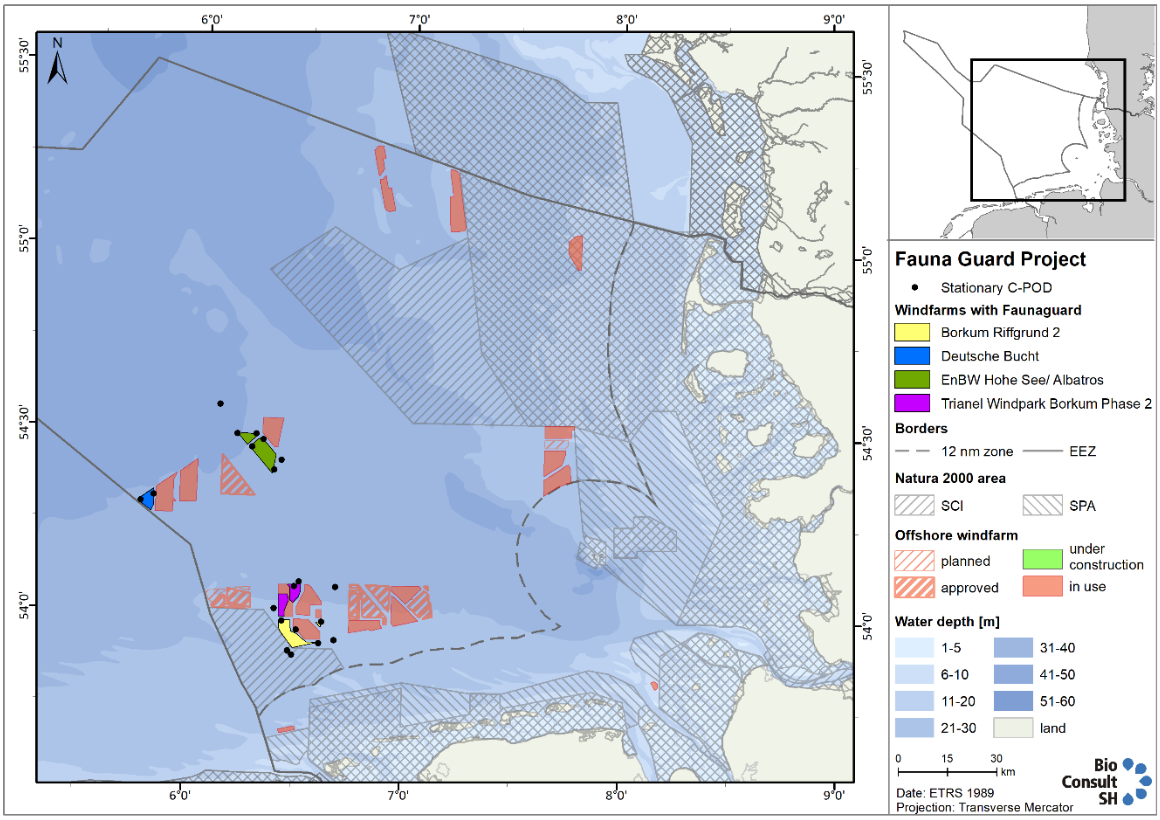


*Figure 3.1* *Map of the German Bight showing the locations of the investigated offshore wind farms with application of a FaunaGuard as AHD (coloured areas), as well as positions of the analysed stationary C-PODs (black dots).*

Different noise abatement systems (NAS) were used during pile driving for these wind farms in order to reduce the noise emission and minimise the negative effects on the marine fauna. The NAS were mostly quite effective, reducing the 5% percentile of the Sound Exposure Level ($SEL_{05}$) in 750 m distance most often to values below 160 dB (Figure 3.2). Only in a few cases noise abatement was less effective. Considered for analyses were the NAS classes "BBC", "DBBC & HSD" and "IHC & BBC" where pile-driving noise was reduced efficiently (Figure 3.2). All other NAS classes were excluded because in these cases noise abatement was less effective. In this way, datasets were kept consistent and not influenced by outliers in terms of piling noise. The excluded pilings affected datasets from different wind farms. In total, C-POD data from the construction activities for 196 of 207 monopiles (FaunaGuard: 193; seal scarer: 3) were considered for subsequent analyses.

*Table 3.1 Number of piles and considered data regarding the investigated OWFs.*

| | Borkum Riffgrund 2 | Deutsche Bucht | Hohe See | Trianel Wind-park Borkum 2 |
|---|---|---|---|---|
| **Date of first piling** | 05.03.2018 | 01.09.2018 | 15.04.2018 | 28.06.2018 |
| **Date of last piling** | 25.05.2018 | 06.01.2019 | 09.04.2019 | 06.11.2018 |
| **Start of considered data** | 01.03.2018 00:00:00 | 10.04.2018 00:00:00 | 01.04.2018 00:00:00 | 01.03.2018 00:00:00 |
| **End of considered data** | 31.12.2018 23:00:00 | 07.01.2019 08:00:00 | 28.04.2019 12:00:00 | 31.12.2018 23:00:00 |
| **Number of piles** | 56 | 32 | 87 | 32 |
| **Number of analysed piles** | 36 | 32 | 87 | 32 |
| **Number of piles with FaunaGuard as AHD** | 36 | 32 | 87 | 29 |
| **Number of piles with seal scarer as AHD** | 0 | 0 | 0 | 3 |
| **C-POD stations** | 9 | 2 | 7 | 7 |
| **C-POD stations: hours of data** | 36,021 | 4,754 | 36,108 | 39,674 |
| **Mobile C-PODs** | 58 | 58 | 156 | 62 |
| **Mobile C-PODs: hours of data** | 912 | 730 | 1,781 | 638 |

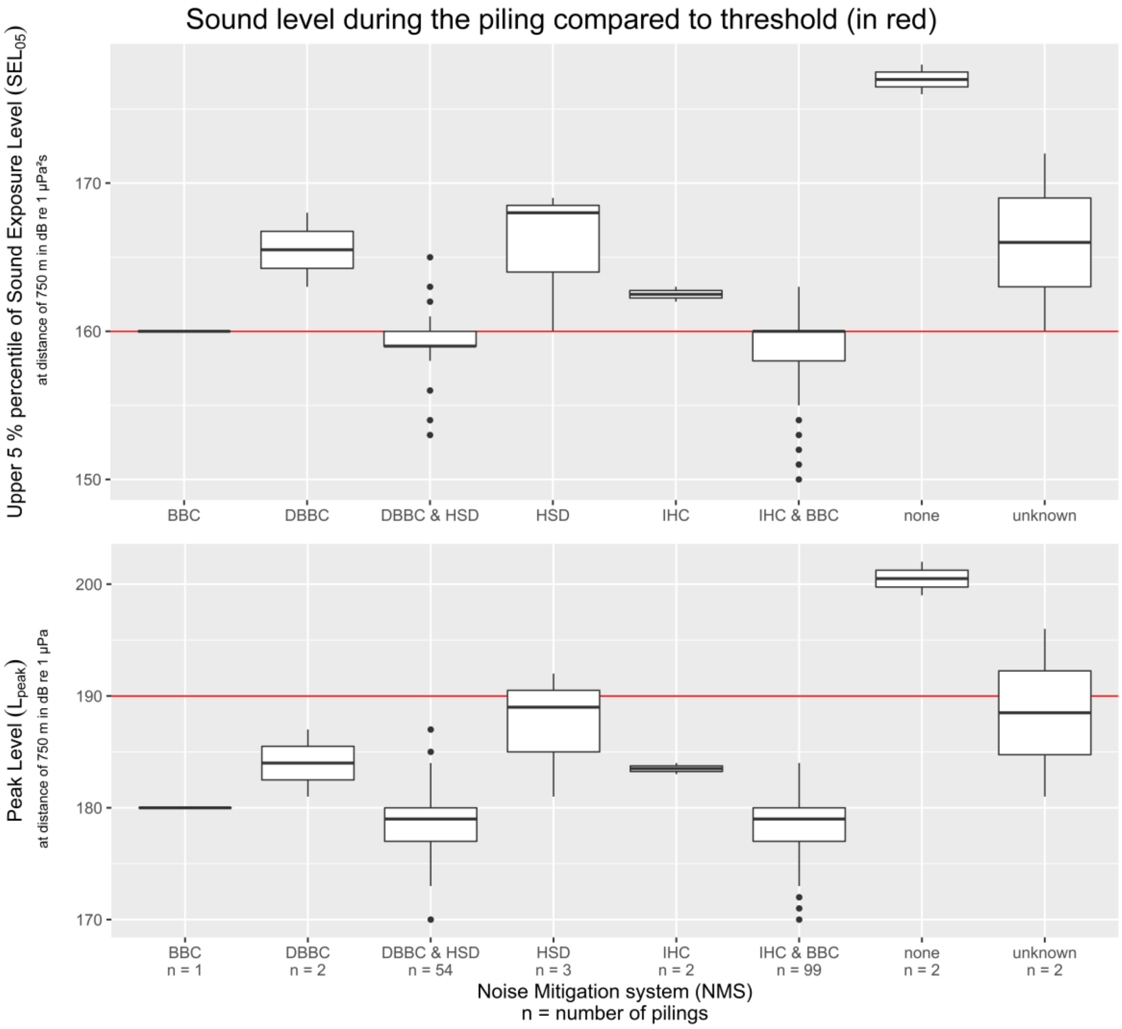

*Figure 3.2 Sound Exposure Level $SEL_{05}$ and Peak Level $L_{Peak}$ of pilings at a distance of 750 m to construction sites, compared to the dual noise protection criterion of the German Federal Maritime and Hydrographic Agency (red lines). Only pilings of the noise abatement system (NAS) classes "BBC", "DBBC & HSD" and "IHC & BBC" did fully comply with the thresholds of this criterion; all others were excluded from final analyses.*

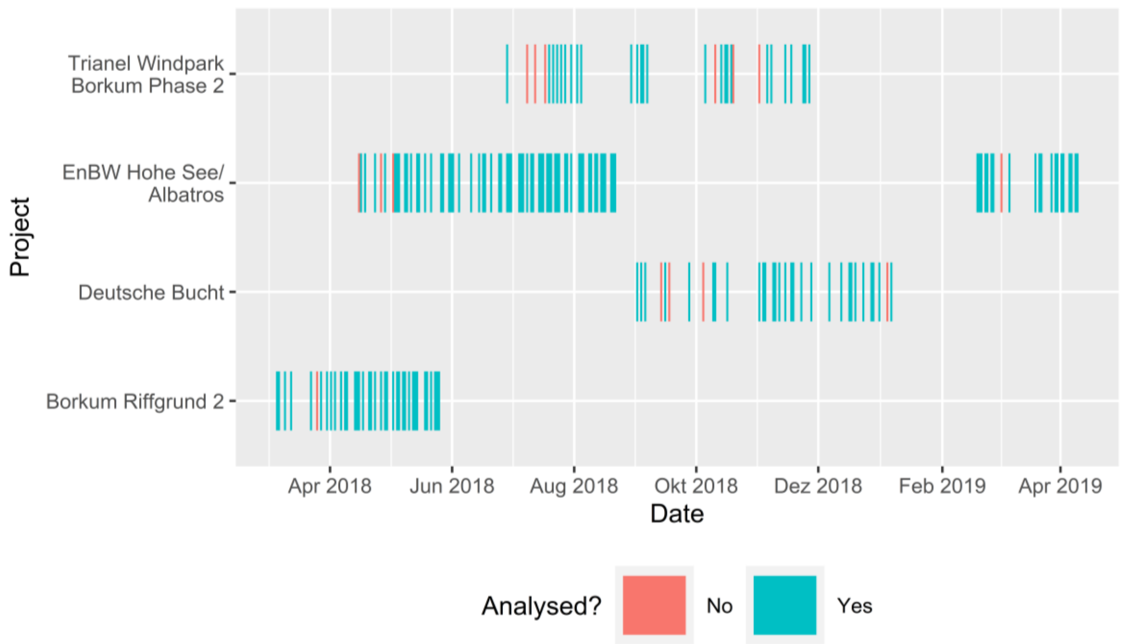


*Figure 3.3 Timeline of pilings conducted for the investigated OWFs in the period from March 2018 to 2019. Only pilings of certain NAS classes were considered for further analysis.*

Harbour porpoises are capable of echolocation by high-frequency click sounds which are emitted to communicate, assess surroundings, and track down prey (AKAMATSU et al. 2001; WISNIEWSKA et al. 2016). Passive Acoustic Monitoring (PAM) by (*Cetacean*) *Porpoise Detectors* (PODs, C-PODs) make use of this behaviour by registering the emitted clicks with hydrophones. Clicks are frontally emitted through the so-called melon in a dorso-ventrally compressed narrow acoustic beam (horizontal 13°, vertical 11°, KOBLITZ et al. 2012). In consequence, C-PODs are only able to register porpoises if the animals (1) emit click sounds, (2) are within the detection range of the hydrophone, and (3) are facing towards the hydrophone. Registration probability is therefore strongly dependent on porpoise activity, distance and emission direction relative to the C-POD.

Tagged harbour porpoises equipped with a hydrophone were shown to make use of their echolocation system almost continuously (AKAMATSU et al. 2007; WISNIEWSKA et al. 2016). Hence, echolocation is assumed to be the most important sensory perception, which by its constant usage allows correlation between detection rates of PODs and porpoise density in its vicinity. TOUGAARD et al. (2006) and KOSCHINSKI et al. (2003) were able to demonstrate a relationship between echolocation and time-congruent observations. TOUGAARD et al. (2006) showed decreasing detection rates (porpoise-positive minutes per day) with increasing distance to the hydrophone by distance-sampling theory (BUCKLAND et al. 2001). Their concept allowed computation of a relationship between POD detection rates and porpoise densities. Such a relationship was also found by KYHN et al. (2012). A significant correlation between densities obtained by aerial surveys and POD detection rates was furthermore observed by DIEDERICHS et al. (2002) and SIEBERT & RYE (2008). Thus, it is a valid assumption that POD detection rates are a rough measure of true harbour porpoise densities: the higher the detection rates the more animals are present in the area.

C-PODs are autonomous data loggers able to register high-frequency sound events. They consist of a plastic tube of 80 cm length with a hydrophone positioned inside at the one end (Figure 3.4). Directly attached to this are an amplifier and electronic filter. The hydrophone works omnidirectional, registering all sound events (clicks) ranging from 20 kHz to 160 kHz.

As the devices include a self-contained data logger that recognizes the trains of odontocete echolocation from characteristics of sequences of clicks, the false-positive rates are much lower than if analysing individual clicks – regardless of whether these are in waveform audio format (wav) or other audio formats (CHELONIA LIMITED 2020). Also data from literature show that false-positive cetacean detections appear to be rare and the hourly detection accuracy very high with C-PODs (GARROD et al. 2018). This makes C-PODs reliable indicators of harbour porpoise presence, e.g. in studies of offshore wind farms, although the maximum detection range for porpoises is only about 400 m (CHELONIA LIMITED 2020).

C-PODs record the time of click events and other features such as main frequency, frequency-response curve, click duration with a resolution of 5 µs and intensity (steps of 8 bit), as well as band width and envelope of the frequency spectrum, using digital waveform analysis. Since porpoise clicks are rather unique with primarily long clicks at high frequencies in a narrow band usually centered around 130 kHz, they can be identified with a certain probability by the internal algorithm. In order to ensure that detection rates are not much influenced by sensitivity differences among C-POD devices, the latter were calibrated prior to their first deployment and regularly during the study period, which minimised errors caused by differences in sensitivity. Calibration was conducted in order to obtain equal-sensitivity threshold levels (± 3 dB) according to the main frequency of harbour porpoise click sounds (calibration at 125 kHz; best hearing ability of harbour porpoises at 100-140 kHz; KASTELEIN et al. 2002, 2015) by the manufacturer Chelonia Ltd. The data are saved on a SD memory card (maximum 4 GB). A total of ten 1.5 Volt D batteries provide the device with energy for at least six weeks.

In overall, C-PODs provide the following important information on harbour porpoises at each station:

- presence/absence of porpoises;
- relative abundance (the higher the detection rate, the more animals were present around a station);
- assessment of diel and seasonal patterns in detection rates.

Generally, PAM is suitable for providing long-term datasets, thus allowing for the assessment of short-term fluctuations. However, POD detections originate from a relatively small area since the detection range of the devices mostly does not exceed 400 metres. In contrast to aerial surveys, PAM provides continuous long-term datasets on a small spatial scale. For this reason, we used PAM data to analyse the short-term response of harbour porpoise to FaunaGuard operation.

**Data collection**

Harbour porpoise presence before, during and after the construction of piles for offshore wind farms was monitored acoustically using C-PODs. Stationary C-PODs were continuously deployed in or around all four wind farms to record harbour porpoise detection rates at different distances from pile-driving operations. Furthermore, mobile C-PODs were deployed in all four wind farms from a few hours before the deployment of the FaunaGuard until a few hours after piling (see Table 3.1). These mobile C-PODs were positioned at distances of 0.75 km and 1.5 km to the construction sites. C-PODs were anchored to the seabed with a mooring system and maintained in the water column by a buoy. The devices were operating at a depth of 5 to 10 m above the seafloor.

For the stationary C-PODs, the scan limit was set to 4,096 clicks per minute. Once this value was reached, e. g. by an excess of background noise like for example noise from wind-induced waves, the C-POD did not record any subsequent clicks in the remaining seconds of this minute and started again to register clicks in the next minute. This was done to prevent the SD card memory from filling up with background noise before the next service took place. For the mobile C-PODs, no scan limit was set as these were deployed only for a few hours with the intention to record all sounds during this period.

When processing the memory card, the current version of CPOD.exe (version 2.045) was used to detect the clicks of harbour porpoises on a minutely and hourly basis with the help of the algorithm. The KERNO classifier was used and only clicks that were clearly classified as originating from harbour porpoises and thus with the quality "high" or "moderate" were included into the analyses.

*Figure 3.4 C-POD device (http://www.chelonia.co.uk/index.html).*

## 3.2 Statistical data analysis according to the research questions

Statistical analyses were conducted using the software R version 4.0.1 (R CORE TEAM 2020). Data from mobile C-PODs were used in order to investigate the 1st to 4th question (sections 3.2.1 to 3.2.4), whereas stationary C-POD data were analysed for answering the 2nd to 5th question (sections 3.2.2 to 3.2.5).

***Phases***

On a scale of minutes (1st to 4th question: sections 3.2.1 to 3.2.4), five phases were defined in order to assess differences in detections rates among different periods of the construction process:

- Phase 1: a few hours before the operation of the FaunaGuard (mobile C-PODs: on average until 6.20 hours before start of the FaunaGuard; stationary C-PODs: cut at 6.20 hours before the start of the FaunaGuard);
- Phase 2: operation of the FaunaGuard;
- Phase 3: pile driving;
- Phase 4: a few hours after piling (mobile C-PODs: on average until 3.04 hours after piling; stationary C-PODs: cut at 3.04 hours after piling);
- Phase Reference (only available for stationary C-PODs): combined timeframes (fully or partly) of a) 48 to 24 hours before deterrence (starting at least 48 hours after previous piling) and b) 48 to 120 hours after piling.

On an hourly scale (5th question: section 3.2.5), four phases were distinguished. In contrast to the previous set of phases, FaunaGuard operation and piling could not be separated exactly, as the analysed time units were full daytime hours. Hence, it could only be looked at the combined effects of FaunaGuard operation and pile driving:

- Baseline (48 to 24 daytime hours before first hour with FaunaGuard operation)
- Pre-piling (3 to 1 daytime hours before first hour with FaunaGuard operation)
- Piling (daytime hours with at least 1 minute of FaunaGuard operation or piling: hours 0)
- Reference after piling (daytime hours +49 to +120 after last piling hour)

***Detection parameters***

The primarily investigated parameter was the number of minutes with porpoise click trains in the C-POD data, or in other words the "Detection-Positive Minutes" (*DPM*). Since the duration of the phases differed, detection rates were standardised to *DPM per minute* for each phase. This variable was computed by dividing the sum of *DPM* per phase by the duration of the phase in minutes. *DPM per minute* was analysed for the 1st to 4th question (sections 3.2.1 to 3.2.4). The resolution on a scale of minutes allowed for exact distinction of the phases.

The 5th question required as dependent variable *DPH per hour* (Detection-Positive Hours per hour, or *DPH/h*) for reasons of comparability, as this parameter was also used within the Gescha 2 study (BioConsult SH et al. 2019). To minimize the impact of background noise on the detection of porpoise clicks and to make the results comparable to the Gescha 2 study, hours with more than 100,000 recorded clicks and more than 2 minutes in which the scan limit was reached were excluded from analyses. On an hourly scale, an exact distinction of the phases was not possible.

***Test statistics***

In order to evaluate differences among phases, a Bayesian proportion test was chosen due to its following desirable properties: 1) neither the user nor the test makes any prior assumptions about the distribution of the data (just the success rate for each group [*DPM*/total minutes sampled] is needed to compare the success ratios among groups); 2) multiple testing does not lead to significances by chance (false positives) instead of actual significances; hence, correction for multiple testing is not necessary in this Bayesian framework (Gelman et al. 2012); 3) not only medians or mean values and standard deviations are compared, but the entire 95 % confidence interval is taken into account (Makowski et al. 2019).

For each phase, the test assessed whether or not a sample from a population represented the true proportion of the entire population (i.e. given N success/fail samples, what was the likelihood of the population median at a 95 % confidence interval?; the smaller the sample size, the higher the uncertainty). If the sample size of a phase was small, the uncertainty was high, hence the confidence interval being wide. This also accounted for the on average shorter FaunaGuard phase compared to the phases before FaunaGuard deployment, during piling and after piling. Given several phases as with our study, the test examined inter-group comparisons and looked for the probability that the median of one phase lay within the 95 % confidence interval of another phase.

***Generalised Additive Modelling***

In order to answer the 3rd question (3.2.3), a Generalised Additive Model (GAM) was conducted. This type of model chosen because GAMs do not require a normal distribution of data points (e.g. compared to Generalized Linear Models) and also because no parametric form of the function has to be specified (Wood 2017). Since the data sets were large, the *bam* function of the R package *mgcv* (Wood 2015) was used.

*DPM per minute* served as response variable. Explanatory variables of main interest were the tensor product of the variables *A_min_FaunaGuard* and *A_dist*. The variable *A_dist* was the distance to the FaunaGuard. The variable *A_min_FaunaGuard* described the minute of FaunaGuard deployment ranging from the start of the FaunaGuard (minute +1 on the x-axis) until the start of piling, or, if the FaunaGuard was switched off before, until the end of FaunaGuard operation. So even if the FaunaGuard stayed activated for a few more minutes during pile driving, these minutes were not taken into account in the analysis as pile driving probably masked the effects of the FaunaGuard.

The GAM included the combined data of all wind farms. A time frame of minute +1 to +43 and a spatial extent of 0 to 10 km distance to the FaunaGuard was considered, as only for this range sufficient data were available. For longer operation time of the FaunaGuard system and greater spatial extent, only occasional data were available and thus not sufficient for modelling. No further models could be created for individual wind farms due to the limited number of data for each.

Different piling- and noise-related, time-related, environmental, as well as POD-related variables were available (Table A.5). The environmental variables were modelled on the surface and at different depths. For the analysis only the calculations on the surface were used. No environmental variables on a time-related basis were used, as the data set is on a minute-by-minute basis and the time-related variables are on an hourly basis or more.

Collinearity between variables can greatly distort model estimates and predictions at correlation coefficients above 0.7 (DORMANN et al. 2013). Consequently, in order not to include variables with a strong correlation into the models, the correlation between all possible variables except factors was investigated at the beginning (Figure A.8). For variables with high collinearity, the biologically more reasonable variable was retained and the other eliminated (Figure A.9). In the case of sand eels, the average value of three different species was considered first and then the best model was used to evaluate whether a single species rather than the average would fit better.

Besides collinearity, GAMs must also be tested for multicollinearity as multicollinearity can negatively affect the estimated coefficients in multiple regression analyses (MANSFIELD & HELMS 1982). Namely, smooth functions are used in GAMs, so it has be investigated if the smooth function of one variable can be created by combining those of the other variables in the model, thus leading to concurvity (AMODIO et al. 2015). Although GAMs do have some degree of built-in amplification against multicollinearity, it should still be tested whether the data are affected by multicollinearity and if concurvity in the GAM occurs.

Multicollinearity can be estimated by computing the so-called variance inflation factor (or VIF), which measures how much the variance of a regression coefficient is expanded due to multicollinearity in the model (MANSFIELD & HELMS 1982). None of the parameters included in the model after correlation analysis (Figure A.9) had a VIF greater than 2.10. Various rules of thumb indicate severe multicollinearity, starting from a VIF of 4, 10, 20 or 40, even if these rules of thumb for the VIF alone cannot actually make clear statements about severe multicollinearity (O'BRIEN 2007). Therefore, other indicators of multicollinearity such as very high standard errors for regression coefficients or an overall significant model with no single significant coefficient were also examined. Overall, none of the analyses indicated a serious effect of multicollinearity in the GAMs. Furthermore, this study aimed to make only estimates and predictions, but not to interpret individual regression coefficients, so that multicollinearity needs less consideration here (MURRAY et al. 2012).

Furthermore, random effects were included into the models: (1) the name of the wind farm (variable *project*), (2) the name of the C-POD station (variable *station*; only one dataset per station and day was included in the analysis) – this variable was just defined for the stationary C-POD data, (3) the ID of the C-POD device (variable *podident*), and (4) the ID of the pile (variable *pile*). In this way, it was corrected for effect differences due to factors like geographical location, C-POD sensitivity or specific characteristics of a piling. However, since a GAM is often faster and more reliable when the number of random effects is modest, only one random effect per GAM was used, and in each case it was tested which random effect was most suitable (WOOD 2017).

GAMs assume that errors (residuals) are identical and independently distributed (i.i.d.). This assumption does not apply to time-series regression because current time series values are often strongly correlated with past values, so that model errors are also correlated (so-called temporal autocorrelation) (PINHEIRO & BATES 2000). In order to reduce autocorrelation, the observations up to a certain previous time step or the observation at the previous time step should be included as a variable. In these analyses, the variable *DPMt*, which equalled *DPM* in the previous minute, was added to the model as a proxy for autocorrelation.

In order to deal with overfitting, a specification for the smoothing factor was defined. Usually, an unmodified smoothness selection will not take off smoothness from a model (WOOD 2017). In order to reduce the chance of overfitting in these analyses, the smooths were modified to shrink to the zero function and thus to filter out of the model. There are two ways to do this: shrinkage smoothers, and the double penalty approach. The second approach is considered to work slightly better (MARRA & WOOD 2011) and was accordingly activated in these analyses by using the *select* argument. The *gamma* value was set to 1.4, as recommended in literature (WOOD 2017).

At the beginning, a GAM was created using all parameters that were not highly correlated. Then, the parameter with the highest p-value was removed from the analysis step by step. The AIC value of the new model was compared with the AIC value of the previous model. If the AIC value of the new model was lower, the parameter with the highest p-value in the new model was removed. This process was repeated until the AIC value of the new model was higher than that of the previous model. The model with the lowest AIC value was considered to be the best explanatory model (WOOD 2017).

However, if the AIC values of two models differed by less than two, the model with the higher AIC value was also substantially supported (BURNHAM & ANDERSON 2002). If this case occurred in this study, the model with fewer variables was considered the best, even though it may have had a slightly higher AIC value. In other words, the inclusion of additional parameters had to result in an AIC difference of more than two, otherwise the inclusion was considered poorly justified.

***Boosted Regression Tree Modeling***

Boosted Regression Tree (BRT) models were created for the overall dataset (all wind farms combined) in order to answer the 3rd question (3.2.3). This kind of modelling is stochastic which improved prediction performance (ELITH et al. 2008).

Five BRT models were computed, one for each of the following five distance classes: 0 to 1.25 km, 1.25 to 2.5 km, 2.5 to 5 km, 5 to 7.5 km, and 7.5 to 10 km. The explanatory variables were the same as in the final GAM model. As response variable, *DPM per minute* was combined for each second pair of subsequent minutes of *A_min_FaunaGuard* to get enough data for each time class on the x-axis. As with the raw data, only if at least 50 minutes were recorded in this class of the response variable for the corresponding distance class, the data were used in the analysis. In addition, the following settings were used for each BRT:

1. The bag fraction was set to 0.5, which means that for each iteration 50 % of the data were drawn randomly and without substitution from the complete training set. In general, bag fractions in the range of 0.5 to 0.75 showed best results for presence-absence data (ELITH et al. 2008) and no deviations were found for our dataset during data exploration.

2. The learning rate is usually specified between 0.1 and 0.001, as smaller values result in lower prediction errors but increase the risk of overlearning (DE'ATH 2007; ELITH et al. 2008). In this study it was set to a value of 0.01.

3. Tree complexity, in other words the number of nodes in a tree, should theoretically correspond to the true sequence of interaction in the modelled response (FRIEDMAN 2001). However, since this is unknown it was set to 5. This number was used as a trade-off because a tree complexity of 1 generally shows an excessive prediction deviation, and a very high tree complexity would have made the model learn very slowly to obtain enough trees for reliable estimates (ELITH et al. 2008). Usually, doubling the tree complexity should be accompanied by a halving of the learning rate in order to obtain about the same number of sites. Thus, a learning rate of 0.01 would result in a tree complexity of 10, but in this study the probability of detection is considerably lower than the probability of no detection. Consequently, with the same total number of sites, less information is provided for the model requiring a slower learning rate.

4. It is recommended to equip models with at least 1000 trees (ELITH et al. 2008) and this rule of thumb was followed in this study.

The environmental variables as well as the random effects from the best descriptive GAM with all wind farms were used. In BRT models, a certain randomness usually improves accuracy and speed in boosted models and reduces overlearning (FRIEDMAN 2002), but it leads to a considerable variability of adjusted values and predictions among runs (ELITH et al. 2008). Therefore, the number of random variables should be approximately $\sqrt{v}$ or log(v) with v being the total number of variables (DE'ATH 2007). This was the case with the best descriptive GAM over all wind farms.

The results for each distance class were presented in Partial Dependence Plots (PDP). These indicated changes in the predicted mean value when one parameter, in this case *A_min_FaunaGuard*, varied while the other parameters remained constant. The mean value of the data distribution was always centered at zero. Positive values on the y-axis therefore indicated that the detection rates increased compared to the mean value. Negative values indicated a decrease in detection rates. In addition, the relative contribution of each variable to the BRT was shown for each distance class in order to be able to assess the relative influence of the variable *A_min_FaunaGuard* on the model.

### 3.2.1 How did the detection rates of harbour porpoises change during FaunaGuard operation at shorter distances up to 1.5 km?

This question was investigated by means of the data from mobile C-PODs deployed at fixed distances of 0.75 km and 1.5 km to the construction sites. Only Phase 1 to Phase 4 could be analysed due to short deployment times of the mobile C-PODs whereby a true reference was not available.

In detail, it was looked at and tested for differences of *DPM per minute* among the four phases for the distances 0.75 km and 1.5 km, and within these distance subsets it was looked at all OWFs combined as well as single wind farms.

### 3.2.2 How did the detection rates of harbour porpoises change during FaunaGuard operation at distances up to 10 km?

Data from C-POD stations, with supplementary data from mobile C-PODs, were analysed to answer this question as these covered various distances from construction sites. Since stationary C-PODs collected data continuously, the average durations of Phase 1 and 4 of the mobile C-POD data could be used as truncation points in order to obtain comparably long datasets of these phases for the stationary C-PODs (see section 3.2). As for these stations, due to continuous data collection a true reference phase before and after piling was available (section 3.2).

It was looked at and tested for differences of *DPM per minute* among the four or five phases at the following distance classes: 0.75-1.5 km (mobile PODs; only four phases), 0-2.5 km, 2.5-5 km, 5-7.5 km, and 7.5-10 km (the latter four classes: stationary PODs, five phases). Effects were assessed for all OWFs combined as well as for single wind farms.

### 3.2.3 How did the detection rates of harbour porpoises change in relation to FaunaGuard duration and distance?

Combined data from mobile C-PODs and C-POD stations were analysed to answer this question. The resulting dataset covered a higher range of distances than the single datasets used in the previous questions. Therefore, the results for this question were partly also suitable to extend the results provided by analyses for the previous topic. In particular, five distance classes were studied (0-1.25 km, 1.25-2.5 km, 2.5-5 km, 5-7.5 km, 7.5-10 km). GAM and BRT models were performed as specified in the respective detailed Methods sections.

### 3.2.4 Did the effects on harbour porpoise detection rates during FaunaGuard operation differ from those during seal scarer operation?

At the wind farm *Trianel Windpark Borkum Phase 2*, the FaunaGuard system did not work properly during three pilings, so that a seal scarer had to be used for deterrence. Although these pilings were necessarily excluded from the analyses under 3.2.1, they were of special interest here, because they provided the chance to directly compare the effects of a FaunaGuard to the effects of a seal scarer. As the data were collected at the same wind farm and over a similar period, most environmental parameters were likely to be similar. Furthermore, piling conditions and construction processes were similar, except for the used AHD. Thus, it was a reasonable assumption that differences in detection rates of harbour porpoises probably would have been caused by different effects of both types of AHD. However, the number of observations was rather low so that analyses had to stay on an explorative level and interpretations were rather restricted.

In detail, two analyses were conducted:

- Mobile C-POD data were explored to look at differences of *DPM per minute* between the FaunaGuard and the seal scarer dataset, separately for both distances from construction sites (0.75 km and 1.5 km).
- Stationary C-POD data were explored to look at differences of *DPM per minute* between the FaunaGuard and the seal scarer dataset at distances of 5 to 10 km from the construction sites. Differences at other distance classes could not be investigated as for the seal scarer data were available only for this distance class.

### 3.2.5 Comparison with the Gescha studies: Were the combined effects of FaunaGuard/piling different from those of seal scarer/piling?

Combined data from mobile C-PODs and C-POD stations were used to answer this question. These were split into the distance classes 0-5 km, 5-10 km, 10-15 km, and 15-20 km. Main analyses were performed on the combined first two classes, i.e. 0-10 km, since this distance range was in the main focus of our study. Results for the other classes are given in the Appendix.

*DPH per hour* was chosen as detection parameter since it was also used in the two Gescha studies, which rendered analyses comparable. The latter was also guaranteed by choosing the same phases as in the Gescha studies, which are provided in section "Phases" (p. 14).

# 4 RESULTS

A major aim of the FaunaGuard project was to evaluate whether improvements in AHD technology led to a more appropriate harbour porpoise effect range of these devices during the construction process, compared to the far-reaching effects of seal scarers. The specific research questions which arose from this main topic and which were asked in detail in sections 3.2.1 to 3.2.4 will be answered here.

## 4.1 How did the detection rates of harbour porpoises change during FaunaGuard operation at shorter distances up to 1.5 km?

This question was investigated based on the dataset of the mobile C-PODs which were positioned relatively close to the construction sites.

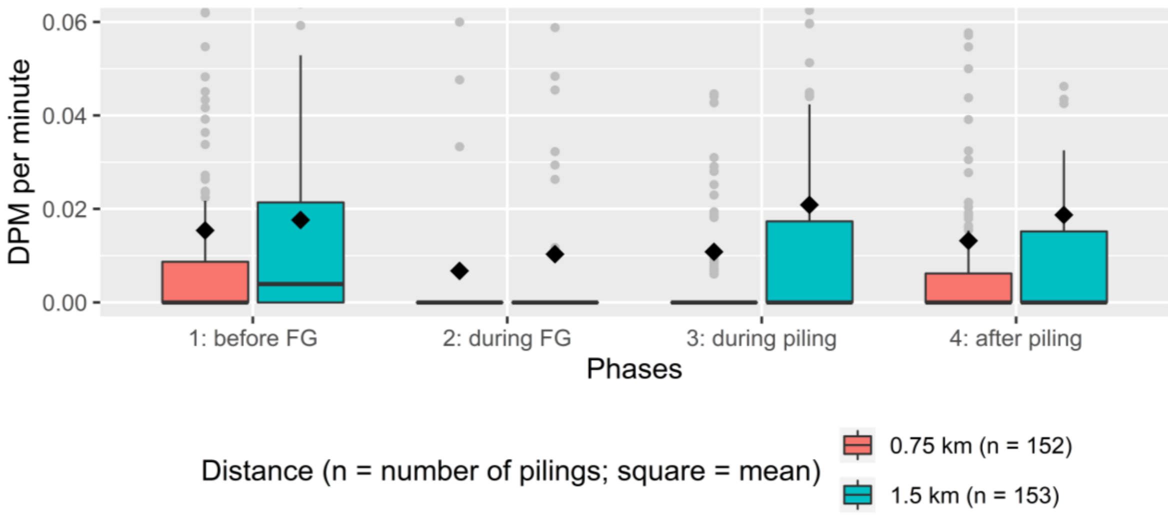


*Figure 4.1 Mobile C-PODs: Boxplots of DPM per minute in the overall dataset during the four investigated phases at distances of 0.75 km respectively 1.5 km to the construction sites (some outliers not shown here); black rhombuses show mean values taken from Table 4.1.*

*Table 4.1 Mobile C-PODs: Data table of DPM per minute (N, mean, standard deviation and error) in the overall dataset during the different phases at distances of 0.75 km respectively 1.5 km to the construction sites.*

| Distance | Phase | N (number of minutes) | *DPM per minute* | | |
|---|---|---|---|---|---|
| | | | Mean | Standard deviation | Standard error |
| **0.75 km** | 1: Before FaunaGuard | 51,497 | 0.0154 | 0.1232 | 0.0005 |
| | 2: During FaunaGuard | 5,178 | 0.0068 | 0.0819 | 0.0011 |
| | 3: During piling | 17,171 | 0.0108 | 0.1035 | 0.0008 |
| | 4: After piling | 25,588 | 0.0132 | 0.1142 | 0.0007 |
| **1.5 km** | 1: Before FaunaGuard | 52,298 | 0.0176 | 0.1317 | 0.0006 |
| | 2: During FaunaGuard | 5,036 | 0.0103 | 0.1011 | 0.0014 |
| | 3: During piling | 17,296 | 0.0209 | 0.1430 | 0.0011 |
| | 4: After piling | 26,164 | 0.0187 | 0.1356 | 0.0008 |

*Table 4.2 Mobile C-PODs at Gescha 2 OWFs (data taken from BIOCONSULT SH et al. 2019): DPM per minute (mean and standard deviation) in 0.75 and 1.5 km distance to the seal scarer and the subsequent piling over the four phases.*

| Project | Distance | Phase | Mean (DPM per minute) | Standard deviation |
|---|---|---|---|---|
| **Gescha 2** | 0.75 km | 1: Before seal scarer | 0.0087 | 0.0296 |
| | | 2: During seal scarer | 0.0055 | 0.0307 |
| | | 3: During piling | 0.0047 | 0.0200 |
| | | 4: After piling | 0.0050 | 0.0205 |
| | 1.5 km | 1: Before seal scarer | 0.0231 | 0.0725 |
| | | 2: During seal scarer | 0.0169 | 0.0654 |
| | | 3: During piling | 0.0157 | 0.0502 |
| | | 4: After piling | 0.0242 | 0.0582 |

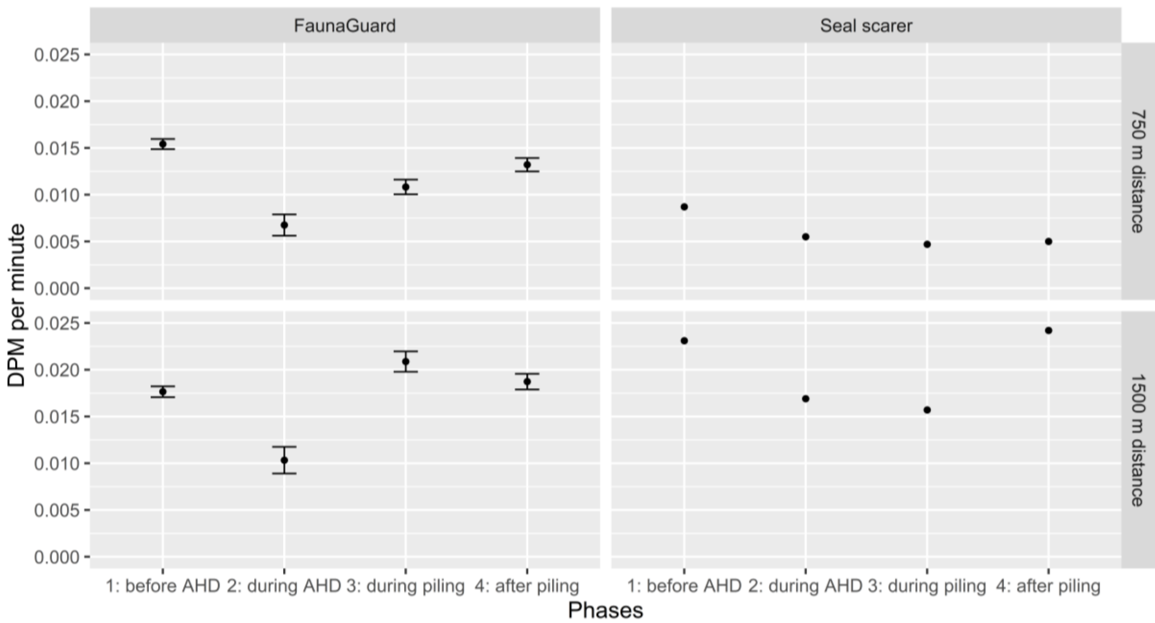


*Figure 4.2 Mobile C-PODs: Comparison of FaunaGuard and seal scarer on mean DPM per minute in the overall dataset during the four investigated phases at distances of 0.75 km respectively 1.5 km to the construction sites; black dots show mean values from Table 4.1 and Table 4.2; standard error (black bars) only available for FaunaGuard; standard deviations in Table 4.2.*

An inspection of the raw data from these C-PODs showed that at a short-range (distances 0.75 km resp. 1.5 km) the rate *DPM per minute* was highest during Phase 1 (on average 6.20 hours before FaunaGuard operation), lowest for Phase 2 (during FaunaGuard operation, on average 0.55 hours), increased again in Phase 3 (during piling, on average 1.72 hours), and remained at this level during the first few hours after piling (Phase 4: on average 3.04 hours after piling) (Figure 4.1, Table 4.1; for both distances combined see Table 4.5).

Thus, up to 1.5 km distance, *DPM per minute* dropped a 48 % during FaunaGuard operation compared to on average 6.20 hours before FaunaGuard operation – more precisely, by 56 % at 750 m distance and by 41 % at 1500 m distance. When using a seal scarer as AHD in the Gescha 2 study, the detection rates decreased by only 36 % (Table 4.2, Figure 4.2).

In the overall dataset, mean detection rates and upper quartiles were higher in 1.5 km distance during most phases (Figure 4.1), except for the upper quartile being zero for both distances during FaunaGuard operation (Phase 2). Differences between both distances were strongest during pile driving (Phase 3).

Baysian proportion tests were conducted to check within each distance class for significant differences among all phases and, if the overall test turned out to be significant, between each pair of phases.

In 0.75 km distance, not only the overall test but also all pairwise tests showed significant differences between any two phases (Table 4.3, Figure 4.3). In 1.5 km distance, the overall test was significant as well, but not each pairwise comparison. Regarding the latter tests, Phase 2 (FaunaGuard) was different from all other phases, showing lowest detection rates of all. Phase 3 (piling) had significantly lower detection rates than Phase 1 (few hours before FaunaGuard). The differences of Phase 4 (few hours after piling) to Phase 1 resp. Phase 3 were not significant (Table 4.3, Figure 4.4).

Regarding effects for single wind farms in 0.75 km and 1.5 km distance to the construction sites some differences to the overall trends became visible. Mean detection rates were still higher in 1.5 km than in 0.75 km distance during all phases for most OWFs, but with the exception of Phase 1, 3 and 4 for *Borkum Riffgrund 2* and Phase 4 for *Trianel Windpark Borkum Phase 2* (Figure 4.5, Table 4.4). However, due to a strongly skewed distribution of *DPM per minute* the mean was considerably influenced by outliers. The median and upper quartile, better suited to represent the distribution of values, were never lower in 1.5 km distance when compared to 0.75 km distance (Figure 4.5). In all four wind farms, *DPM per minute* decreased by 37 % to 75 % from Phase 1 to Phase 2 at distances of up to 1.5 km.

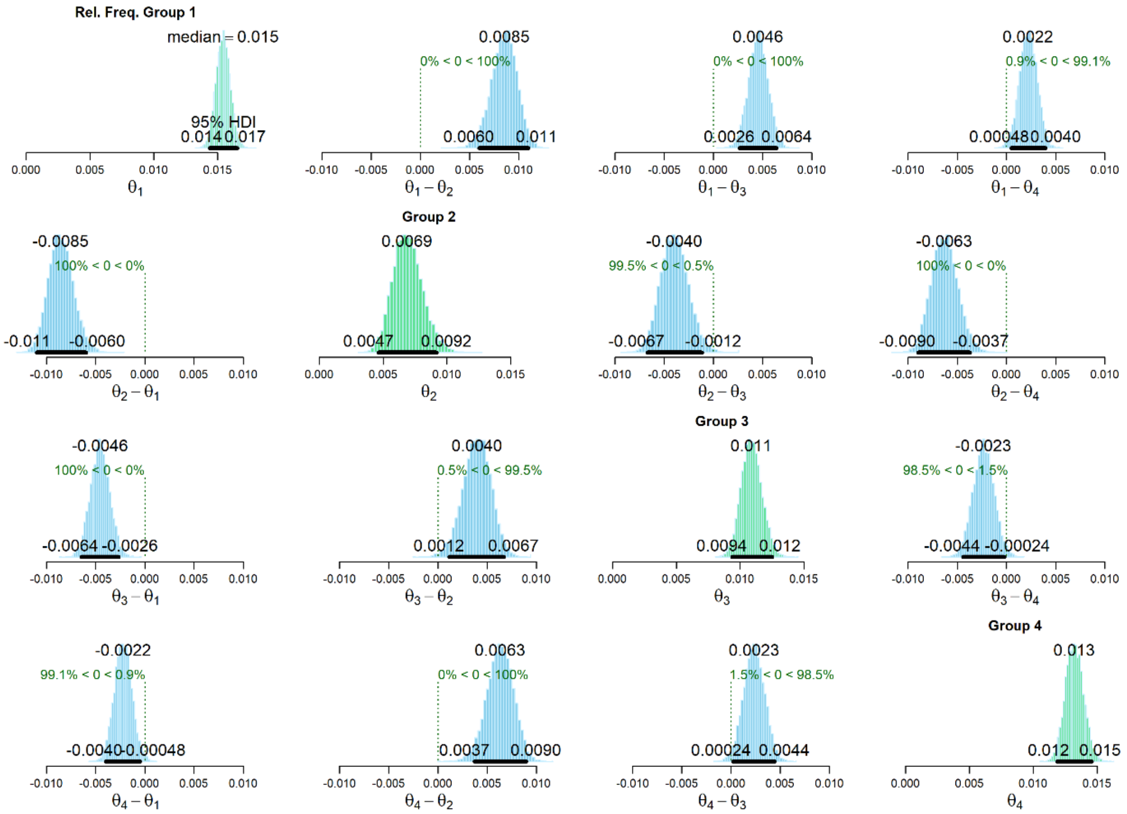

*Figure 4.3* *Plots of pairwise Bayesian proportion tests for the overall dataset from mobile C-PODs in 0.75 km distance to the piling location, using the parameter "DPM per minute". For each phase, it was examined how high the probability was that the median of one phase lay within the 95 % confidence interval of another phase. Group 1 = Phase 1 (few hours before FaunaGuard operation), Group 2 = Phase 2 (during FaunaGuard operation), Group 3 = Phase 3 (during piling), and Group 4 = Phase 4 (few hours after piling). The numbers above the green distributions (the actual phase of interest) show the median of DPM per minute for each phase. Blue colours are used for distributions of another phase in relation to the actual phase (vertical dotted line: median of actual phase which is set to zero; green numbers show what proportion of values are expected to be left and right of this zero line); numbers above blue distributions show the deviation to the median of actual phase (a positive value indicates a higher median of the actual phase, a negative value a lower median). Black bars with respective numbers below the distributions indicate the Highest Density Interval (HDI). For test results see Table 4.3.*

*Table 4.3* *Results of the overall and pairwise Bayesian proportion tests for the overall dataset from mobile C-PODs in 0.75 km and 1.5 km distance to construction sites; visualisation of test results in Figure 4.3 and Figure 4.4.*

| Distance | Comparison | | Probability of equality | Significance |
|---|---|---|---|---|
| **0.75 km** | 4-sample test for equality of proportions without continuity correction | | X-squared = 40.83; df = 3; *p*-value = 7.11e-09* | |
| | Phase 1 | Phase 2 | 0 % | * |
| | Phase 1 | Phase 3 | 0 % | * |
| | Phase 1 | Phase 4 | 0.9 % | * |
| | Phase 2 | Phase 3 | 0.5 % | * |
| | Phase 2 | Phase 4 | 0 % | * |
| | Phase 3 | Phase 4 | 1.5 % | * |
| **1.5 km** | 4-sample test for equality of proportions without continuity correction | | X-squared = 25.76; df = 3; *p*-value = 1.07e-05* | |
| | Phase 1 | Phase 2 | 0 % | * |
| | Phase 1 | Phase 3 | 0.4 % | * |
| | Phase 1 | Phase 4 | 14.1 % | ns |
| | Phase 2 | Phase 3 | 0 % | * |
| | Phase 2 | Phase 4 | 0 % | * |
| | Phase 3 | Phase 4 | 5.8 % | ns |

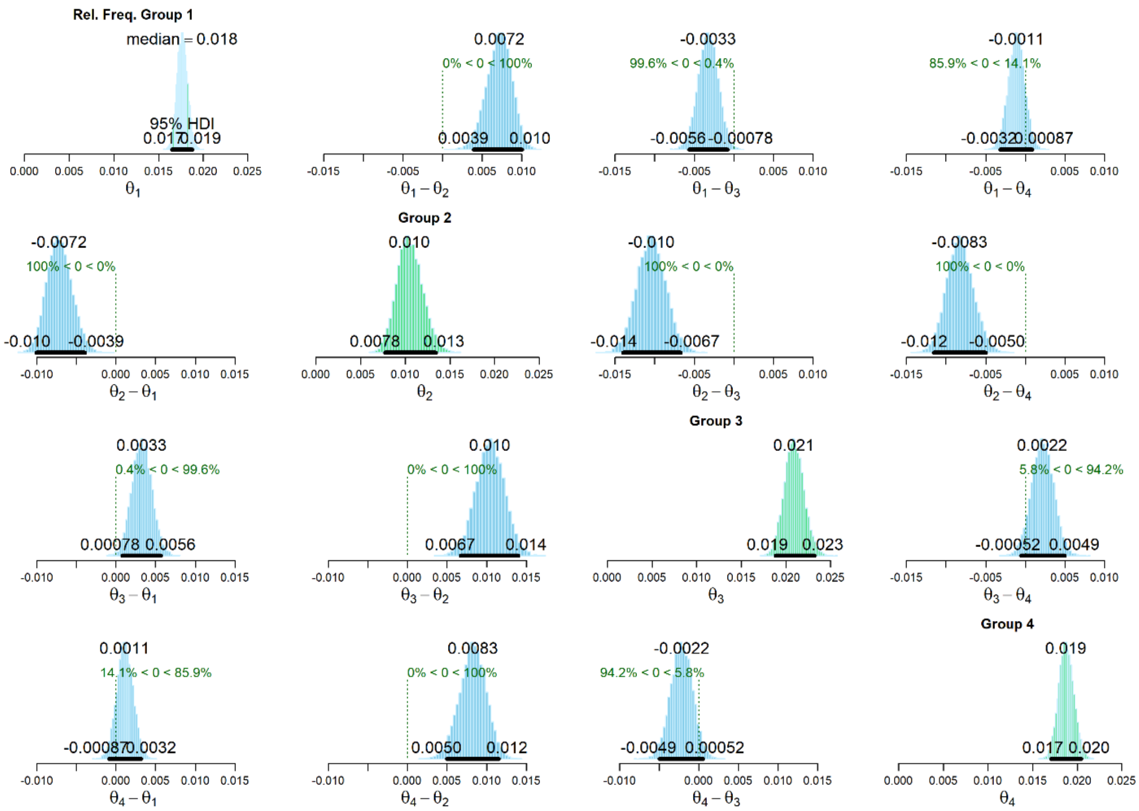


*Figure 4.4* *Plots of pairwise Bayesian proportion tests for the overall dataset from mobile C-PODs in 1.5 km distance to the piling location using the parameter "DPM per minute". Further explanations are given in Figure 4.3 for test results see Table 4.3.*

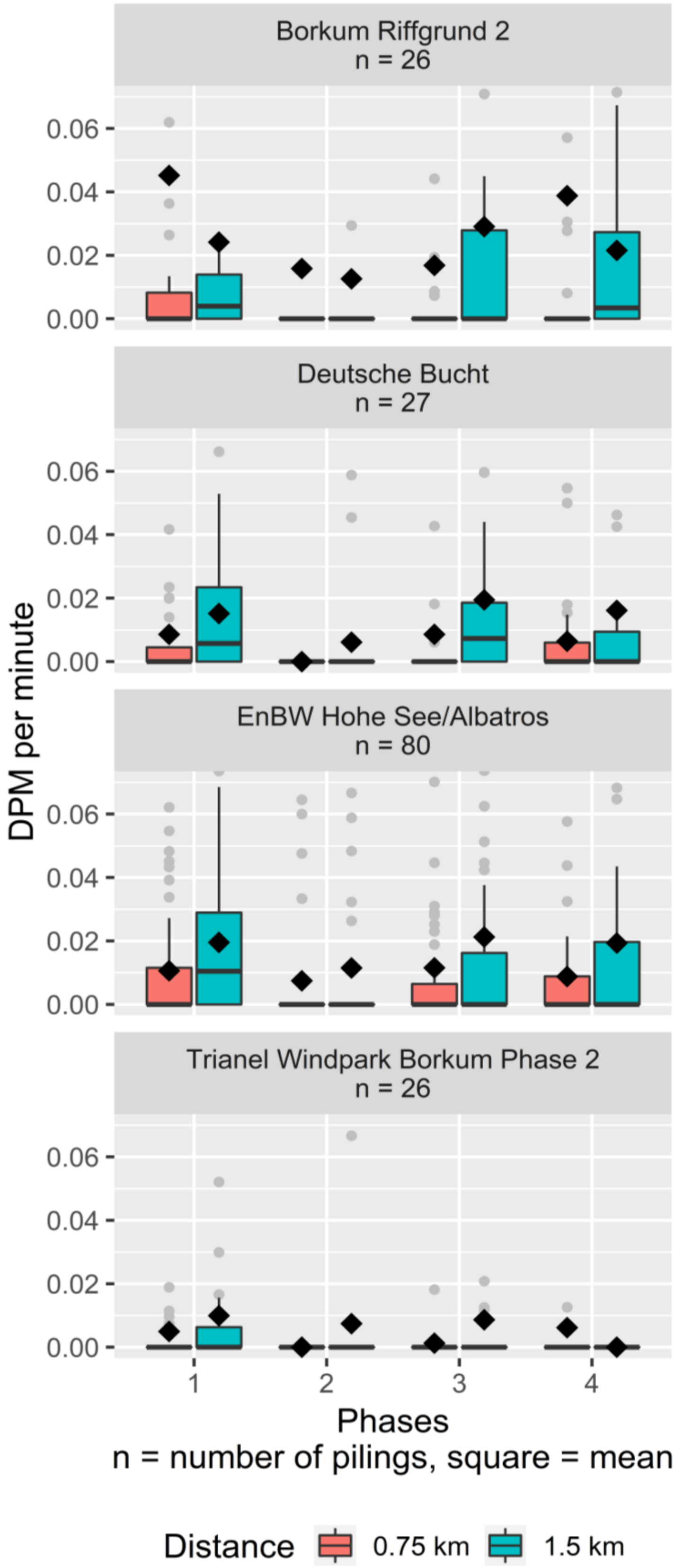


*Figure 4.5* *Mobile C-PODs: Boxplots of DPM per minute at the single OWFs during the four investigated phases at distances of 0.75 km respectively 1.5 km to the construction sites (some outliers not shown here); black rhombuses show mean values taken from Table 4.4.*

*Table 4.4* *Mobile C-PODs: Data table of DPM per minute (N, mean, standard deviation and error) at the single OWFs during the four investigated phases at distances of 0.75 km respectively 1.5 km to the construction sites.*

| OWF | Distance | Phase | *DPM per minute* | | | |
|---|---|---|---|---|---|---|
| | | | N (number of minutes) | Mean | Standard deviation | Standard error |
| **Borkum Riffgrund 2** | **0.75 km** | 1: Before FaunaGuard | 9,265 | 0.0452 | 0.2078 | 0.0022 |
| | | 2: During FaunaGuard | 947 | 0.0158 | 0.1249 | 0.0041 |
| | | 3: During piling | 2,670 | 0.0169 | 0.1287 | 0.0025 |
| | | 4: After piling | 4,098 | 0.0388 | 0.1931 | 0.0030 |
| | **1.5 km** | 1: Before FaunaGuard | 8,440 | 0.0242 | 0.1536 | 0.0017 |
| | | 2: During FaunaGuard | 873 | 0.0126 | 0.1116 | 0.0038 |
| | | 3: During piling | 2,580 | 0.0291 | 0.1680 | 0.0033 |
| | | 4: After piling | 4,589 | 0.0216 | 0.1453 | 0.0021 |
| **Deutsche Bucht** | **0.75 km** | 1: Before FaunaGuard | 7,795 | 0.0086 | 0.0923 | 0.0010 |
| | | 2: During FaunaGuard | 636 | 0.0000 | 0.0000 | 0.0000 |
| | | 3: During piling | 3,485 | 0.0086 | 0.0924 | 0.0016 |
| | | 4: After piling | 3,583 | 0.0064 | 0.0799 | 0.0013 |
| | **1.5 km** | 1: Before FaunaGuard | 10,098 | 0.0152 | 0.1222 | 0.0012 |
| | | 2: During FaunaGuard | 656 | 0.0061 | 0.0779 | 0.0030 |
| | | 3: During piling | 3,598 | 0.0195 | 0.1381 | 0.0023 |
| | | 4: After piling | 3,900 | 0.0162 | 0.1261 | 0.0020 |
| **EnBW Hohe See/ Albatros** | **0.75 km** | 1: Before FaunaGuard | 24,339 | 0.0106 | 0.1024 | 0.0007 |
| | | 2: During FaunaGuard | 2,679 | 0.0075 | 0.0861 | 0.0017 |
| | | 3: During piling | 9,433 | 0.0116 | 0.1069 | 0.0011 |
| | | 4: After piling | 17,260 | 0.0088 | 0.0934 | 0.0007 |
| | **1.5 km** | 1: Before FaunaGuard | 24,015 | 0.0195 | 0.1384 | 0.0009 |
| | | 2: During FaunaGuard | 2,698 | 0.0115 | 0.1066 | 0.0021 |
| | | 3: During piling | 9,496 | 0.0213 | 0.1443 | 0.0015 |
| | | 4: After piling | 16,957 | 0.0193 | 0.1377 | 0.0011 |
| **Trianel Windpark Borkum Phase 2** | **0.75 km** | 1: Before FaunaGuard | 10,098 | 0.0050 | 0.0702 | 0.0007 |
| | | 2: During FaunaGuard | 916 | 0.0000 | 0.0000 | 0.0000 |
| | | 3: During piling | 1,583 | 0.0013 | 0.0355 | 0.0009 |
| | | 4: After piling | 647 | 0.0062 | 0.0784 | 0.0031 |
| | **1.5 km** | 1: Before FaunaGuard | 9,745 | 0.0100 | 0.0993 | 0.0010 |
| | | 2: During FaunaGuard | 809 | 0.0074 | 0.0859 | 0.0030 |
| | | 3: During piling | 1,622 | 0.0086 | 0.0925 | 0.0023 |
| | | 4: After piling | 718 | 0.0000 | 0.0000 | 0.0000 |

## 4.2 How did the detection rates of harbour porpoises change during FaunaGuard operation at distances up to 10 km?

This question was investigated based on both mobile C-PODs and C-POD stations, the latter being positioned at various distances relative to the construction sites. Only distances up to 10 km were considered here as data became sparser and environmental heterogeneity more and more an issue in larger distances.

At distances up to 2.5 km from piling locations, values of *DPM per minute* were highest during Reference (48 to 24 hours before FaunaGuard operation, as well as 48 to 72 hours after piling; only available for stationary C-POD data) and lowest during Phase 2 (During FaunaGuard) (Figure 4.6, Table 4.5). In contrast, at distances from 2.5 to 5 km and from 7.5 to 10 km detection rates were highest during FaunaGuard operation. Although the rates were low again at 5 to 7.5 km distance for Phase 2, FaunaGuard effects were probably not reaching that far, as the device is barely perceptible at those distances amidst background noise (ROSEMEYER et al. 2021) and no negative effects were found in the previous distance class (2.5 to 5 km). Piling effects were surprisingly low in a short range, though there seemed to be a considerable variability within the dataset.

*Table 4.5 Mobile and stationary C-PODs: Data table of DPM per minute (N, mean, standard deviation and error) in the overall dataset during the different phases at five distance classes relative to construction sites (class 0.75 to 1.5 km: mobile PODs; all other classes: stationary PODs).*

| Distance class (with mean) | Phase | *DPM per minute* | | | |
|---|---|---|---|---|---|
| | | N (number of minutes) | Mean | Standard deviation | Standard error |
| **0.75 and 1.5 (1.13) km** | 1: Before FaunaGuard | 109,814 | 0.0156 | 0.1241 | 0.0004 |
| | 2: During FaunaGuard | 10,635 | 0.0082 | 0.0901 | 0.0009 |
| | 3: During piling | 35,262 | 0.0155 | 0.1236 | 0.0007 |
| | 4: After piling | 56,749 | 0.0146 | 0.1200 | 0.0005 |
| | Reference | NA | NA | NA | NA |
| **0-2.5 (1.54) km** | 1: Before FaunaGuard | 33,359 | 0.0312 | 0.1739 | 0.0010 |
| | 2: During FaunaGuard | 3,205 | 0.0228 | 0.1492 | 0.0026 |
| | 3: During piling | 10,974 | 0.0360 | 0.1863 | 0.0018 |
| | 4: After piling | 18,026 | 0.0252 | 0.1567 | 0.0012 |
| | Reference | 79,510 | 0.0401 | 0.1962 | 0.0007 |
| **2.5-5 (3.83) km** | 1: Before FaunaGuard | 62,081 | 0.0337 | 0.1806 | 0.0007 |
| | 2: During FaunaGuard | 5,300 | 0.0357 | 0.1855 | 0.0025 |
| | 3: During piling | 20,153 | 0.0330 | 0.1786 | 0.0013 |
| | 4: After piling | 31,939 | 0.0279 | 0.1646 | 0.0009 |
| | Reference | 115,867 | 0.0341 | 0.1814 | 0.0005 |
| **5-7.5 (6.23) km** | 1: Before FaunaGuard | 49,029 | 0.0374 | 0.1898 | 0.0009 |
| | 2: During FaunaGuard | 4,571 | 0.0287 | 0.1669 | 0.0025 |
| | 3: During piling | 15,392 | 0.0298 | 0.1699 | 0.0014 |
| | 4: After piling | 24,889 | 0.0369 | 0.1885 | 0.0012 |
| | Reference | 84,946 | 0.0380 | 0.1913 | 0.0007 |
| **7.5-10 (8.78) km** | 1: Before FaunaGuard | 44,177 | 0.0447 | 0.2067 | 0.0010 |
| | 2: During FaunaGuard | 4,573 | 0.0494 | 0.2168 | 0.0032 |
| | 3: During piling | 13,901 | 0.0478 | 0.2133 | 0.0018 |
| | 4: After piling | 23,699 | 0.0440 | 0.2050 | 0.0013 |
| | Reference | 87,164 | 0.0395 | 0.1949 | 0.0007 |

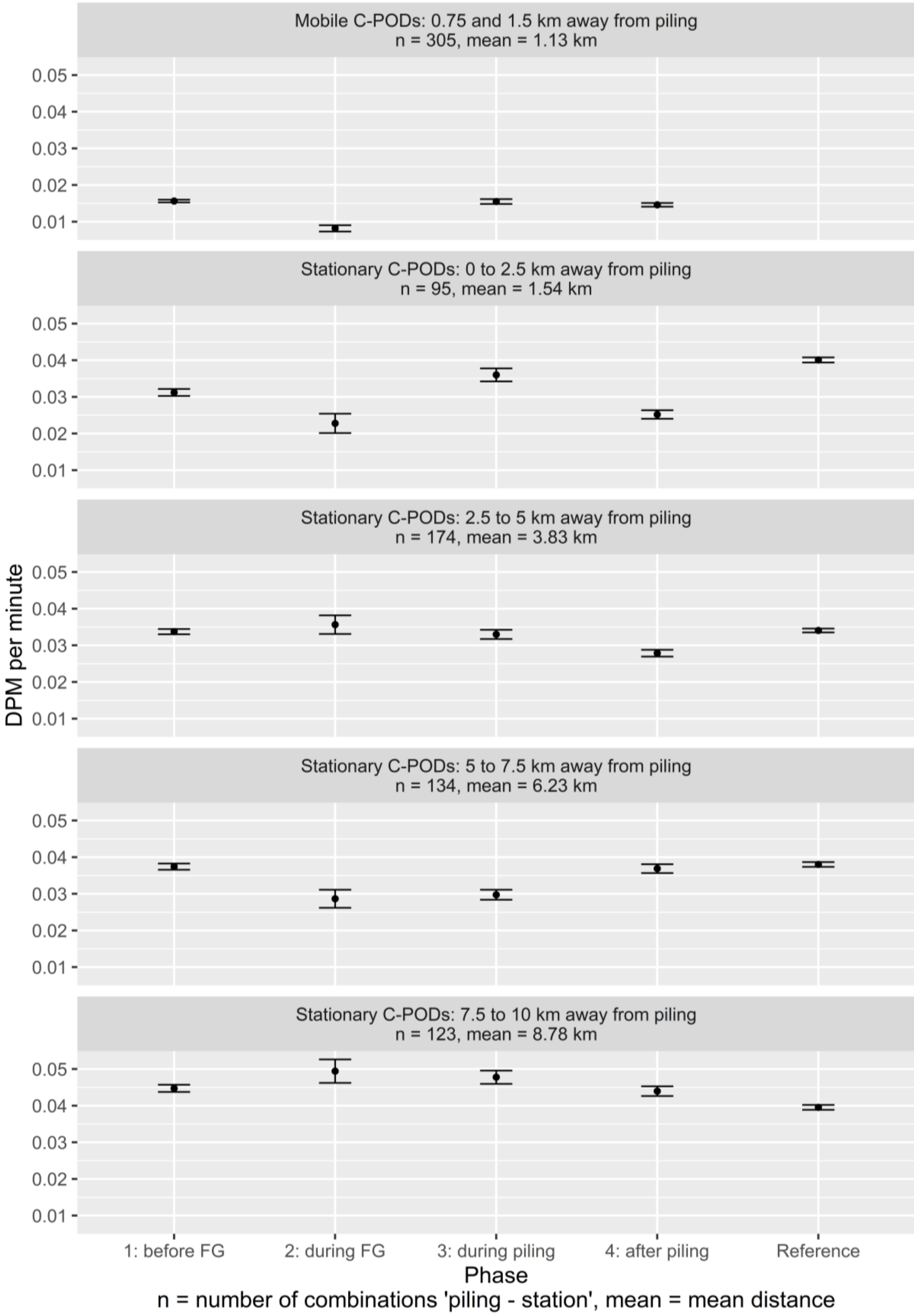


*Figure 4.6 Mobile and stationary C-PODs: DPM per minute (mean and standard error) in the overall dataset during the different phases at five distance classes relative to construction sites (class 0.75 to 1.5 km: mobile PODs; all other classes: stationary PODs).*

## 4.3 How did the detection rates of harbour porpoises change in relation to FaunaGuard duration and distance?

Like the previous question, this topic was investigated by data from mobile C-PODs and C-POD stations. Only distances up to 10 km were considered here due to the reasons mentioned in the previous section.

A Generalised Additive Model (GAM) with covariates (Table A.5) uncovered that within the available range of FaunaGuard operation times ($1^{st}$ to $43^{rd}$ minute; variable *A_min_FaunaGuard*) the detection rates were reduced up to distances of 1.5 to 2.5 km from piling locations (Figure 4.7). The effect range differed slightly with respect to duration, with effect ranges being farther-reaching with ongoing FaunaGuard operation. In 3 to 10 km distance, detection rates were higher than in a close range and within these larger distances stayed on a quite similar level over the whole range of FaunaGuard operation times, providing evidence that FaunaGuard effects were not reaching farther than 3 km from construction sites.

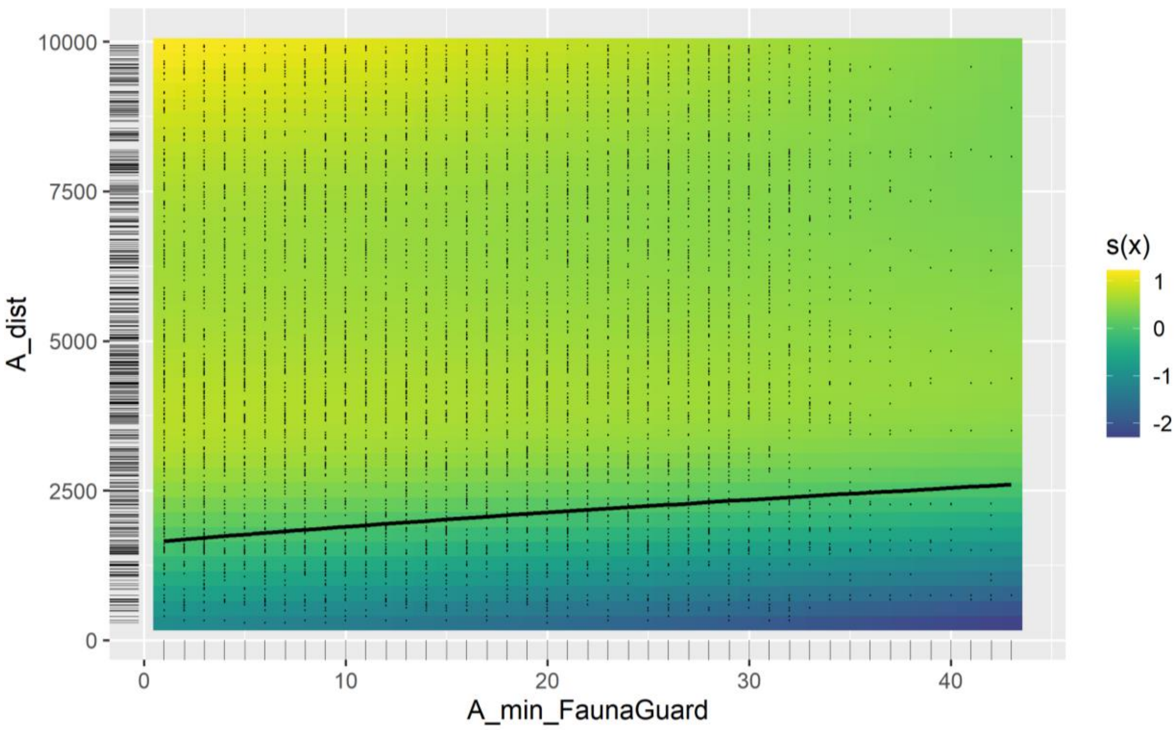


*Figure 4.7 GAM with covariates on the overall dataset from mobile and stationary C-PODs: Effects of distance and the duration of FaunaGuard operation on harbour porpoise detection rate (DPM per minute). The variable "A_dist" is the measured distance to the FaunaGuard; the variable "A_min_FaunaGuard" denotes the minute of FaunaGuard deployment ranging from the start of the FaunaGuard until the start of piling or, if the FaunaGuard was switched off before, until the end of the FaunaGuard, hence an x-value of 1 means the first minute of FaunaGuard operation. The black line is the model zero line showing the minimum effect range. The black dots mark data points.*

In order to gain closer insight into porpoise reactions during FaunaGuard operation, the dataset was split into five distance classes of which the first two (0 to 1.25 km; 1.25 to 2.5 km) were different from the previous chapter's in that they contained mixed data from both POD types.

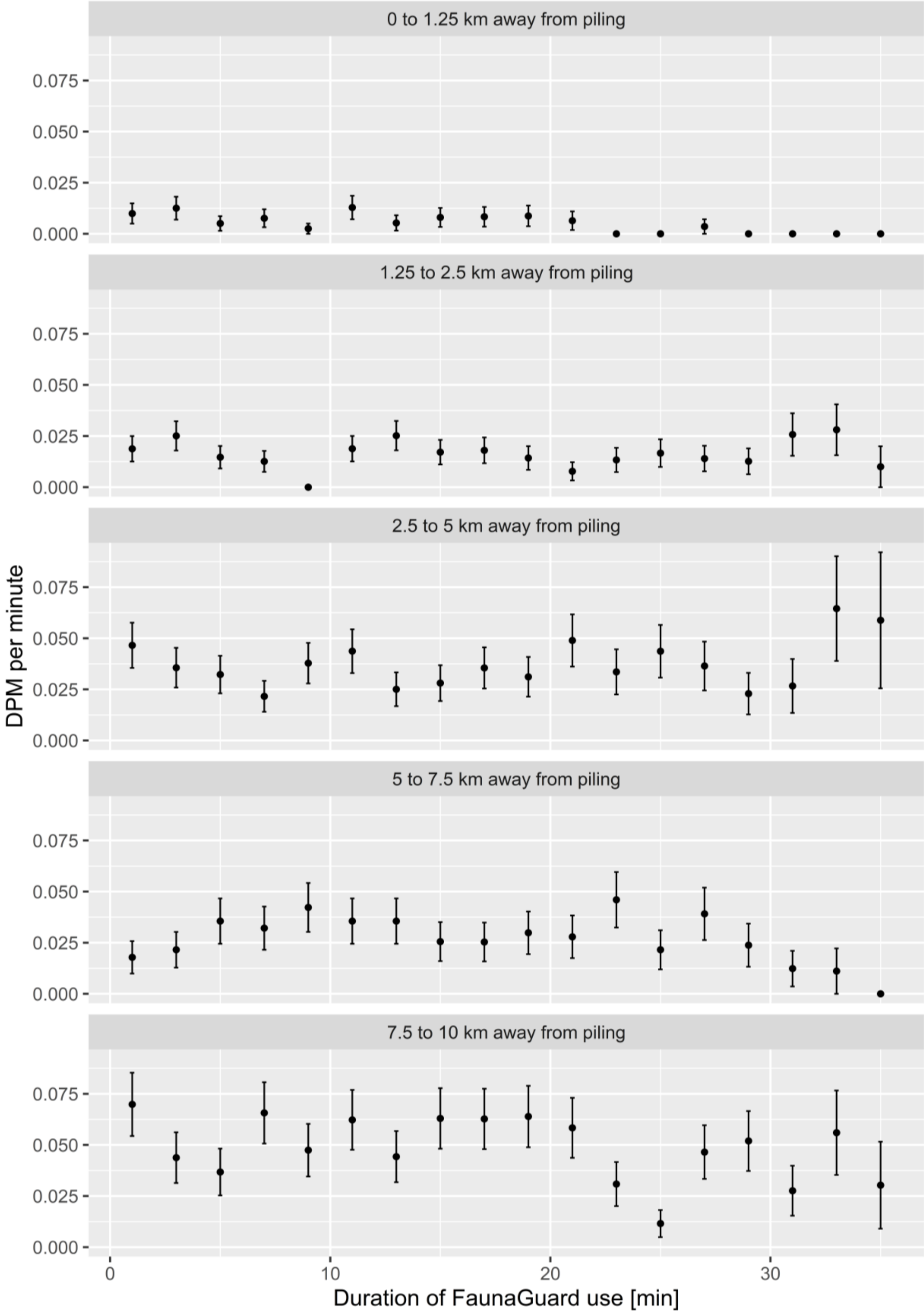


*Figure 4.8* *Overall dataset from mobile and stationary C-PODs: Development of DPM per minute (mean and standard error) with ongoing FaunaGuard operation (shown here for pairs of subsequent minutes of FG operation, e.g. minutes 1-2, 3-4 etc.) at various distance classes (scale of y-axis fixed).*

The raw data for these distance classes were plotted (Figure 4.8), as well as Boosted Regression Tree (BRT) models with covariates being computed and values of the partial dependence function as well as the relative contribution of the considered variables to the respective Boosted Regression Trees being shown (Figure 4.9).

Both, raw data plots (Figure 4.8) and Partial Dependence Plots (PDP; Figure 4.9), show for the closest range (0 to 1.25 km distance) a decline of the detection rate *DPM per minute*, resp. of the modelled marginal effect of the duration of FaunaGuard use (*A_min_FaunaGuard)* on *DPM per minute*, until about minute 22 of FaunaGuard operation, with a detection rate level of close to zero from minute 23 onwards until piling. It is important to note that detection rates at these short distances were – though not at zero – already rather low when the FaunaGuard was switched on. For all other distance classes, detection rates started at higher levels.

In the next distance class (1.25 to 2.5 km) the modelled marginal effect of the duration of FaunaGuard use on *DPM per minute* was rather constant until about minute 24, after which it started to increase.

In 2.5 to 5 km distance there was an apparent contradiction between a stepwise increase of detection rates from minute 33 of FaunaGuard operation until piling (though only few data in the latter time classes) and the decrease from minute 23 onwards in the BRT model. At the same time, a decrease in 5 to 7.5 km distance was observable in the raw data (Figure 4.8). For the latter distance class, there seemed to be a contradiction between constant marginal model effects in the first minutes of FaunaGuard operation and a simultaneous increase of *DPM per minute* in the raw data. Both apparent contradictions were due to the inclusion of covariates in the BRT model. Effects in these distance classes from 2.5 km upwards (also in the next distance class from 7.5 km to 10 km) were probably prone to a higher heterogeneity within those datasets which were based on a few C-POD stations at various positions.

As there was a concern in the previous section about the relatively low values during FaunaGuard operation in 5 to 7.5 km distance (Figure 4.6), it becomes visible here that the detection rates were especially low in the first and last minutes (the latter with only few data), but not during the majority of minutes inbetween (Figure 4.8). As detection rates already started at rather low levels in this distance class, it was probably not the FaunaGuard that caused those low rates.

In overall, not the variable *A_min_FaunaGuard* had the highest explanatory power in the BRT models, but the total number of clicks (*allClx*), the pile ID (*pile*), and *DPM per minute* in the previous minute (*DPMt*; to correct for autocorrelation). The duration of FaunaGuard use (A_min_*FaunaGuard)* was mostly ranked fourth, in one case ranked fifth regarding its relative importance (Figure 4.9).

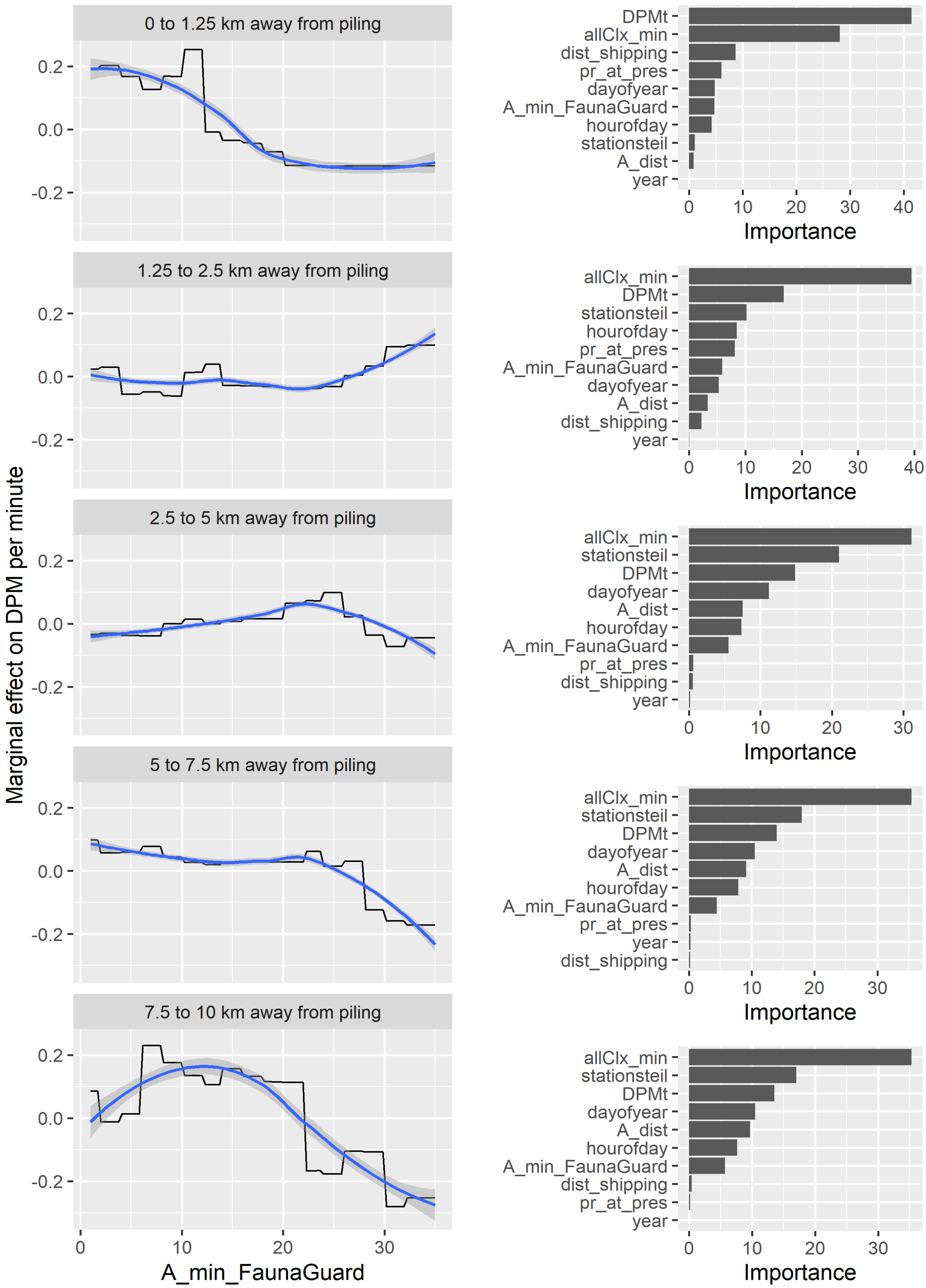


*Figure 4.9* *Left panels: Partial Dependence Plots (PDP) of Boosted Regression Tree (BRT) models with co-variates on the overall dataset from mobile and stationary C-PODs; response variable: DPM per minute with ongoing FaunaGuard operation (2-minute steps) for various distance classes; y-axis: marginal effect of A_min_FaunaGuard on DPM per minute. Right panels: relative contribution of the considered variables to the respective boosted regression trees.*

## 4.4 Did the effects on harbour porpoise detection rates during FaunaGuard operation differ from those during seal scarer operation?

Due to technical problems the FaunaGuard system did not work properly for a few pilings of the OWF *Trianel Windpark Borkum Phase 2*. Along with three of these pilings, a seal scarer instead of a FaunaGuard was used as AHD. This offered the rare chance to directly compare the effects of both AHD systems within the same area under similar conditions. It was looked at stationary C-POD data from 5 to 10 km distance from construction sites, as this was the distance range of interest where possible differences were most relevant.

When using the FaunaGuard as AHD, *DPM per minute* was quite similar for all phases (Phase 1: before AHD; Phase 2: during AHD; Phase 3: during piling; Phase 4: after piling; Phase Reference): However, when using a seal scarer as AHD, *DPM per minute* was considerably lower in Phase 2, i.e. during the operation of the seal scarer, compared to all other phases (Figure 4.10). This indicated that the effects of the seal scarer were farther-reaching than those of the FaunaGuard.

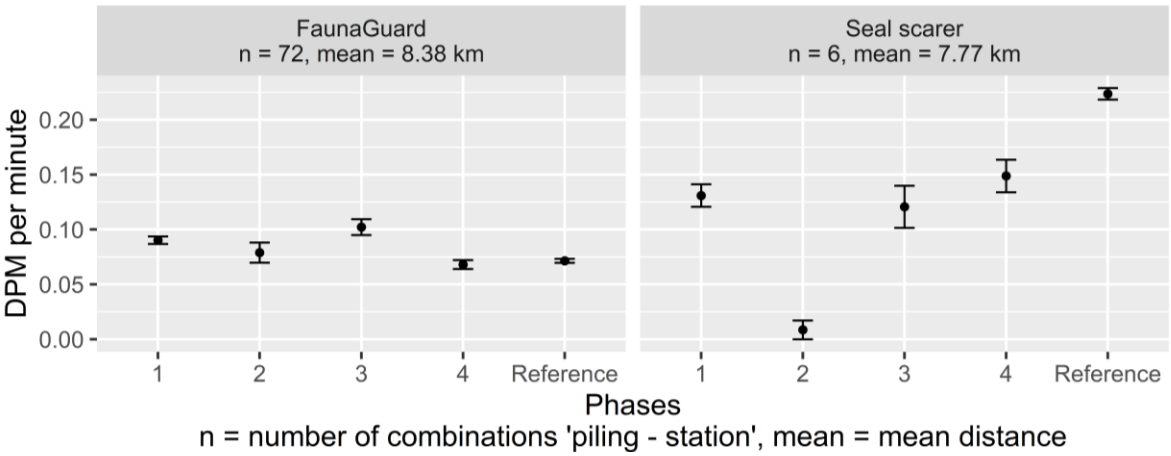


*Figure 4.10 Stationary C-PODs: Comparison of effects during FaunaGuard and seal scarer operation in the wind farm "Trianel Windpark Borkum Phase 2" (DPM per minute in 5 km to 10 km distance from pilings; n: number of analysed POD/pile combinations).*

*Table 4.6 Stationary C-PODs: Data table for comparison of effects during FaunaGuard and seal scarer operation in the wind farm "Trianel Windpark Borkum Phase 2" (DPM per minute in 5 km to 10 km distance from pilings; with N, mean, standard deviation and error).*

| AHD (mean distance) | Phase | *DPM per minute* | | | |
|---|---|---|---|---|---|
| | | N (number of minutes) | Mean | Standard deviation | Standard error |
| **FaunaGuard (8.38 km)** | 1: Before AHD | 7,210 | 0.0903 | 0.2866 | 0.0034 |
| | 2: During AHD | 862 | 0.0789 | 0.2697 | 0.0092 |
| | 3: During piling | 1,741 | 0.1022 | 0.3031 | 0.0073 |
| | 4: After piling | 3,892 | 0.0681 | 0.2519 | 0.0040 |
| | Reference | 21,066 | 0.0714 | 0.2576 | 0.0018 |
| **Seal scarer (7.77 km)** | 1: Before AHD | 1,077 | 0.1309 | 0.3375 | 0.0103 |
| | 2: During AHD | 117 | 0.0085 | 0.0925 | 0.0085 |
| | 3: During piling | 290 | 0.1207 | 0.3263 | 0.0192 |
| | 4: After piling | 578 | 0.1488 | 0.3562 | 0.0148 |
| | Reference | 6,207 | 0.2236 | 0.4167 | 0.0053 |

## 4.5 Comparison with the Gescha studies: Were the combined effects of FaunaGuard/piling different from those of seal scarer/piling?

Data from stationary C-PODs were explored to answer this question. The detection rate *DPH per hour* (named *DPH* or *DPH/h* in the Gescha reports) was analysed here instead of *DPM per minute*, in order to keep results comparable to those of the Gescha reports (Gescha 1: (BioConsult SH et al. 2016a); Gescha 2: BioConsult SH et al. 2019).

*DPH per hour* was highest during the phases Baseline (48 to 24 hours before the deployment of the FaunaGuard) and Reference after piling (hours +49 to +120 after piling) and lowest during the phase Piling (at least one minute of FaunaGuard or piling). The phase Pre-piling (back to 3 hours before the deployment of the FaunaGuard) is comparable to the phase "Traffic" in the Gescha 2 report and thus includes considerable human pre-piling activities; *DPH per hour* of this phase showed a strong decline relative to the phase Baseline (Figure 4.11).

*Table 4.7 Stationary C-PODs at FaunaGuard OWFs: DPH per hour (N, mean, standard deviation [sd] and error [se], 95 % confidence interval [ci]) in the overall dataset in up to 10 km distance from piling locations (mean: 4.9 km) during the four phases available for the hourly dataset; phase of interest in red; results are visualised in Figure 4.11.*

| Phase | Definition | *DPH per hour* | | | | |
|---|---|---|---|---|---|---|
| | | N (hours) | Mean | sd | se | ci |
| **Baseline** | 48 to 24 daytime hours before first FaunaGuard/piling hour 0 | 3,027 | 0.50 | 0.50 | 0.009 | 0.018 |
| **Pre-piling** | 3 to 1 daytime hours before first FaunaGuard/piling hour 0 | 427 | 0.43 | 0.50 | 0.240 | 0.048 |
| **Piling** | Daytime hours with at least 1 minute of FaunaGuard and/or piling (= hour[s] 0) | 2,180 | 0.38 | 0.49 | 0.010 | 0.020 |
| **Reference after piling** | 49 to 120 daytime hours after last Piling hour 0 | 6,351 | 0.48 | 0.50 | 0.006 | 0.012 |

*Table 4.8 Stationary C-PODs at Gescha 1 and 2 OWFs (data taken from BioConsult SH et al. 2019): DPH per hour (N, mean, standard deviation [sd] and error [se], 95 % confidence interval [ci]) in up to 10 km distance over the four phases shown above; phase of interest in red; results are visualised in Figure 4.12.*

| Project | Phase | N (hours) | Mean | sd | se | ci |
|---|---|---|---|---|---|---|
| **Gescha 1** | **Baseline** | 13,703 | 0.46 | 0.50 | 0.004 | 0.008 |
| | **Pre-piling** ("Traffic") | 1,542 | 0.40 | 0.49 | 0.012 | 0.024 |
| | **Piling** (and/or seal scarer) | 8,043 | 0.29 | 0.45 | 0.005 | 0.010 |
| | **Reference after piling** | 23,389 | 0.50 | 0.50 | 0.003 | 0.006 |
| **Gescha 2** | **Baseline** | 4,864 | 0.54 | 0.50 | 0.007 | 0.014 |
| | **Pre-piling** ("Traffic") | 714 | 0.41 | 0.49 | 0.018 | 0.036 |
| | **Piling** (and/or seal scarer) | 5,052 | 0.32 | 0.47 | 0.007 | 0.013 |
| | **Reference after piling** | 8,732 | 0.51 | 0.50 | 0.005 | 0.010 |

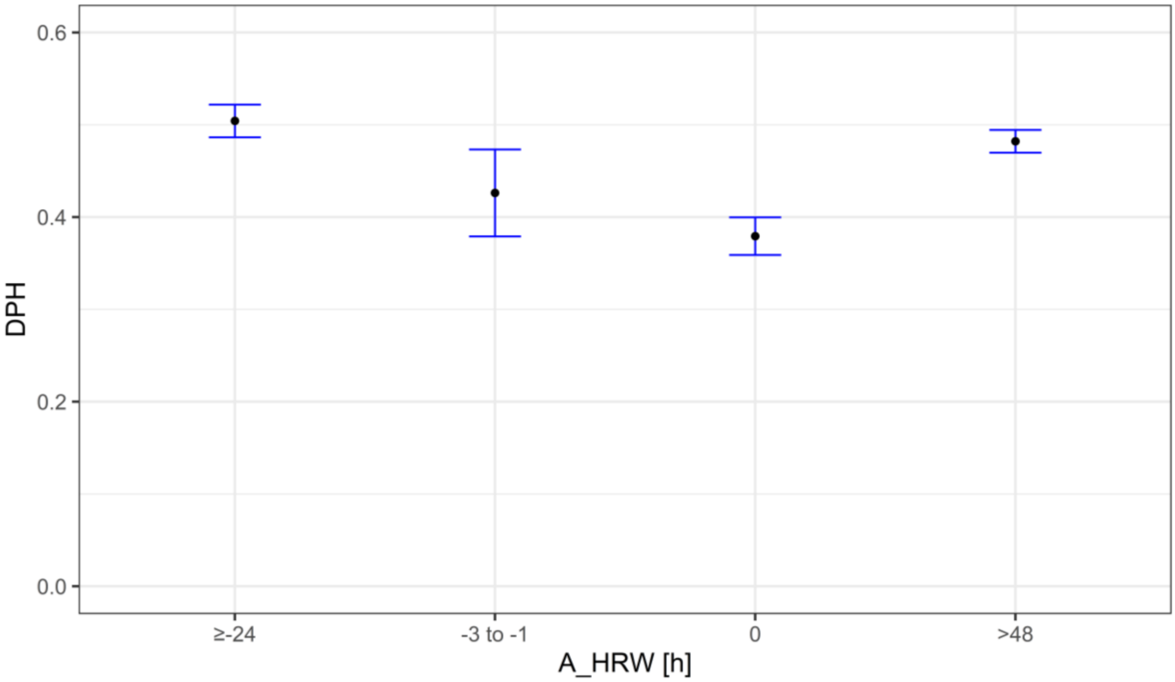


*Figure 4.11 Stationary C-PODs at FaunaGuard OWFs: DPH per hour (mean and 95 % confidence intervals) in the overall dataset in up to 10 km distance from piling locations (mean: 4.9 km) during the four phases available for the hourly dataset (e.g. phase "Piling" denotes full daytime hours with at least one minute of piling and/or FaunaGuard operation); A_HRW: hours relative to piling/FaunaGuard hours (=0); see Table 4.7 for used data.*

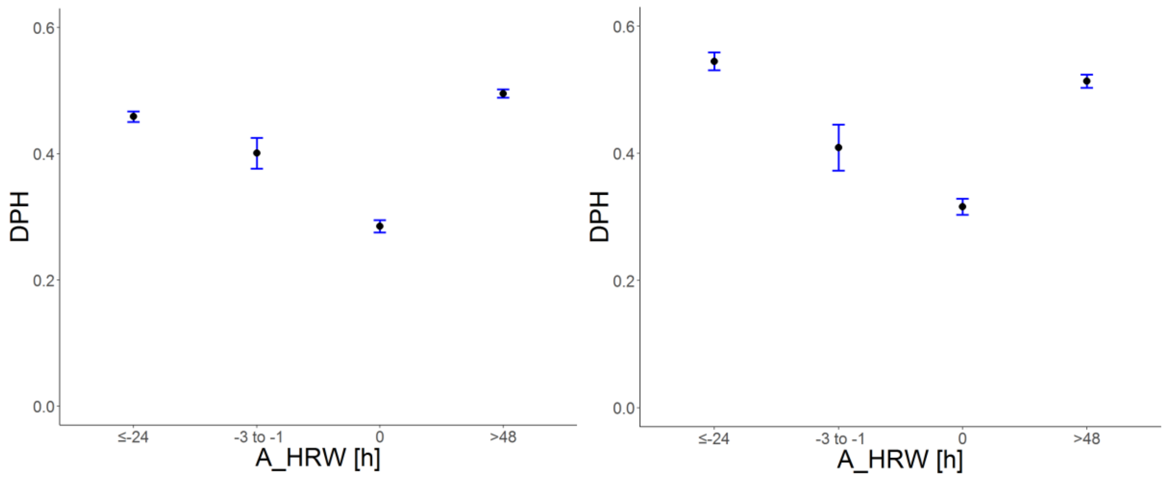


*Figure 4.12 Stationary C-PODs at the OWFs analysed for the projects Gescha 1 (left; OWFs built between 2010 and 2013; AHD: seal scarer) and Gescha 2 (right; OWFs built between 2014 and 2016; AHD: seal scarer): mean of DPH per hour (with 95 % confidence intervals) from stationary C-PODs in up to 10 km distance; four phases from left to right: Baseline, Pre-piling (in Gescha reports: Traffic), Piling (and seal scarer), Reference after piling (plots taken from BIOCONSULT SH et al. 2019). Hourly definitions of phases are given in Table 4.7 (Phase Piling: seal scarer instead of FaunaGuard).*

The overall picture is very similar to what was found during Gescha 1 and 2 (Figure 4.11, Figure 4.12). However, the decline from Baseline over Pre-piling to Piling is slightly less steep for the

FaunaGuard OWFs with a detection rate mean of 0.38 *DPH per hour* during FaunaGuard/piling (Table 4.7), compared to 0.29 resp. 0.32 during seal scarer/piling for Gescha 1 and 2 (Table 4.8).

Regarding the Bayesian proportion tests at FaunaGuard OWFs, not only the overall test on differences among all phases was significant, but also each pairwise comparison of phases showed a significant difference (Table 4.9, Figure 4.13). Unexpectedly, this was also true for a comparison of "Baseline" with "Reference after piling", but since the absolute effect difference was rather small here (0.50 vs 0.48) the significance was partly attributable to the high *N* being available for this pairwise comparison, causing the strongest discriminative power of all pairwise comparisons.

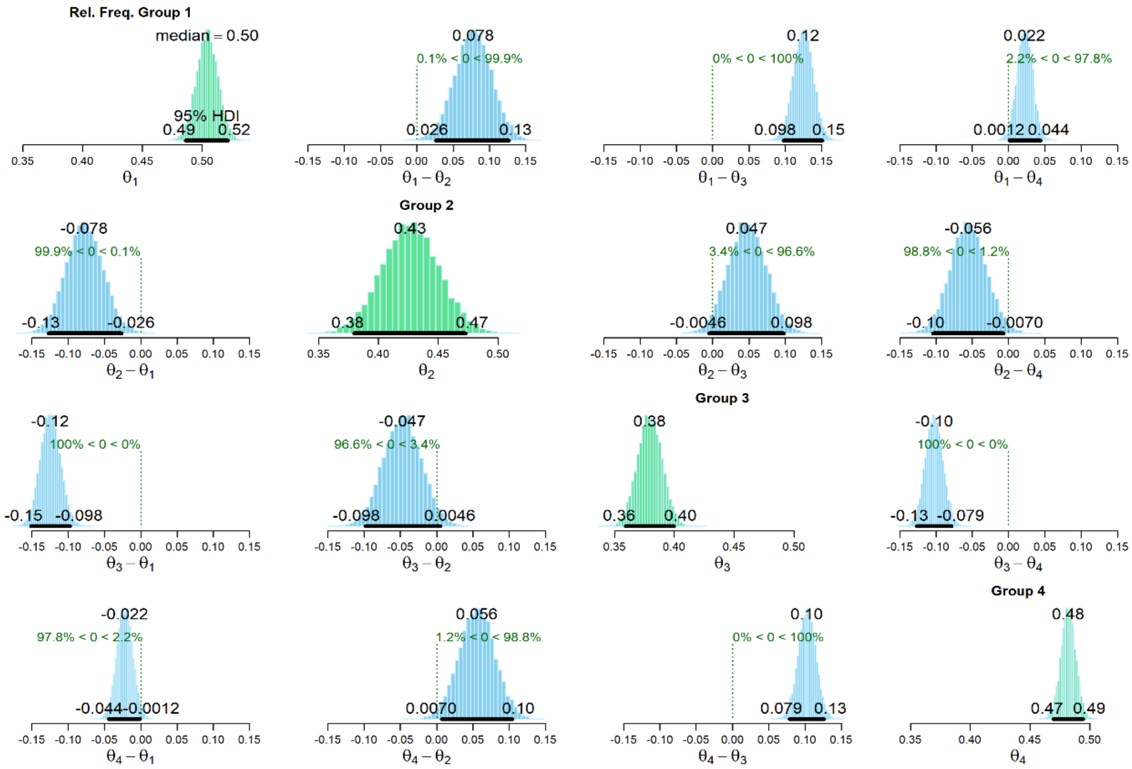


*Figure 4.13 Plots of pairwise Bayesian proportion tests on DPH per hour for the overall dataset from stationary C-PODs in up to 10 km distance from piling locations (mean: 4.9 km) during the four phases available for the hourly dataset; groups in sequence of Table 4.7. Further explanations are given in Figure 4.3; for test results see Table 4.9.*

*Table 4.9 Results of the overall and pairwise Bayesian proportion tests on DPH per hour for the overall dataset from stationary C-PODs in up to 10 km distance from piling locations (mean: 4.9 km) during the four phases available for the hourly dataset; visualisation in Figure 4.13.*

| Distance class (with mean) | Comparison | | Probability of equality | Significance |
|---|---|---|---|---|
| **0-10 (4.9) km** | 4-sample test for equality of proportions without continuity correction | | X-squared = 93.07; df = 3 *p*-value < 2.2e-16* | |
| | Baseline | Pre-piling | 0.1 % | * |
| | Baseline | Piling | 0 % | * |
| | Baseline | Reference after piling | 2.2 % | * |
| | Pre-piling | Piling | 3.4 % | * |
| | Pre-piling | Reference after piling | 1.2 % | * |
| | Piling | Reference after piling | 0 % | * |

# 5 DISCUSSION

Harbour porpoises are the most common cetaceans in the continental shelf waters of north-western Europe (REID et al. 2003). An estimated 350,000 to 370,000 animals live in the North Sea and adjacent waters (HAMMOND et al. 2013, 2017). Particularly the German Bight, where all offshore wind farms considered in this study are located, is known to be a region of relatively high porpoise density (GILLES et al. 2009; PESCHKO et al. 2016). The population appears to be stable although a high degree of year-to-year variability occurs and trends tend to vary among different subareas of the German Bight (BIOCONSULT SH et al. 2019).

In Europe, the harbour porpoise is classified as "vulnerable" species, as it showed a declining population trend at the time of assessment (SPECIES ACCOUNT BY IUCN SSC CETACEAN SPECIALIST GROUP; REGIONAL ASSESSMENT BY EUROPEAN MAMMAL ASSESSMENT TEAM 2007). Threats for this species include chemical contamination (JOIRIS et al. 1991; KAKUSCHKE & PRANGE 2007; WEIJS et al. 2010; MAHFOUZ et al. 2014), gillnet fishery leading to by-catch (VINTHER & LARSEN 2004; HERR et al. 2009; BJØRGE et al. 2013; KOCK & BENKE 1996), predation by grey seals (JAUNIAUX et al. 2014; VAN BLEIJSWIJK et al. 2014; LEOPOLD et al. 2015; STRINGELL et al. 2015; PODT & IJSSELDIJK 2017), as well as noise pollution (PIROTTA et al. 2014; DYNDO et al. 2015; CULLOCH et al. 2016; WISNIEWSKA et al. 2018; BIOCONSULT SH et al. 2019).

Noise in general can affect the individual fitness and structure of ecological communities (SHANNON et al. 2016). The precise response of marine mammals to noise depends on three components: The source, the path and the receiver (ERBE et al. 2016). For the source, in this case the noise during the construction of the offshore wind farms, factors such as the piling source level, frequency, duration and sequence are crucial. Whether piling noise is more likely to be absorbed or reflected depends on the path and related environmental factors such as sediment, bathymetry, temperature, salinity and pressure (FARCAS et al. 2016). For harbour porpoises as noise receivers, factors such as hearing, frequency, distance to the source, previous exposure, demographics, and food availability are decisive for the behavioural response (ERBE et al. 2016). In consequence, each harbour porpoise shows an individual response pattern with respect to noise originating from construction activities for offshore wind farms.

In general, harbour porpoises move away from loud construction activities for offshore wind farms (JOHNSTON 2002; OLESIUK et al. 2002; BRANDT et al. 2013b). Apart from the influence on behaviour, pile driving can emit such source levels that harbour porpoises may suffer from temporary hearing-threshold shifts (TTS), permanent hearing-threshold shifts (PTS), or even death if being present in close vicinity of the sound source (KASTELEIN et al. 2011).

In order to minimize the effects of noise emissions during piling, the German Federal Maritime and Hydrographic Agency (BSH) set a dual noise mitigation value: The $SEL_{05}$ must remain below 160 dB re 1 µPa² s, the $L_{Peak}$ below 190 dB re 1 µPa at a distance of 750 m from piling locations. Due to the ongoing development of noise abatement systems (NAS), many construction projects now comply with these limits.

Additional to noise reduction, the BSH demands a standardised deterrence procedure before the start of pile driving, in order to scare all harbour porpoises away from the area where the animals could suffer TTS or PTS. Using a seal scarer as acoustic harassment device (AHD) desirably reduced the sighting rates of harbour porpoises within 1 km distance of this device to only 1 %. However, C-

POD recordings also showed a significant deterrence effect on harbour porpoises up to a distance of 7.5 km, which is much larger than intended (BRANDT et al. 2013a; b).

Due to this adverse property of the seal scarer, *Van Oord* and the Dutch company *SEAMARCO (Sea Mammal Research Company)* developed the *FaunaGuard Porpoise* module (VAN DER MEIJ et al. 2015). This AHD on the one hand aims at deterring all harbour porpoises from a short range of about 1 km around construction sites before the start of noise-intensive piling, whereas on the other hand the effect should not to be as far-reaching as that of the seal scarer. Our cross-project study examined whether both targets were achieved.

**Short-range effects**

In order to avoid TTS or PTS during pile driving, all harbour porpoises should be deterred to an area where the noise levels fall below 160 dB SEL, which is at a distance of 750 m if the German noise threshold criteria are met. Regarding our data from mobile C-PODs, the detection rates of harbour porpoises indeed significantly decreased by 48 % during the deployment of a FaunaGuard in distances up to of 1.5 km, compared to the preceding six hours (Table 4.1). Thus, during the operation of a FaunaGuard as AHD the detection rates seemed to have halved. When using a seal scarer as AHD in the Gescha 2 study, the detection rates decreased by only 36 % (BIOCONSULT SH et al. 2019). Therefore, in up to 1.5 km distance the FaunaGuard probably led to a slightly stronger decrease in detection rates than the seal scarer.

Generally, individuals react to noise in different ways, depending on e. g. habitat conditions (VAN BEEST et al. 2018). For instance, areas with good food supply are less likely to be abandoned in case of noise. On the contrary, areas with low food supply are more likely to be left in case of disturbance, resulting in a greater effect of noise on detection rates. It also takes a longer time for animals to return to less attractive areas after noise exposure. Even though the studied OWFs were positioned in unequally attractive areas for harbour porpoises, the detection rates in all wind farms significantly decreased by 37 % to 75 % during the deployment of a FaunaGuard in up to of 1.5 km distance, compared to the six hours before FaunaGuard operation. During the three hours after piling the detection rates increased again to 84-93 % of the level during the six hours before the deployment of the FaunaGuard. Hence, the FaunaGuard as AHD seemed to lead to a significant short-term decrease in detection rates at shorter distances, irrespective of the wind farm.

However, the percentage decrease of detection rates by the FaunaGuard as AHD relative to a true reference would probably have been higher, because for the mobile C-POD data the six hours prior to AHD operation were considered as a kind of baseline, and the decrease during the operation of the AHD was compared to this period. However, during the few hours preceding the operation of the AHD, vessel traffic for preparing the NAS and the upcoming pile driving already increases. Hence, the phase "Before FaunaGuard" could not be considered a true undisturbed reference, as the presence of marine mammals and especially harbour porpoises might have been reduced by construction-related vessel traffic (CULLOCH et al. 2016; NEHLS et al. 2016). The animals either react directly to this type of noise, or associate it with subsequent piling noise in which case animals would be conditioned (DIEDERICHS et al. 2010; HERMANNSEN et al. 2014; DYNDO et al. 2015; OAKLEY et al. 2017; WISNIEWSKA et al. 2018). Harbour porpoises may respond to vessel noise by altered diving and echolocation behaviour as well as by displacement (WISNIEWSKA et al. 2018). That the phase "Before FaunaGuard" of the mobile C-POD data was not a true baseline was also supported by the results of the stationary C-PODs in up to 2.5 km distance from pile-driving sites: In the six hours before using the FaunaGuard, data from stationary C-PODs showed that the detection rate was already reduced by 22% compared to a true reference phase more than one day from piling times. During the operation of the FaunaGuard the detection rate decreased by a further 27 % (relative to six hours before using the FaunaGuard).

The FaunaGuard system produces sounds of increasing noise levels during the first five minutes of operation, in order to gradually deter porpoises from piling locations (VAN DER MEIJ et al. 2015). Accordingly, a Boosted Regression Tree model showed that porpoise detections were more likely to occur at the beginning of AHD operation in up to 1.25 km distance when the full volume was not yet reached. Furthermore, the model provided evidence that it would be sufficient for the FaunaGuard to be switched on for about 20-25 minutes, as after this time nearly no detections were observed anymore within this radius. In the next distance class (1.25 to 2.5 km) the modelled marginal effect of the duration of FaunaGuard use on *DPM per minute* was rather constant until about minute 24, after which it started to increase. The increase in this distance class might have been related to the decrease in 0 to 1.25 km distance (Figure 4.9). Data of these two distance classes mostly stem from the mobile PODs in 0.75 km and 1.5 km distance with few data inbetween, which might explain the time lag between the decrease and increase (porpoises have to swim for some minutes to cover a distance of 750 m). A Generalised Additive Model supplemented these results by the fact that animals were probably deterred farther away over ongoing FaunaGuard operation. However, no long-term deterrence occurred in the close range as the detection rates about six hours before FaunaGuard operation were only about 7 % higher than those three hours after piling (data of mobile C-PODs).

However, it remained unsure whether the decrease in detection rates during the operation of a FaunaGuard was due to true displacement of harbour porpoises or partly due to a reduction of echolocation activities. In an experiment, one harbour porpoise in a pool was observed to swim away from the FaunaGuard's location during its deployment (KASTELEIN et al. 2017). However, this result may not have been representative because (1) only one individual was studied when individuals might react differently to this kind of noise (KASTELEIN et al. 2000, 2001, 2008), and (2) the behavioural response to noise also depends on habitat conditions (VAN BEEST et al. 2018), which could not be studied in the pool. In contrast, in a field study on visual observations and acoustic monitoring in the tidal inlet between Den Helder and Texel, almost all harbour porpoises seemed to be deterred to a distance of at least 1000 m during the deployment of a FaunaGuard (GEELHOED et al. 2017). However, some harbour porpoises dove considerably longer during FaunaGuard operation and were therefore not seen again. Consequently, no evidence was given by that study that those animals had actually left the area. Whether or not harbour porpoises left the piling areas of the here investigated four OWFs during the deployment of the FaunaGuard, was not further examined in our study. Yet, for the seal scarer as AHD, it has already been shown that fewer detections were not caused by reduced echolocation, but by a true displacement of animals (BRANDT et al. 2013b; HAELTERS et al. 2015; BIOCONSULT SH et al. 2016a). Ultimate evidence for true displacement is still missing for the FaunaGuard as AHD but there is no reason to assume that the animals react differently to FaunaGuard signals than to seal scarer signals. If it will be provided by future experimental studies, this would be the final prove that the FaunaGuard system is a highly effective measure to deter harbour porpoises from the vicinity of pile-driving sites.

The short-range effects of the FaunaGuard may be summarised as follows: (1) The acoustic activity decreased to lowest levels of all phases when using a FaunaGuard as AHD – this being true for four OWFs with different habitat characteristics. (2) When compared with the seal scarer as AHD, the FaunaGuard showed an even slightly stronger effect on porpoise detection rates in the vicinity of up to 1.5 km distance to the construction sites (Table 4.1, Table 4.2, Figure 4.2). (3) The FaunaGuard seemed to reduce detection rates of harbour porpoises in a short range to a greater extent than piling (with applied NAS) itself. (5) FaunaGuard operation led to a significant decrease in detection rates up to a distance of 2.5 km around construction sites, the effect becoming slightly more far-reaching with longer ongoing operation. (6) As after 20-25 minutes nearly no detections were observed anymore in up to 1.25 km distance, it would be sufficient for the FaunaGuard to be switched on for only that timespan. (7) No long-term deterrence was shown but the variation of sound signals makes a habituation effect unlikely.

Harbour porpoises seem to avoid the proximity (< 1.500 m) of construction sites around piling hours due to multiple reasons: work-associated traffic, AHD operation and piling. But even though detection rates had already declined in the hours before the FaunaGuard was switched on, the rates further decreased in the close range around construction sites during FaunaGuard operation, stressing its separate effect. Being even stronger than the piling effect, the close-range effect of the FaunaGuard system shown in this study and the seal scarer shown by Gescha 2 (BioConsult SH et al. 2019) led to greatly decreased detection rates in the vicinity of piling locations. Both systems deterred animals effectively from the close range and most probably prevented animals from any injury by the high noise levels of pile driving successfully. Interestingly, the sound emissions from noise-reduced pile driving seem to be perceived as less disturbing by the animals, as the detection rates in the close range increased again significantly during pile driving after having dropped to near zero during FaunaGuard operation.

**Long-range effects**

The *FaunaGuard Porpoise* module was developed with the intention to avoid large-scale disturbances as produced by the seal scarer, an AHD which was used as deterrence measure before pile driving so far. The seal scarer caused a displacement of harbour porpoises in up to 7.5 km distance (Brandt et al. 2013b), and it was critically discussed if the temporary habitat loss due to seal scarer operation was even greater than that caused by noise-mitigated piling itself. One major question of the study was whether the FaunaGuard system was successful in reaching this goal.

In fact, a Generalised Additive Model on the overall dataset from stationary C-PODs shows that the modelled detection rate *DPM per minute* was only reduced up to a distance of about 2.5 km during FaunaGuard operation. This is a strong indication that effects of the FaunaGuard are not as far-reaching as those of the seal scarer. The modeling result that harbour porpoises were not particularly sensitive to the FaunaGuard above distances of 2.5 km may be due to the fact that high-frequency noise, such as the sound of a FaunaGuard, is absorbed more rapidly in the water column and is therefore less audible at greater distances (Rosemeyer et al. 2021). In contrast, lower-frequency noise like vessel traffic, seal scarer signals or pile driving is absorbed to a lesser extent and therefore transmitted over larger distances.

Also the analysis of *DPM per minute* from the raw data of the stationary C-PODs shows that in the first distance class of the mobile C-PODs (0 to 1.5 km) as well as of the stationary C-PODs (0 to

2.5 km) the detection rates were lowest during FaunaGuard operation when compared to all other investigated phases. In contrast, no such effect was found in the next distance class of 2.5 to 5 km, this being an indication that the effect was not farther-reaching. However, rates were lower again during FaunaGuard operation at a distance of 5 to 7.5 km from pile-driving sites, compared to the other phases, though the overall *DPM per minute* level of all phases was higher here than in the lower distance classes. The result is unexpected, as in the next-lower distance class no effect could be proven (as in all larger classes) and it can be assumed (supported by ROSEMEYER et al. 2021) that the FaunaGuard can no longer be heard by the animals at this distance. We explain this result by a higher heterogeneity since analyses were based on only a few C-POD stations at various regions, compared to the many mobile PODs analysed for the distances below 2.5 km. In addition, it turned out from the raw data that in 5 to 7.5 km distance the detection rates were especially low in the very first and last minutes of FaunaGuard operation (the latter minutes with only few data), but not during the majority of minutes inbetween (Figure 4.8). Since detection rates already started at rather low levels in 5 to 7.5 km distance and even increased during the first minutes of FaunaGuard operation, and as the FaunaGuard is unlikely to be audible anymore in these larger distances (ROSEMEYER et al. 2021), it was probably not the FaunaGuard but other processes and/or data issues that caused the lowered rates in this distance class.

When pooling all data from distances between 0.5 and 10 km, harbour porpoises seemed to respond less strongly to pile driving with a FaunaGuard as AHD mitigation tool when compared to piling with a seal scarer (combined AHD and piling effects in both cases). When comparing our results to both Gescha studies, DPH rates were similar in all studies during the reference phases before and after pile driving as well as during the three hours before pile driving (BIOCONSULT SH et al. 2016b, 2019), meaning that the base level of detection rates and the effects of pre-piling activities were similar in all three studies. However, the *DPH per hour* rates during FaunaGuard/piling were considerably higher than those for seal scarer/piling. In this distance class, the reduction relative to the reference was only about half as strong with a FaunaGuard than with a seal scarer. Possible causes for the difference are: 1) improved noise abatement systems (NAS); 2) habitat and individual-response differences; 3) the used acoustic harassment device (AHD). These are discussed in further detail.

Re 1: The main difference between the Gescha 1 and the Gescha 2 study was the improvement of the noise abatement systems. But even though noise abatement systems were able to reduce the emitted sound levels by about 9 dB ($SEL_{05}$) on average in 750 m distance, *DPH per hour* rates in up to 10 km distance were not different during the operation of a seal scarer and the subsequent pile-driving phase (Figure 4.12). Hence, in the Gescha 2 report it was discussed that harbour porpoises may have reacted more strongly to the seal scarer noise than to the actual (mitigated) pile-driving noise (BIOCONSULT SH et al. 2019). Since the noise abatement systems used in the projects for the present report have not changed since the Gescha 2 study and sound levels reached similar values, it can be assumed that there is no difference in the sound emission by the pile-driving process between this study and the Gescha 2 study. Therefore, the difference cannot be explained by a change in the noise reduction systems.

Re 2: Although factors such as previous exposure, age and food availability may also be important for the behavioural response of individual animals (JOHNSTON 2002; OLESIUK et al. 2002; BRANDT et al. 2013b; VAN BEEST et al. 2018), the differences in detection rates during AHD operation and subsequent piling are most likely not explainable by such factors alone. We have not checked in particular differences in specific habitat characteristics between the project areas of the present study and the project areas of the Gescha studies. But since different habitat variables were included into the models and all studies made cross-project analyses where different habitats and many individuals were considered, leading to an averaging of conditions, individual responses and effects, differences between the studies cannot be explained by habitat and individual-response differences alone.

Re 3: The main difference between this study and the two Gescha studies is the different type of acoustic harassment device being used before pile driving started (this study: FaunaGuard versus Gescha studies: seal scarer). Since piling and mitigation procedures otherwise remained similar, the seal scarer seems to have substantially contributed to the much more far-reaching effects of AHD/piling being found in the Gescha 2 study (BIOCONSULT SH et al. 2019) when compared to the findings of this study where a FaunaGuard was used as AHD before piling.

Furthermore, the present dataset offers a very good opportunity for a direct comparison of long-range effects on harbour porpoises of the FaunaGuard with those of the seal scarer. At the OWF *Trianel Windpark Borkum Phase 2*, the FaunaGuard was not working during pilings for a few foundations, so that a seal scarer had to be used instead. Using both AHDs in the same wind farm provided the chance to directly compare the effects of the FaunaGuard and the seal scarer under similar conditions. It turned out that in 5-10 km distance (mean of available distances: ~ 8 km) the seal scarer led to a much stronger response by harbour porpoises than the FaunaGuard. The detection rates during the FaunaGuard decreased by only 12 % compared to the detection rates in the six hours before, but by 94 % when using a seal scarer. Although especially the seal scarer sample was only small, data were collected in the same wind farm and thus under similar initial conditions. Even though the seal scarer was only used in summer and the FaunaGuard was used until December, harbour porpoise densities in summer and autumn are generally rather similar in this area (GILLES et al. 2011). This provided further evidence regarding our former findings that the FaunaGuard leads to a significant decrease in detection rates only up to a distance of 2.5 km, whereas a far-reaching deterrence, as observed for the seal scarer here and in other studies on the subject (BRANDT et al. 2013a; b), is unlikely.

In summary, during operation of a FaunaGuard the detection rates were only reduced up to a distance of about 2.5 km. No far-reaching disturbance was detected in any of the wind farms positioned in different regions of the German Bight, North Sea. As expected, the FaunaGuard seemed to lead to a much more localised disturbance, this being in clear contrast to the long-range effects of the seal scarer. These results are in accordance to the results of the *itap GmbH*: As shown in the first part of this report, the FaunaGuard generates sound in a high-frequency range while at the same time the sound propagation in water is significantly more attenuated in this frequency range than at lower frequencies (such as produced by pile driving or by the seal scarer) (ROSEMEYER et al. 2021). Therefore, the sound signals of a FaunaGuard are absorbed more substantially with increasing distance than those of a seal scarer, rendering the audibility of FaunaGuard sounds for harbour porpoises much more unlikely in larger distances, while masking by background noise further reduces the distance range of perceptibility.

## Conclusions

The *FaunaGuard Porpoise* module aims at deterring all harbour porpoises from a radius of 1 km around OWF construction sites before the start of pile driving, but was intended not to lead to far-reaching deterrence as caused by a seal scarer. This cross-project study examined whether these targets were met and the FaunaGuard system was suitable as an effective acoustic deterrent measure without strong adverse effects. The study produced the following results:

1. The FaunaGuard as AHD reduces detection rates in a short range of up to 1.5 km distance slightly more effective than the seal scarer, without leading to long-term deterrence. Therefore, the FaunaGuard was shown to be a highly effective AHD for decreasing detection rates of harbour porpoises in the vicinity of pile driving. Hence, the FaunaGuard met the original demand to scare porpoises safely out of a danger zone of at least 750 m around the piling location.

2. After the first 20-25 minutes of FaunaGuard operation, the detection rates had nearly declined to zero in the close range of up to 1.25 km distance, so it is recommended that the device should operate for around 25 minutes. As longer operation times lead to a moderate extension of the effect range, an upper limit of 30 minutes should not be exceeded.

3. Longer operation times lead to a moderate extension of the effect range.

4. During the operation of a FaunaGuard reduced detection rates were observed only in up to 2.5 km distance, so that in contrast to the seal scarer obviously no far-reaching deterrence occurred. For the latter device we could show a clear effect in about 8 km distance.

5. Probably due to the shorter effect range of the FaunaGuard, the combined effects of FaunaGuard/piling on harbour porpoises were not as strong as the combined effects of seal scarer/piling (Gescha 1 and 2).

As noise abatement systems became more and more elaborated over recent years, pile-driving noise levels in 750 m distance were reduced accordingly and nowadays mostly meet the dual noise protection criterion of the BSH (BSH 2013). On the other hand, improved noise abatement technology causes increased vessel traffic a few hours before pile driving, and also over-effective deterrence became an issue in recent years. Therefore, a trade-off will have to be made in future regarding the most effective strategy to protect harbour porpoises from noise, such that the weakest link in the sequence of construction-related noise has to be identified. Whereas the role of vessel noise is still under discussion, the seal scarer might well have been the weakest link in the recent past. Hence, the FaunaGuard will improve the situation for harbour porpoises considerably.

All results from the present study clearly indicate that regarding the upcoming construction of offshore wind farms, the FaunaGuard should be used instead of the seal scarer, assuming there is no habituation effect. Detailed recommendations for action are presented in Part 3 of the FaunaGuard study (DIEDERICHS & BELLMANN 2021). Although this study only covers projects in the North Sea, we suppose that the FaunaGuard will also work in the Baltic Sea. Due to lower salinity (ROSEMEYER et al. 2021) the FaunaGuard signals would be slightly more far-reaching in that area, probably resulting in a slightly extended range of audibility.

Acoustic porpoise deterrent and harassment devices (APDs and AHDs) especially designed to scare porpoises like the here tested *FaunaGuard Porpoise* module are an important step forward to a less harmful piling procedure in the North and Baltic Seas. With this module or similar devices, a suitable mitigation tool has been developed to approach this goal. Monitoring results from future projects should be further analysed to get insight in multivariate factors influencing behaviour of harbour porpoise in the vicinity of construction sites.

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# A APPENDIX

## A.1 Methods and piling information

### Noise abatement system (NAS) and sound level

*Table A.1 Sound Exposure Level $SEL_{05}$ and Peak Level $L_{Peak}$ at a distance of 750 m to the piling location (with N, mean, standard deviation and error). Only pilings of the NAS (noise abatement system) classes "BBC", "DBBC & HSD" and "IHC & BBC" (green) did comply with the thresholds for the Sound Exposure and Peak Level; all others were excluded from final analyses. The number of pilings is partly lower than in Table A.2 as the sound level was not measured for all pilings.*

| Sound level in 750 m distance | NAS | Number of pilings | Mean (dB) | Standard deviation | Standard error |
|---|---|---|---|---|---|
| **Sound Exposure Level $SEL_{05}$** | BBC | 1 | 160.00 | NA | NA |
| | DBBC | 2 | 165.50 | 3.54 | 2.50 |
| | DBBC & HSD | 54 | 159.54 | 2.06 | 0.28 |
| | HSD | 3 | 165.67 | 4.93 | 2.85 |
| | IHC | 1 | 180.00 | NA | NA |
| | IHC & BBC | 99 | 158.52 | 2.58 | 0.26 |
| | None | 2 | 177.00 | 1.41 | 1.00 |
| | Unknown | 2 | 166.00 | 8.49 | 6.00 |
| **Peak Level $L_{Peak}$** | BBC | 1 | 180.00 | NA | NA |
| | DBBC | 2 | 184.00 | 4.24 | 3.00 |
| | DBBC & HSD | 54 | 178.78 | 2.76 | 0.38 |
| | HSD | 3 | 187.33 | 5.69 | 3.29 |
| | IHC | 1 | 201.00 | NA | NA |
| | IHC & BBC | 99 | 178.15 | 2.75 | 0.28 |
| | None | 2 | 200.50 | 2.12 | 1.50 |
| | Unknown | 2 | 188.50 | 10.61 | 7.50 |

*Table A.2 Number of observations (piles) for the used NAS. In the OWFs "Deutsche Bucht" and "Trianel Windpark Borkum Phase 2", a combination of the Double Big Bubble Curtain (DBBC) and Hydro Sound Dampers (HSD) was used in most cases, while in the wind farms "Borkum Riffgrund 2", "EnBW Hohe See" and "Albatros" a combination of pile sleevers (IHC) and the Big Bubble Curtain (BBC) was mostly used.*

| NAS | All wind farms | Borkum Riffgrund 2 | Deutsche Bucht | EnBW Hohe See/Albatros | Trianel Wind-park Borkum Phase 2 |
|---|---|---|---|---|---|
| **BBC** | 1 | 0 | 0 | 1 | 0 |
| **DBBC** | 2 | 0 | 1 | 0 | 1 |
| **DBBC & HSD** | 56 | 0 | 27 | 0 | 29 |
| **HSD** | 3 | 0 | 2 | 0 | 1 |
| **IHC** | 2 | 0 | 0 | 2 | 0 |
| **IHC & BBC** | 119 | 35 | 0 | 84 | 0 |
| **None** | 2 | 0 | 1 | 0 | 1 |
| **Unknown** | 2 | 1 | 0 | 1 | 0 |

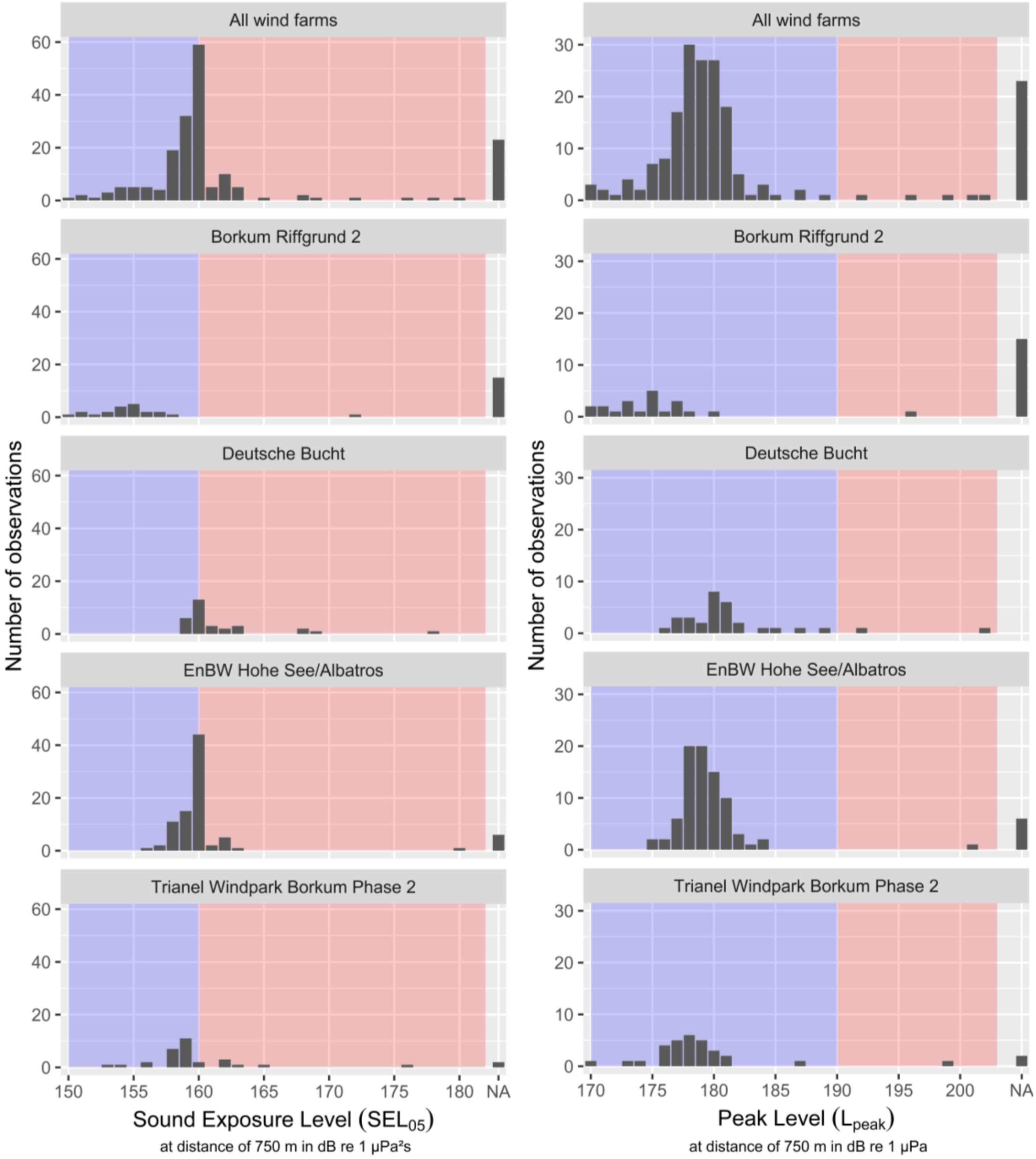


*Figure A.1* *Number of observations for Sound Exposure Level $SEL_{05}$ and Peak Level $L_{Peak}$. In order to reduce the effects of noise emissions during piling, the German Federal Maritime and Hydrographic Agency (BSH) has set a dual noise protection criterion: The Sound Exposure Level ($SEL_{05}$) must stay below 160 dB re 1 µPa² s at a distance of 750 m, the Peak Level ($L_{Peak}$) below 190 dB re 1 µPa. Due to the continuous development of noise abatement systems, the $L_{Peak}$ was met with most pilings (blue background) and just a few pilings exceeded the limit (red background), whereas the $SEL_{05}$ was exceeded more often. Mean values are given in Table A.1.*

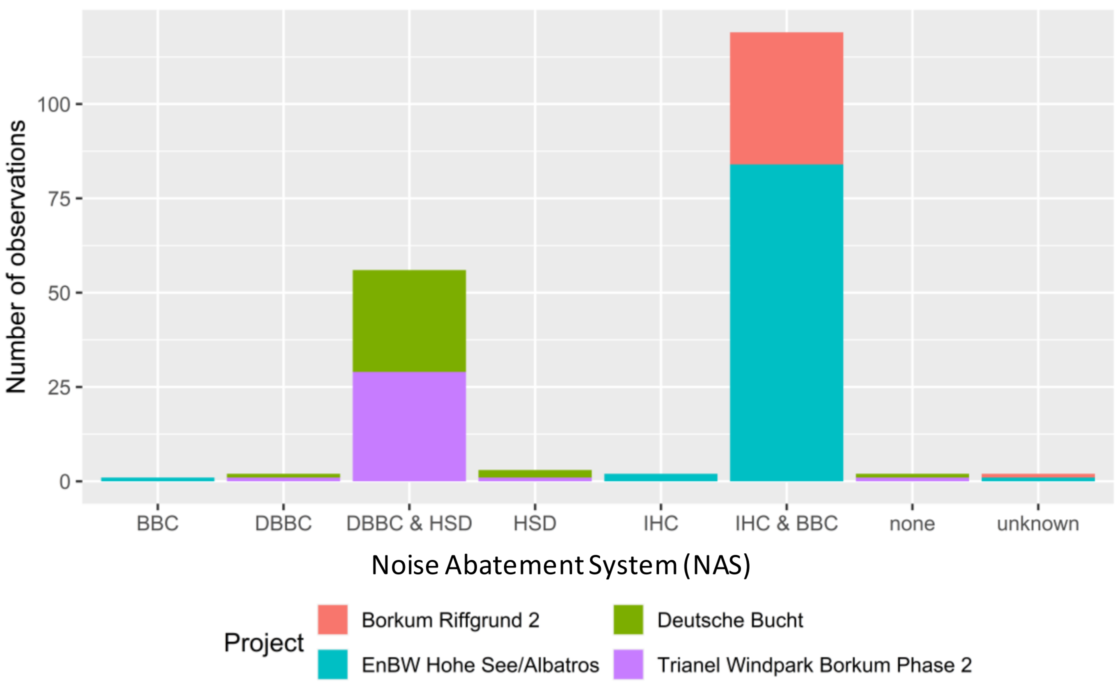


*Figure A.2 Plot of the number of observations for the used NAS shown in Table A.2.*

## A.2 Results

### A.2.1 How did the detection rates of harbour porpoises change during FaunaGuard operation at shorter distances up to 1.5 km?

***Results for single OWFs***

*Table A.3 Results of the overall and pairwise Bayesian proportion tests for single OWFs; combined dataset of mobile C-PODs in 0.75 km and 1.5 km distance to construction sites; visualisation of test results in Figure 4.3 and Figure 4.4.*

| OWF | Comparison | | Probability of equality | Significance |
|---|---|---|---|---|
| **Borkum Riffgrund 2** | 4-sample test for equality of proportions without continuity correction | | X-squared = 39.62; df = 3<br>*p*-value = 1.29e-08* | |
| | Phase 1 | Phase 2 | 0 % | * |
| | Phase 1 | Phase 3 | 0 % | * |
| | Phase 1 | Phase 4 | 1 % | * |
| | Phase 2 | Phase 3 | 1.4 % | * |
| | Phase 2 | Phase 4 | 0 % | * |
| | Phase 3 | Phase 4 | 0.8 % | * |
| **Deutsche Bucht** | 4-sample test for equality of proportions without continuity correction | | X-squared = 11.41; df = 3<br>*p*-value = 9.69e-03* | |
| | Phase 1 | Phase 2 | 0 % | * |
| | Phase 1 | Phase 3 | 11.8 % | ns |
| | Phase 1 | Phase 4 | 30.5 % | ns |
| | Phase 2 | Phase 3 | 0 % | * |
| | Phase 2 | Phase 4 | 0.2 % | * |
| | Phase 3 | Phase 4 | 8 % | ns |
| **EnBW Hohe See/Albatros** | 4-sample test for equality of proportions without continuity correction | | X-squared = 15.47; df = 3<br>*p*-value = 1.46e-03* | |
| | Phase 1 | Phase 2 | 0 % | * |
| | Phase 1 | Phase 3 | 9.2 % | ns |
| | Phase 1 | Phase 4 | 12.3 % | |
| | Phase 2 | Phase 3 | 0 % | * |
| | Phase 2 | Phase 4 | 0.3 % | * |
| | Phase 3 | Phase 4 | 1.5 % | * |
| **Trianel Windpark Borkum Phase 2** | 4-sample test for equality of proportions without continuity correction | | X-squared = 8.58; df = 3<br>*p*-value = 3.54e-02* | |
| | Phase 1 | Phase 2 | 3.4 % | * |
| | Phase 1 | Phase 3 | 7.3 % | ns |
| | Phase 1 | Phase 4 | 3 % | * |
| | Phase 2 | Phase 3 | 25.7 % | ns |
| | Phase 2 | Phase 4 | 40.7 % | ns |
| | Phase 3 | Phase 4 | 20.2 % | ns |

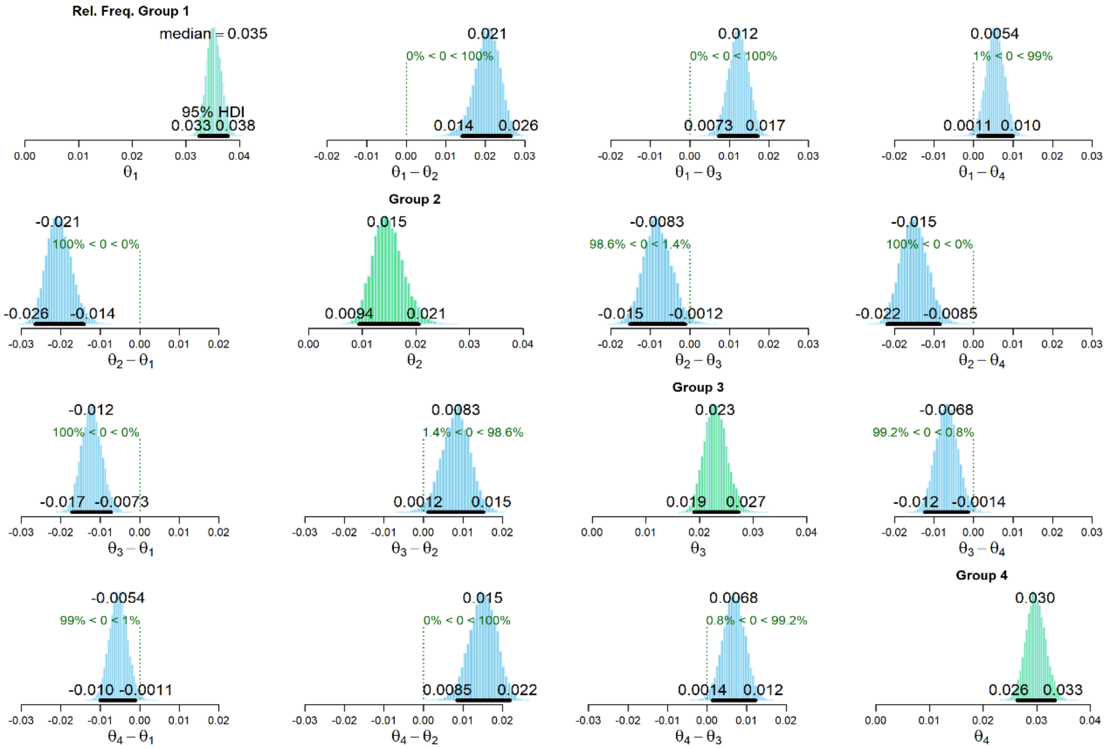

*Figure A.3 Plots of pairwise Bayesian proportion tests for the OWF "Borkum Riffgrund 2", using the parameter "DPM per minute"; combined dataset of mobile C-PODs in 0.75 km and 1.5 km distance to construction sites. Further explanations are given in Figure 4.3; for test results see Table A.3.*

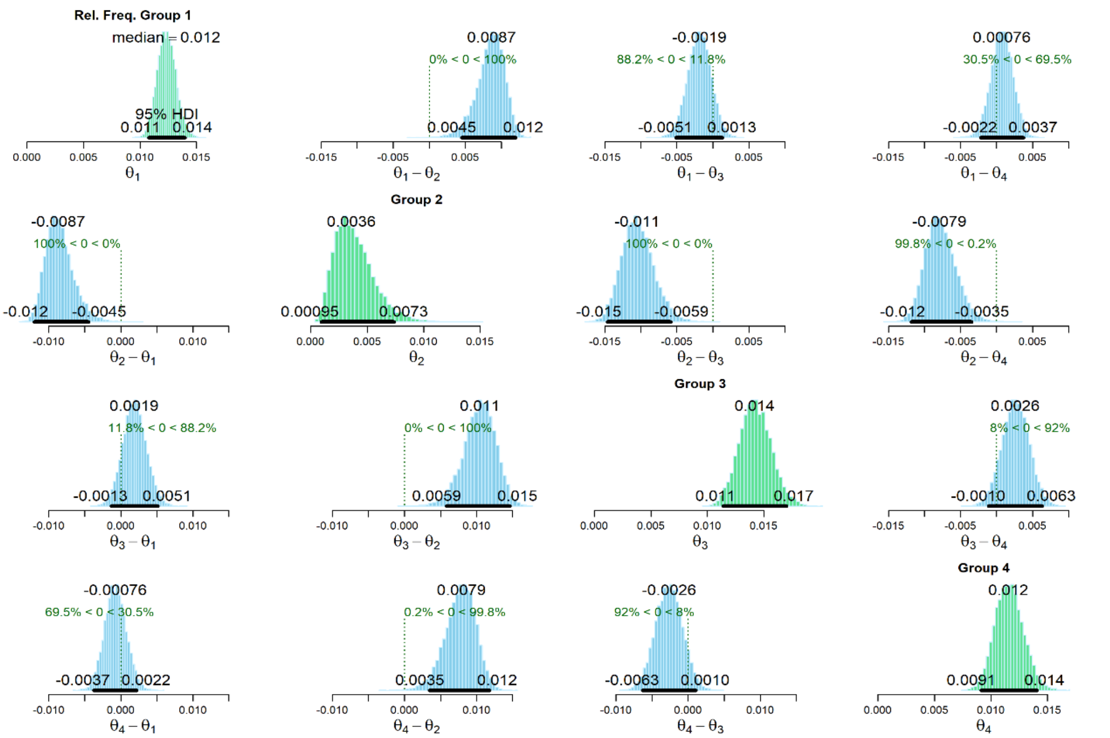

*Figure A.4 Plots of pairwise Bayesian proportion tests for the OWF "Deutsche Bucht", using the parameter "DPM per minute"; combined dataset of mobile C-PODs in 0.75 km and 1.5 km distance to construction sites. Further explanations are given in Figure 4.3; for test results see Table A.3.*

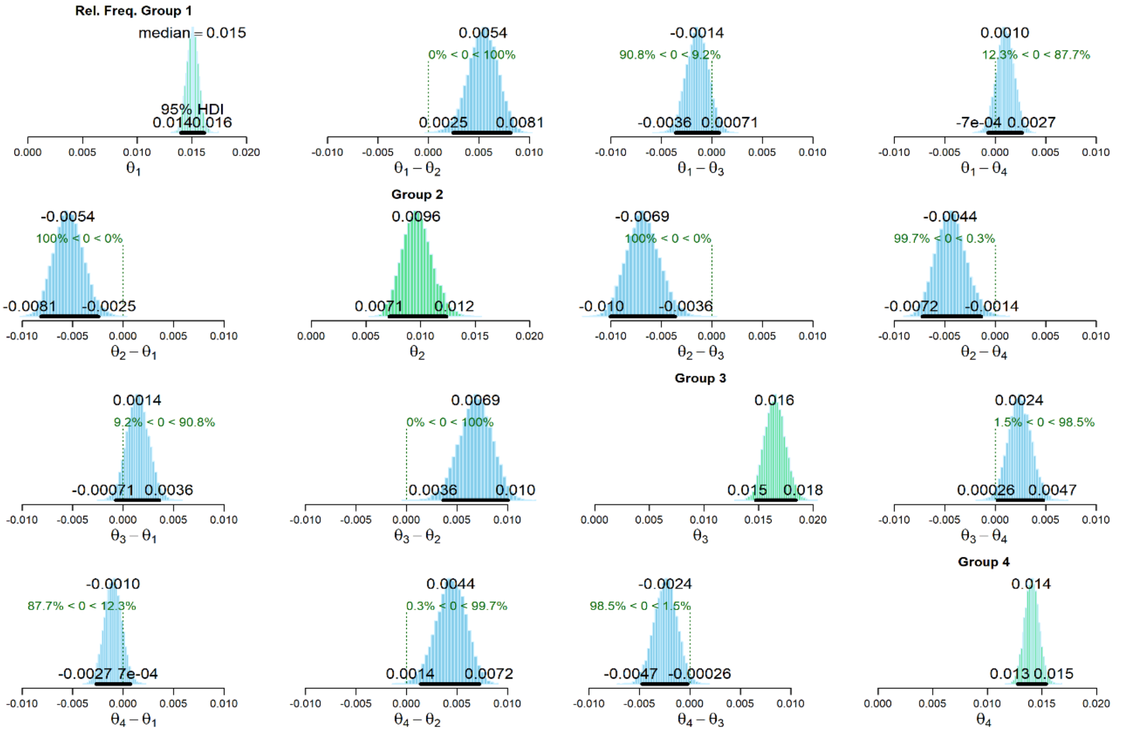

*Figure A.5* *Plots of pairwise Bayesian proportion tests for the OWFs "EnBW Hohe See" and "Albatros", using the parameter "DPM per minute"; combined dataset of mobile C-PODs in 0.75 km and 1.5 km distance to construction sites". Further explanations are given in Figure 4.3; for test results see Table A.3.*

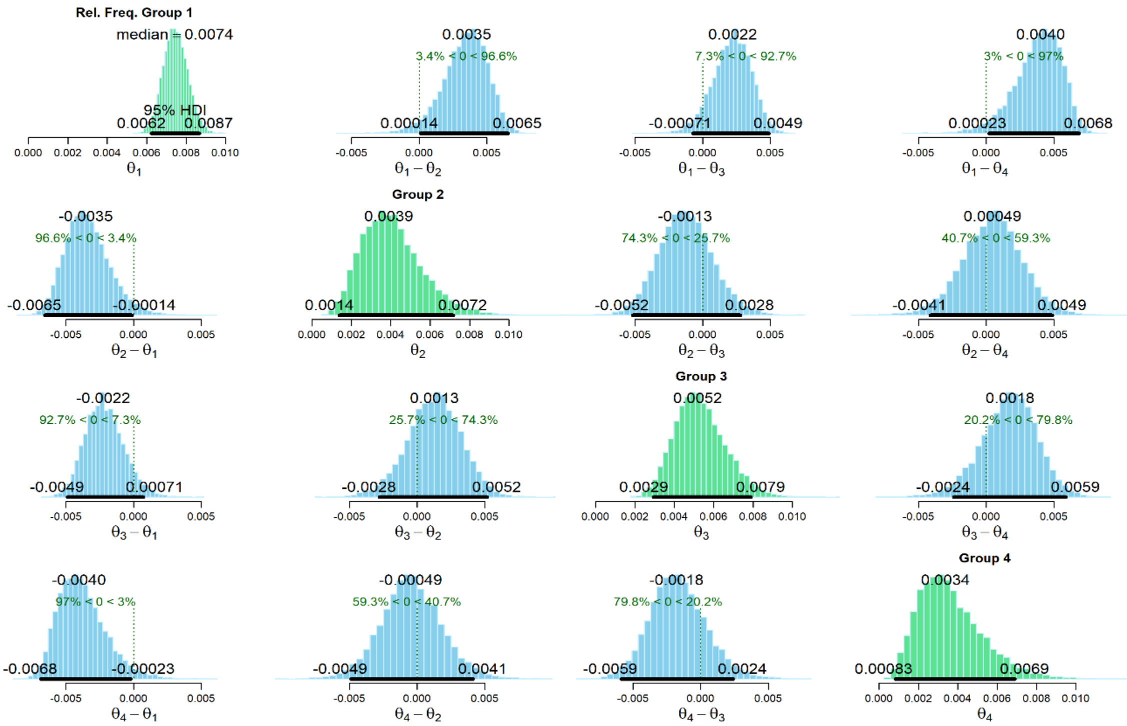

*Figure A.6* *Plots of pairwise Bayesian proportion tests for the OWF "Trianel Windpark Borkum Phase 2", using the parameter "DPM per minute"; combined dataset of mobile C-PODs in 0.75 km and 1.5 km distance to construction sites. Further explanations are given in Figure 4.3; for test results see Table A.3.*

### A.2.2 How did the detection rates of harbour porpoises change during FaunaGuard operation at distances up to 10 km?

***Effects at single OWFs***

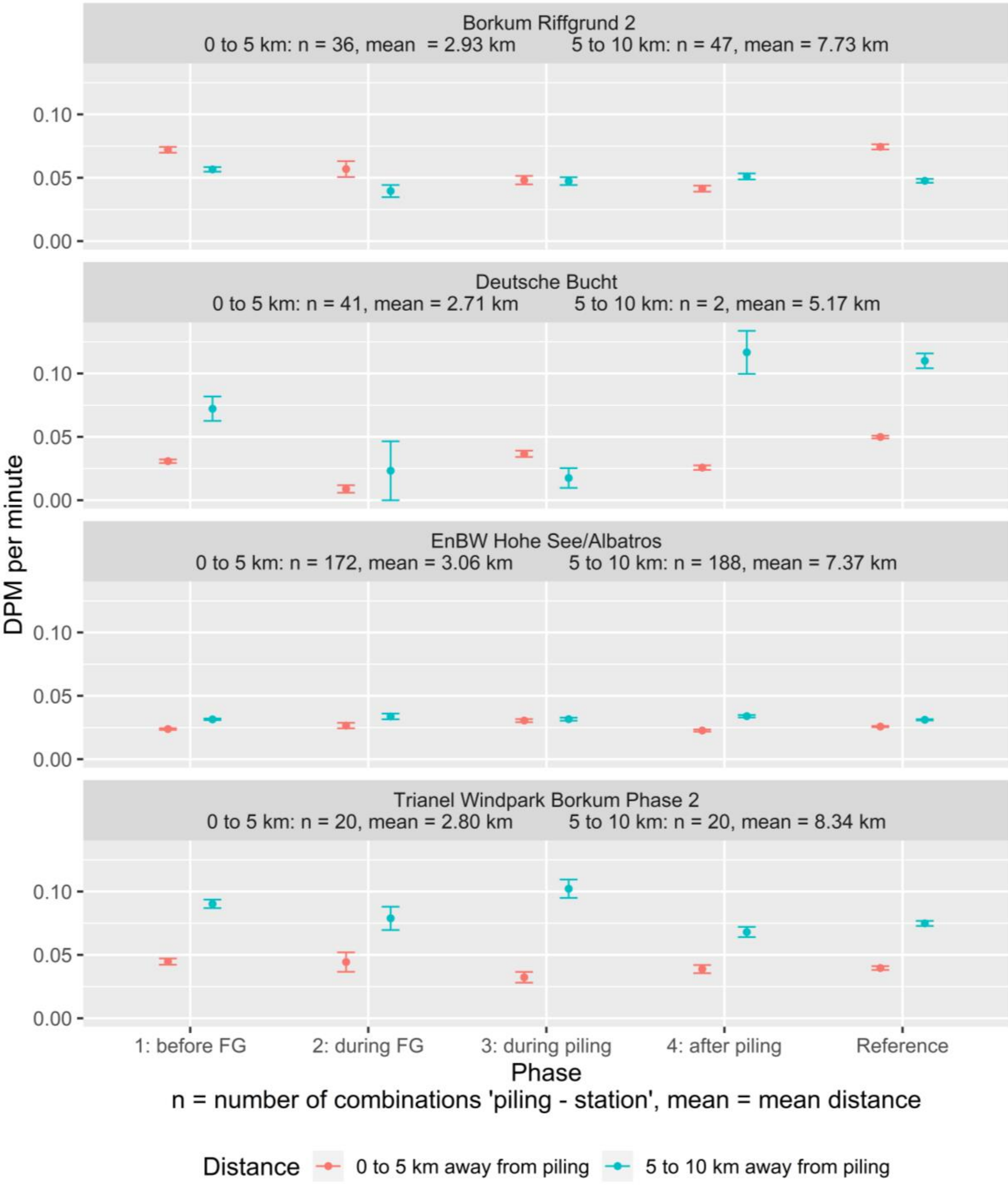


*Figure A.7 Stationary C-PODs: DPM per minute (mean and standard error) during five phases in single wind farms at two distance classes (0-5 km, 5-10 km). For distances up to 5 km from piling locations, detection rates either decreased during Phase 1 (Before FaunaGuard), Phase 2 (During FaunaGuard) and Phase 3 (During piling) or were mostly at a similar level in all phases. For distances of 5 to 10 km from piling locations, the detection rates seemed to be related to the average distance of this distance category which varied among the OWFs. Raw data in Table A.4.*

*Table A.4 Stationary C-PODs: DPM per minute during five phases in single wind farms at two distance classes (0-5 km, 5-10 km). Visualisation in Figure A.7.*

| OWF | Dis-tance (mean) in km | Phase | *DPM per minute* | | | |
|---|---|---|---|---|---|---|
| | | | N (number of minutes) | Mean | Standard deviation | Standard error |
| **Borkum Riffgrund 2** | 0-5 (2.93) | 1: Before FaunaGuard | 12,681 | 0.072 | 0.259 | 0.002 |
| | | 2: During FaunaGuard | 1,354 | 0.057 | 0.232 | 0.006 |
| | | 3: During piling | 4,089 | 0.048 | 0.214 | 0.003 |
| | | 4: After piling | 6,900 | 0.041 | 0.199 | 0.002 |
| | | Reference | 16,833 | 0.074 | 0.262 | 0.002 |
| | 5-10 (7.73) | 1: Before FaunaGuard | 16,749 | 0.057 | 0.231 | 0.002 |
| | | 2: During FaunaGuard | 1,669 | 0.040 | 0.195 | 0.005 |
| | | 3: During piling | 4,835 | 0.047 | 0.212 | 0.003 |
| | | 4: After piling | 8,530 | 0.051 | 0.220 | 0.002 |
| | | Reference | 20,151 | 0.048 | 0.213 | 0.002 |
| **Deutsche Bucht** | 0-5 (2.71) | 1: Before FaunaGuard | 14,686 | 0.031 | 0.173 | 0.001 |
| | | 2: During FaunaGuard | 1,014 | 0.009 | 0.094 | 0.003 |
| | | 3: During piling | 5,707 | 0.037 | 0.188 | 0.002 |
| | | 4: After piling | 8,126 | 0.026 | 0.158 | 0.002 |
| | | Reference | 43,624 | 0.050 | 0.218 | 0.001 |
| | 5-10 (5.17) | 1: Before FaunaGuard | 720 | 0.072 | 0.259 | 0.010 |
| | | 2: During FaunaGuard | 43 | 0.023 | 0.152 | 0.023 |
| | | 3: During piling | 285 | 0.018 | 0.132 | 0.008 |
| | | 4: After piling | 360 | 0.117 | 0.321 | 0.017 |
| | | Reference | 2,882 | 0.110 | 0.313 | 0.006 |
| **EnBW Hohe See/ Albatros** | 0-5 (3.06) | 1: Before FaunaGuard | 61,008 | 0.024 | 0.152 | 0.001 |
| | | 2: During FaunaGuard | 5,416 | 0.027 | 0.161 | 0.002 |
| | | 3: During piling | 19,571 | 0.031 | 0.172 | 0.001 |
| | | 4: After piling | 31,308 | 0.023 | 0.149 | 0.001 |
| | | Reference | 118,786 | 0.026 | 0.159 | 0.000 |
| | 5-10 (7.37) | 1: Before FaunaGuard | 68,527 | 0.032 | 0.175 | 0.001 |
| | | 2: During FaunaGuard | 6,570 | 0.034 | 0.181 | 0.002 |
| | | 3: During piling | 22,432 | 0.032 | 0.175 | 0.001 |
| | | 4: After piling | 35,806 | 0.034 | 0.181 | 0.001 |
| | | Reference | 131,705 | 0.031 | 0.174 | 0.000 |
| **Trianel Windpark Borkum Phase 2** | 0-5 (2.80) | 1: Before FaunaGuard | 7,065 | 0.045 | 0.207 | 0.002 |
| | | 2: During FaunaGuard | 721 | 0.044 | 0.206 | 0.008 |
| | | 3: During piling | 1,760 | 0.032 | 0.177 | 0.004 |
| | | 4: After piling | 3,631 | 0.039 | 0.193 | 0.003 |
| | | Reference | 16,134 | 0.040 | 0.195 | 0.002 |
| | 5-10 (8.34) | 1: Before FaunaGuard | 7,210 | 0.090 | 0.287 | 0.003 |
| | | 2: During FaunaGuard | 862 | 0.079 | 0.270 | 0.009 |
| | | 3: During piling | 1,741 | 0.102 | 0.303 | 0.007 |
| | | 4: After piling | 3,892 | 0.068 | 0.252 | 0.004 |
| | | Reference | 17,372 | 0.075 | 0.263 | 0.002 |

### A.2.3 How did the detection rates of harbour porpoises change in relation to FaunaGuard duration and distance?

***Model specifications (GAM & BRT)***

*Table A.5 List of variables considered for GAM and BRT models on FaunaGuard duration and distance.*

| Variable | Type | Description |
|---|---|---|
| **Response variables** | | |
| *DPM_min_rate* | binary | Detection Positive Minute per minute (0 = no detection, 1 = detection) |
| **Piling- and noise-related variables** | | |
| *A_min_FaunaGuard* | integer | Minute of deployment of FaunaGuard ranging from +1 (start of FaunaGuard) to start of piling, or if the FaunaGuard was switched off before, until the end of the FaunaGuard |
| *A_dist* | continuous | Distance to piling event in metres |
| *week_events* | integer | Number of piling events occurring during seven days before a given piling event in a 40 km radius |
| *dist_shipping* | continuous | Distance to the next major shipping lane in metres |
| *allClx_min* | continuous | Number of all clicks within a minute; these could originate from different noise sources (e.g. waves, sediment movement, ships, porpoises) |
| **Time-related variables** | | |
| *DPMt* | factor | Detection Positive Minute per minute in previous minute |
| *hourofday* | circular integer | Hour of the day |
| *dayofyear* | circular integer | Day of the year |
| *year* | factor | Year |
| **Modelled environmental variables** | | |
| *pr_pm_pres* | continuous | Probability of presence of sand goby *Pomatoschistus minutus* per station |
| *pr_am_pres* | continuous | Probability of presence of sand eel *Ammodytes marinus* per station |
| *pr_at_pres* | continuous | Probability of presence of sand eel *Ammodytes tobianus* per station |
| *pr_hl_pres* | continuous | Probability of presence of sand eel *Hyperoplus lanceolatus* per station |
| *pr_sand_eel* | continuous | Average probability of presence of the three sand eel species *Hyperoplus lanceolatus, Ammodytes marinus* and *Pomatoschistus minutus* per station |
| *biozone* | factor (two levels) | Either “circalittoral” or “infralittoral” |
| *depth* | continuous | Water depth at the C-POD station |
| *node_SST* | continuous | Sea surface temperature anomaly on a daily basis |
| *wind_speed* | continuous | Speed of surface currents in m/s on a 6 hours basis |
| *wind_dir* | circular & continuous | Wind direction in degree on a 6 hours basis |
| *cur_speed_depth0* | continuous | Speed of currents in m/s at surface on hourly basis |
| *cur_dir_depth0* | circular & continuous | Direction of currents in degree at surface on an hourly basis |
| *temp_depth0* | continuous | Temperature in degree Celsius at surface on an hourly basis |
| *phyto_depth0* | continuous | Phytoplankton concentration in mmol/m³ at surface on a daily basis |
| *sal_depth0* | continuous | Salinity in ‰ at surface on a daily basis |

| C-POD-related variables | | |
|---|---|---|
| *station* | factor (as many levels as C-POD positions) | Name of C-POD station |
| *project* | factor (as many levels as wind farms) | Name of wind farm |
| *podident* | factor (as many levels as used C-POD devices) | ID of C-POD device |
| *pile* | factor (as many levels as piles) | ID of pile |
| *pos_long* | continuous | Longitude of C-POD station |
| *pos_lat* | continuous | Latitude of C-POD station |

*Table A.6 Effect of FaunaGuard operation on the spatial extent and intensity of decrease for all wind farm data combined, using a Generalised Additive Model. For variables included into the best explanatory model the p-value were given.*

| Variable | p-value |
|---|---|
| Tensor product: *A_min_FaunaGuard & A_dist* | < 2e-16 (***) |
| *project* | excluded |
| *station* | excluded |
| *podident* | excluded |
| *pile* | < 2e-16 (***) |
| *week_events* | excluded |
| *dist_shipping* | 1.07e-05 (***) |
| *allClx_min* | < 2e-16 (***) |
| *DPMt* | < 2e-16 (***) |
| *hourofday* | 5.67e-05 (***) |
| *dayofyear* | 1.36e-04 (***) |
| *year* | 3.52e-03 (**) |
| *pr_pm_pres* | excluded |
| *pr_sand_eel:* best: *pr_at_pres* | < 2e-16 (***) |
| **N (number of analysed hours)** | **26796** |
| **R-squared (adjusted)** | **0.286** |
| **Deviance explained** | **40.2 %** |

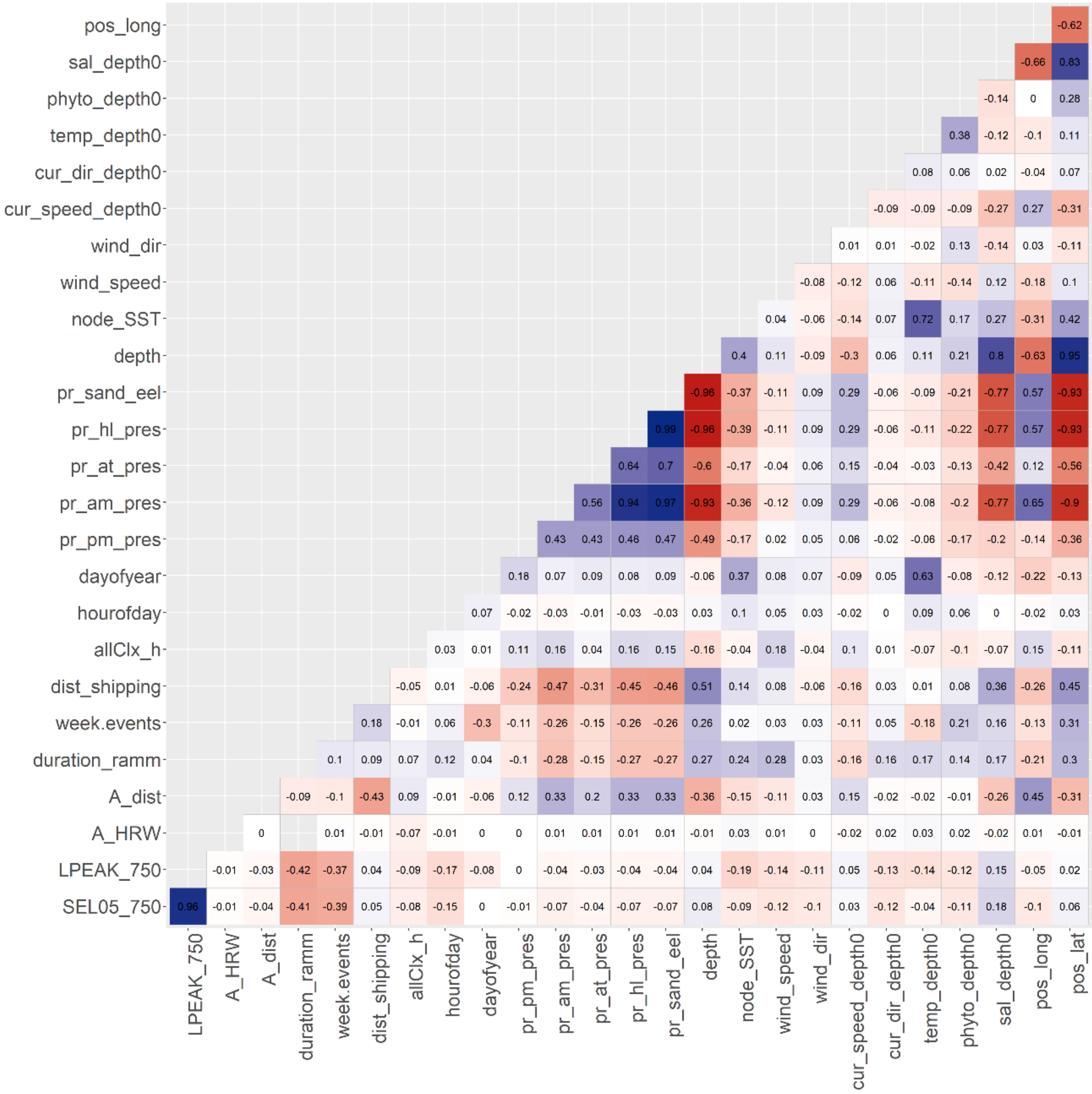


*Figure A.8 Pearson correlation coefficients of all possible combinations of two variables (except for factors) for the GAM and BRT models on FaunaGuard duration and distance. Red boxes show a negative, blue boxes a positive r-value.*

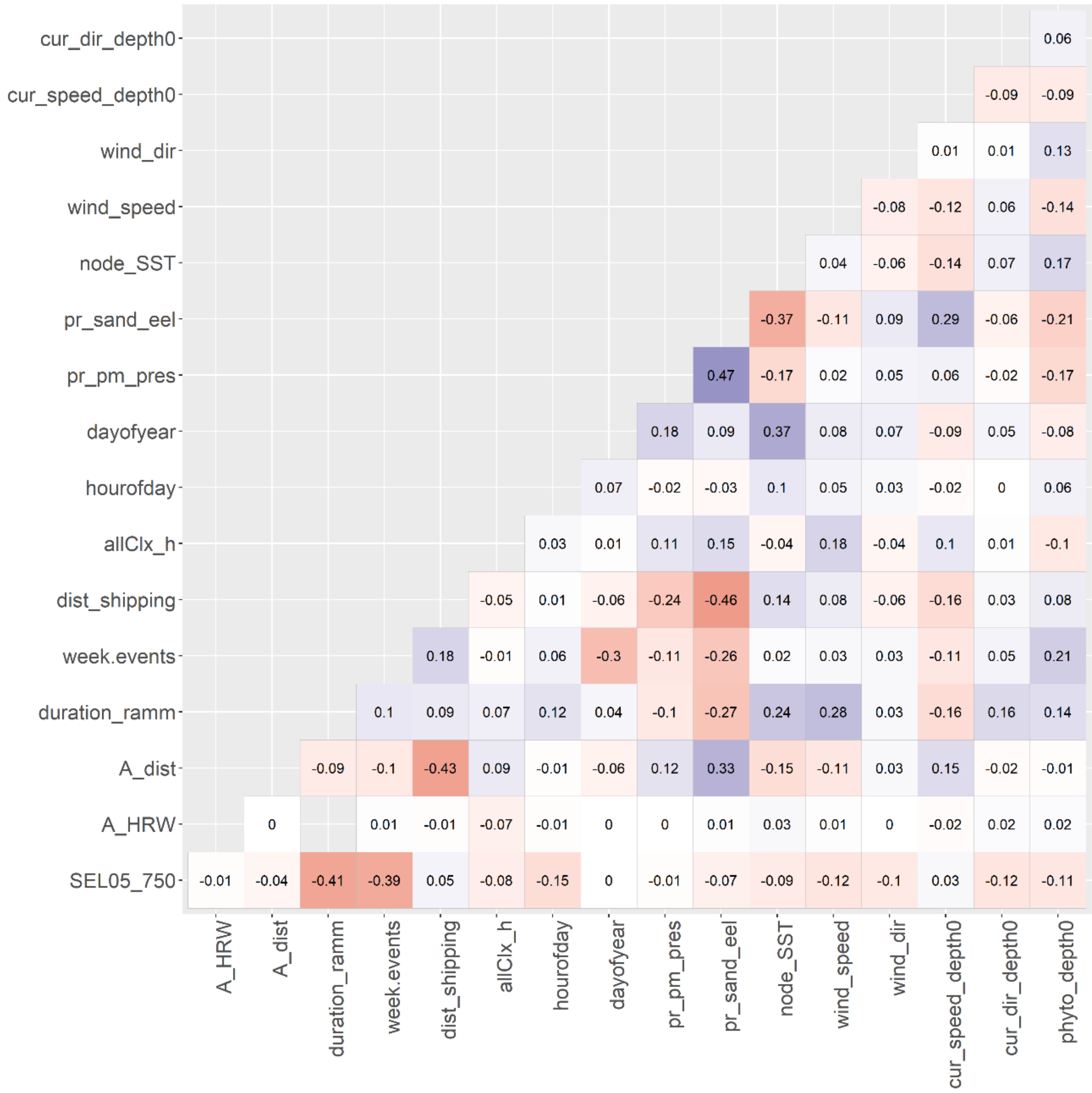


*Figure A.9* *Pearson correlation coefficients of all combinations of the finally used variables (except for factors) for the GAM and BRT models on FaunaGuard duration and distance. Red boxes show a negative, blue boxes a positive r-value.*

### A.2.4 Did the effects on harbour porpoise detection rates during FaunaGuard operation differ from those during seal scarer operation?

***Additional information on pilings with different AHD systems***

*Table A.7 Comparing the information of the pilings using a FaunaGuard with those using a seal scarer as AHD. Despite the low number of observations, the specifications of the pilings were similar; thus it was assumed that differences in detection rates of harbour porpoises would probably have been caused by having used different AHDs.*

| AHD | Variable | N (number of pilings) | Mean | Standard error | Standard deviation |
|---|---|---|---|---|---|
| **FaunaGuard** | Period | June to November 2018 | | | |
| | Time of piling | Spread over different daytimes | | | |
| | Piling duration in minutes | 24 | 84.75 | 27.97 | 5.71 |
| | Sound Exposure Level $SEL_{05}$ at a distance of 750 m | 21 | 159.38 | 4.59 | 1.00 |
| | Peak Level $L_{Peak}$ at a distance of 750 m | 21 | 178.38 | 5.71 | 1.25 |
| **Seal scarer** | Period | July 2018 | | | |
| | Time of piling | Spread over different daytimes | | | |
| | Piling duration in minutes | 4 | 78.38 | 38.13 | 19.07 |
| | Sound Exposure Level $SEL_{05}$ at a distance of 750 m | 4 | 158.25 | 0.50 | 0.25 |
| | Peak Level $L_{Peak}$ at a distance of 750 m | 4 | 177.75 | 1.50 | 0.75 |

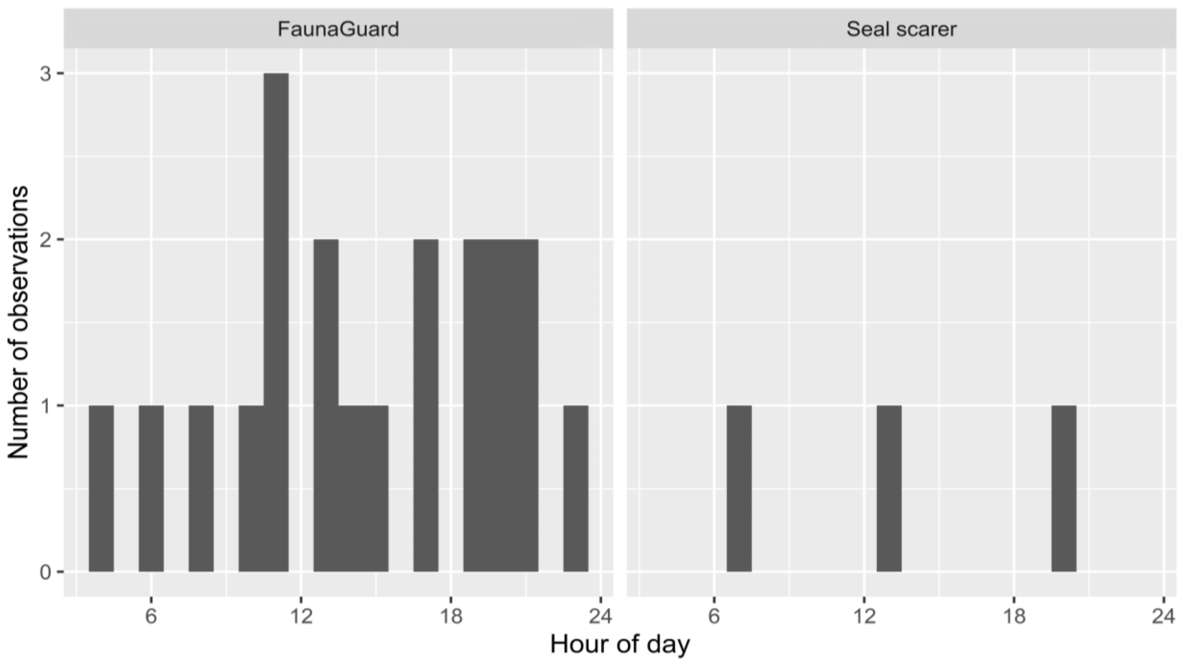


*Figure A.10 Hour of day for pilings using a FaunaGuard resp. a seal scarer as ADD in the wind farm "Trianel Windpark Borkum Phase 2".*

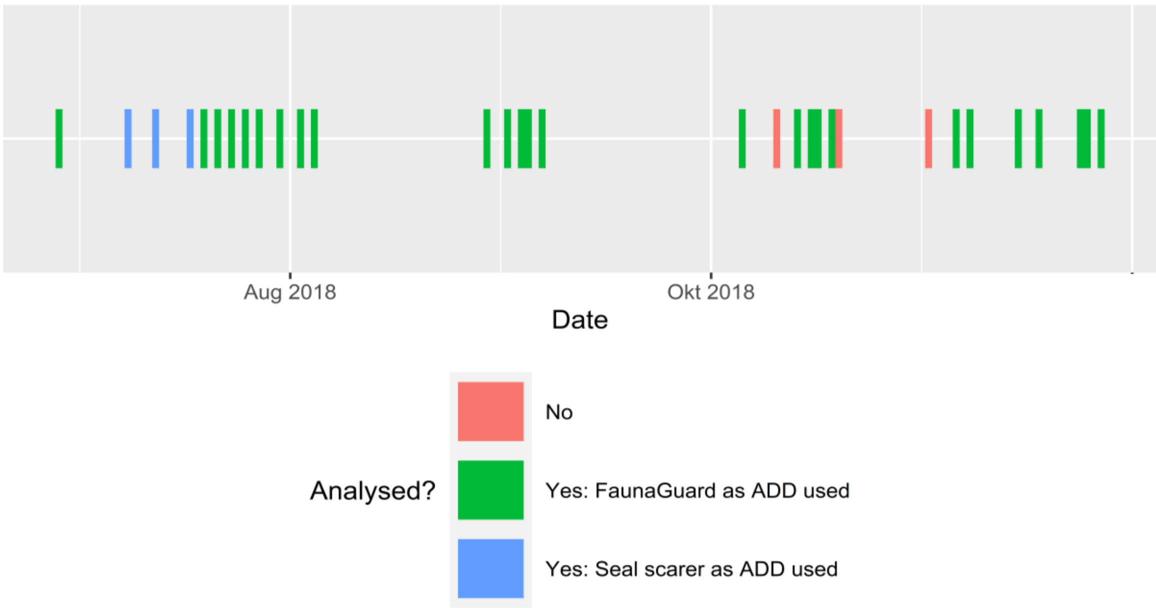


*Figure A.11 Day of the year for pilings using a FaunaGuard resp. seal scarer as AHD in the wind farm "Trianel Windpark Borkum Phase 2" (pilings excluded from analyses in red).*

### A.2.5 Comparison with the Gescha studies: Were the combined effects of FaunaGuard/piling different from those of seal scarer/piling?

***Overall dataset: four distance classes up to 20 km from construction sites***

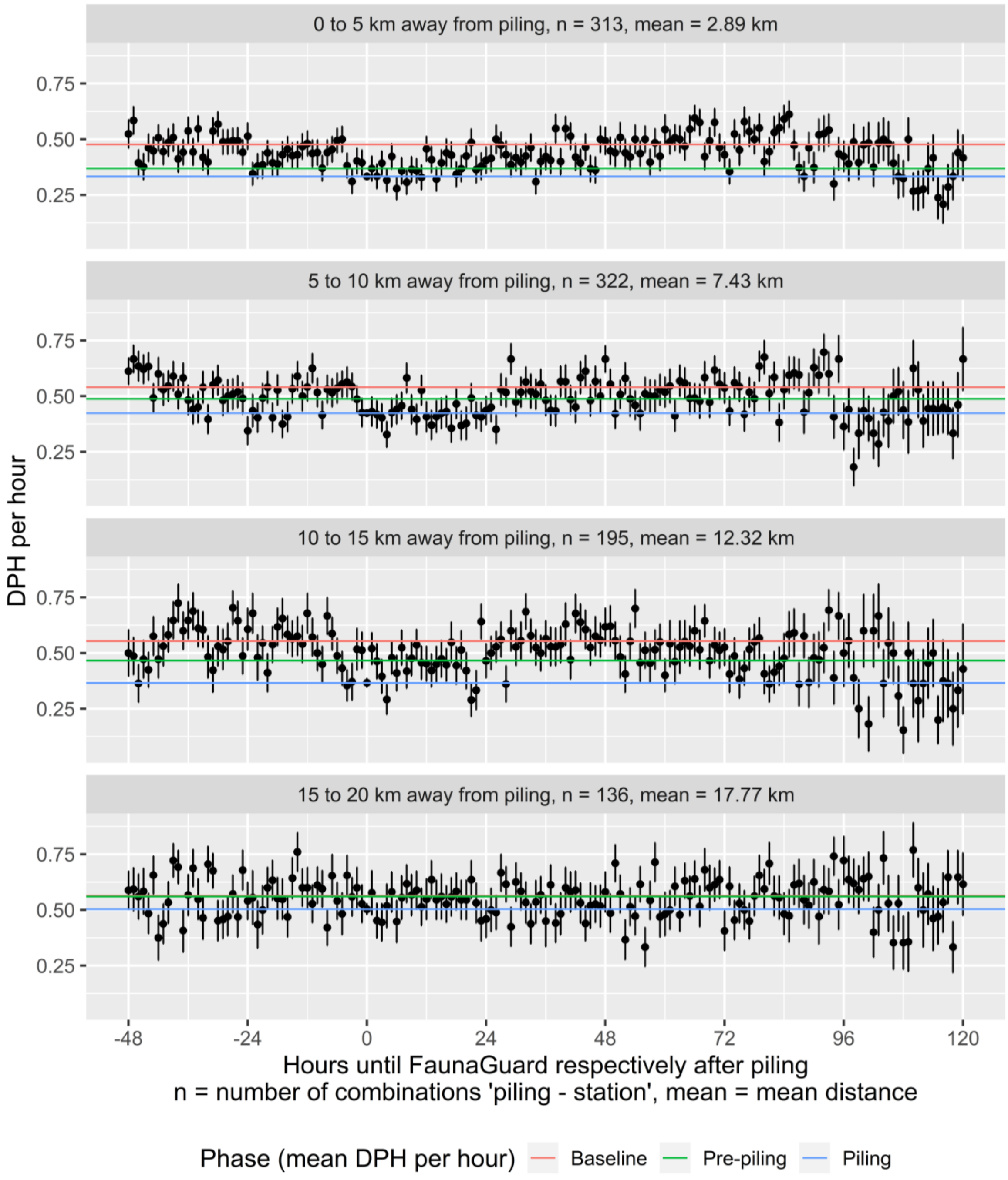


*Figure A.12 Stationary C-PODs: Raw data of DPH per hour (mean and standard error) from 48 daytime hours before the deployment of the FaunaGuard until 120 hours after piling at four distance classes up to 20 km from piling locations. Mean values for the phases Baseline, Pre-piling and Piling for each distance class are shown as horizontal lines (values from Table A.8).*

Raw data plots show that in the distance class 0-5 km the *DPH per hour* rate decreased a few hours before the deployment of the FaunaGuard and increased again to the level of the phase Baseline about one day after piling (values in Table A.8); this trend became less visible with increasing distance (Figure A.12).

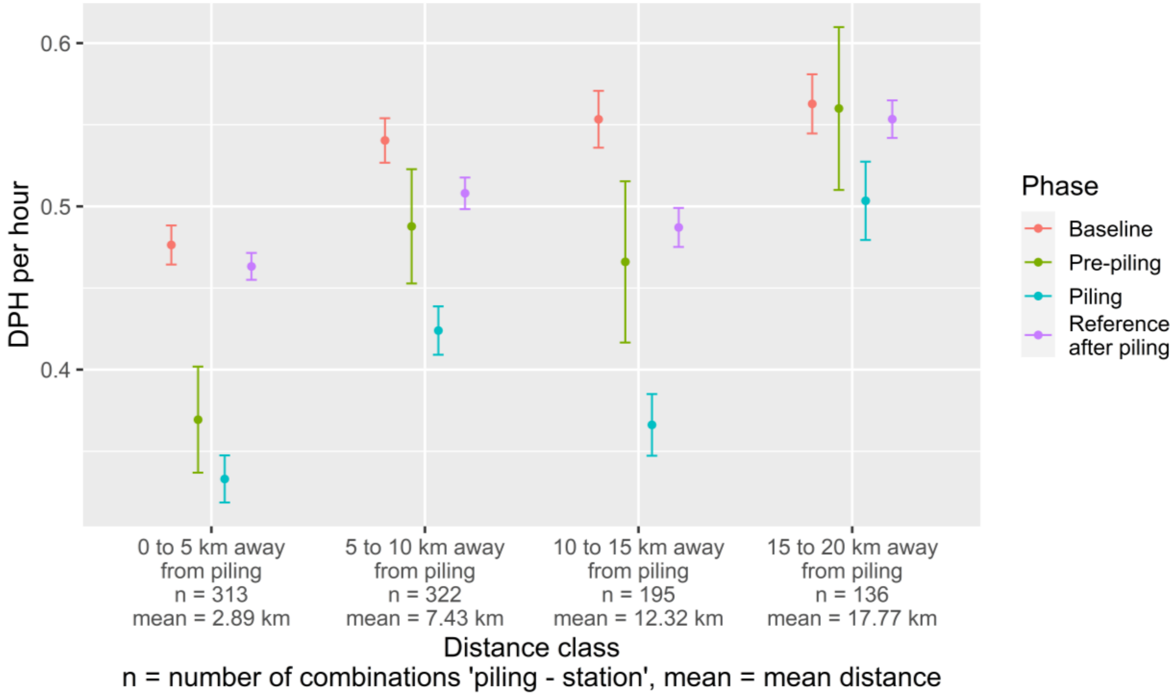


*Figure A.13 Stationary C-PODs: DPH per hour (mean and standard error) during the four investigated phases for distance classes up to 20 km from piling locations.*

When looking at the individual phases, detection rates were highest during the phase Baseline (48 to 24 hours before the deployment of the FaunaGuard), in an intermediate range during the phases Pre-piling (3 to 1 hours before the deployment of the FaunaGuard) and Reference after piling (hours +49 to +120 after piling) and lowest during the phase Piling (at least 1 minute of FaunaGuard or piling). During the phase Piling the rate *DPH per hour* remained on a quite low level in up to 15 km distance, but increased strongly at 15-20 km distance (Figure A.13). In the phase Pre-piling in up to 15 km distance a decrease was found relative to the phase Baseline. However, the detection rate level during Pre-piling in 5-15 km distance was similar to that of Baseline and Reference after piling in the distance class 0-5 km. Hence, it is not sure whether the decrease was really due to human pre-piling activities or a kind of artifact. In any case, the pre-piling effect was strong in the class of 0-5 km distance (on average 2.89 km distance).

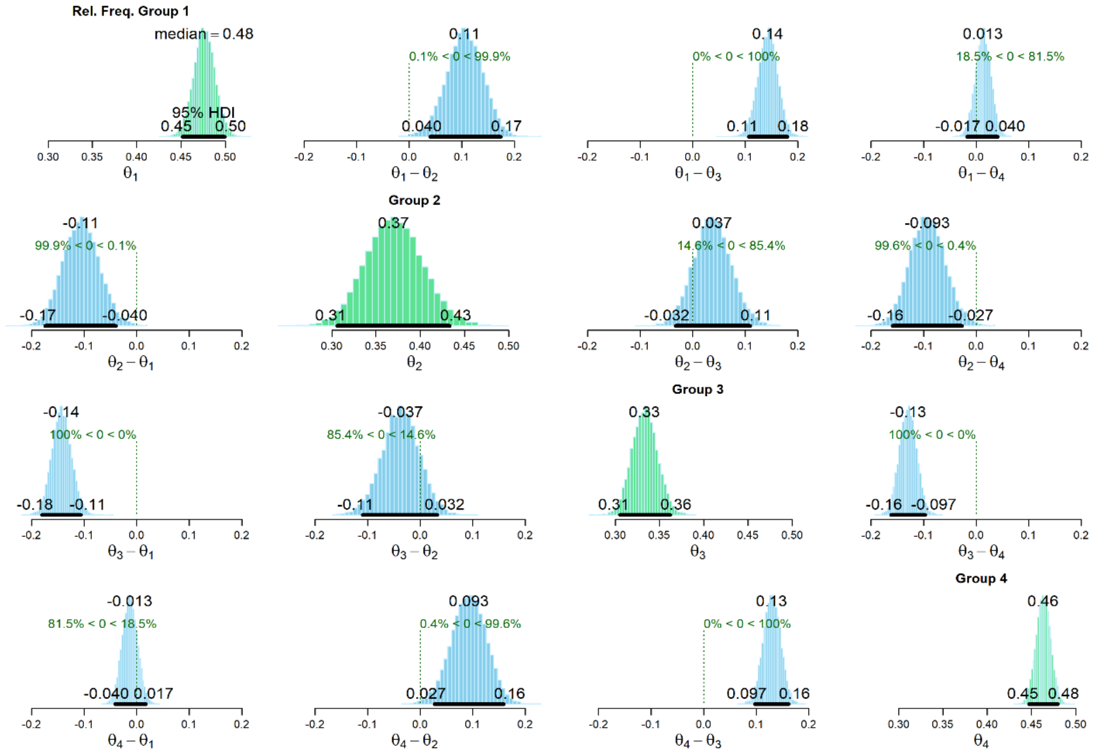

*Figure A.14 Plots of pairwise Bayesian proportion tests for the overall stationary C-POD dataset, using the parameter DPH per hour: distance class 0-5 km from piling locations; groups in sequence of Table 4.7. Further explanations are given in Figure 4.3; for test results see Table A.9.*

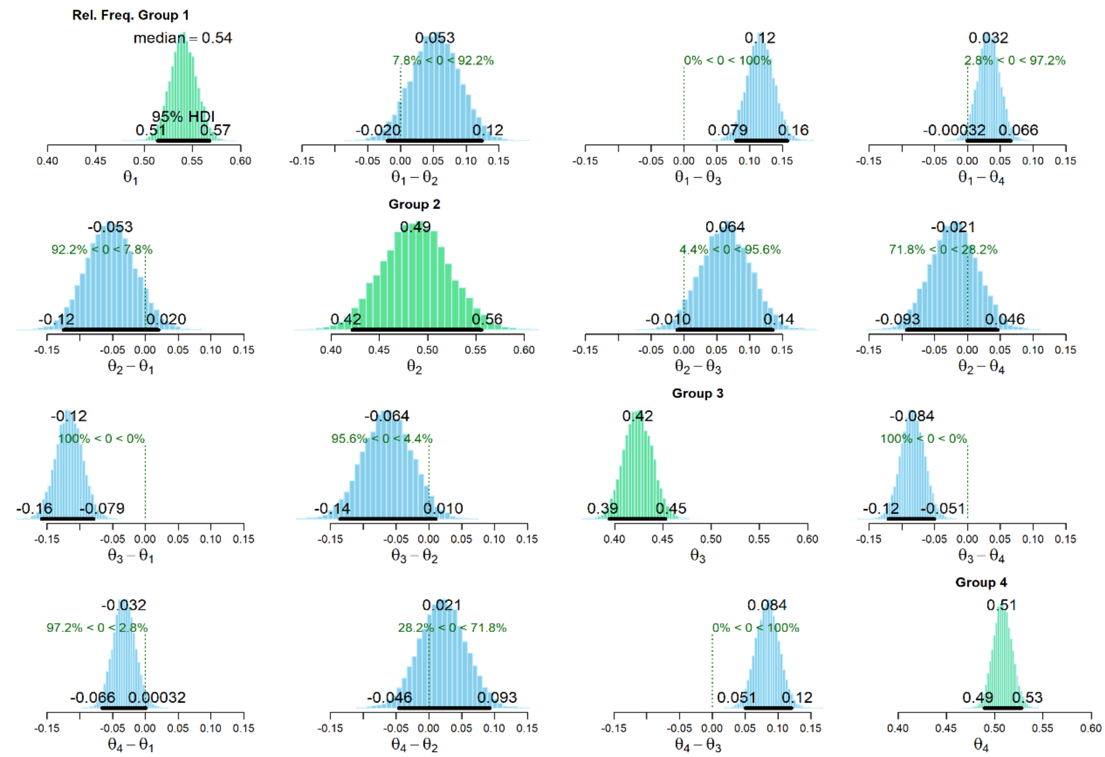

*Figure A.15 Plots of pairwise Bayesian proportion tests for the overall stationary C-POD dataset, using the parameter DPH per hour: distance class 5-10 km from piling locations; groups in sequence of Table 4.7. Further explanations are given in Figure 4.3; for test results see Table A.9.*

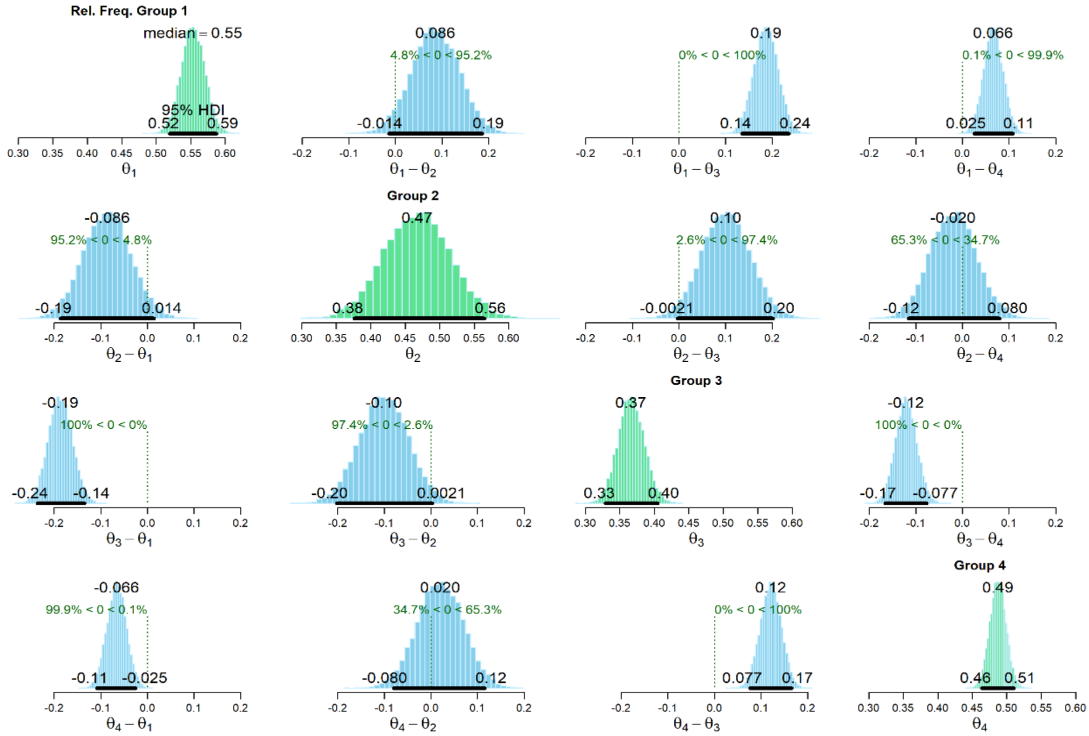


*Figure A.16* *Plots of pairwise Bayesian proportion tests for the overall stationary C-POD dataset, using the parameter DPH per hour: distance class 10-15 km from piling locations. No plot for the class 15-20 km is shown as the overall test was not significant; groups in sequence of Table 4.7. Further explanations are given in Figure 4.3; for test results see Table A.9.*

*Table A.8* *Mean values of DPH per hour (N, mean, standard deviation and error) in the overall dataset for the four investigated phases and four distance classes up to 20 km from piling locations.*

| Distance class (with mean) | Phase | *DPH per hour* | | | |
|---|---|---|---|---|---|
| | | N (number of hours) | Mean | Standard deviation | Standard error |
| **0-5 (2.89) km** | Baseline | 1,736 | 0.48 | 0.50 | 0.012 |
| | Pre-piling | 222 | 0.37 | 0.48 | 0.032 |
| | Piling | 1,069 | 0.33 | 0.47 | 0.014 |
| | Reference after piling | 3,676 | 0.46 | 0.50 | 0.0082 |
| **5-10 (7.43) km** | Baseline | 1,336 | 0.54 | 0.50 | 0.014 |
| | Pre-piling | 205 | 0.49 | 0.50 | 0.035 |
| | Piling | 1,111 | 0.42 | 0.49 | 0.015 |
| | Reference after piling | 2,675 | 0.51 | 0.50 | 0.0097 |
| **10-15 (12.32) km** | Baseline | 815 | 0.55 | 0.50 | 0.017 |
| | Pre-piling | 103 | 0.47 | 0.50 | 0.050 |
| | Piling | 650 | 0.37 | 0.48 | 0.019 |
| | Reference after piling | 1,749 | 0.49 | 0.50 | 0.012 |
| **15-20 (17.77) km** | Baseline | 748 | 0.56 | 0.50 | 0.018 |
| | Pre-piling | 100 | 0.56 | 0.50 | 0.050 |
| | Piling | 435 | 0.50 | 0.50 | 0.024 |
| | Reference after piling | 1,861 | 0.55 | 0.50 | 0.012 |

*Table A.9 Results of the overall and pairwise Bayesian proportion tests for single OWFs; parameter DPH per hour in four distance classes up to 20 km from piling locations; visualisation of test results in Figure A.14 to Figure A.16.*

| Distance class | Comparison | | Probability of equality | Significance |
|---|---|---|---|---|
| **0-5 km** | 4-sample test for equality of proportions without continuity correction | | X-squared = 71.25; df = 3 *p*-value = 2.31e-15* | |
| | Baseline | Pre-piling | 0.1 % | * |
| | Baseline | Piling | 0 % | * |
| | Baseline | Reference after piling | 18.5 % | ns |
| | Pre-piling | Piling | 14.6 % | ns |
| | Pre-piling | Reference after piling | 0.4 % | * |
| | Piling | Reference after piling | 0 % | * |
| **5-10 km** | 4-sample test for equality of proportions without continuity correction | | X-squared = 35.15; df = 3 p-value = 1.13e-07* | |
| | Baseline | Pre-piling | 7.8 % | ns |
| | Baseline | Piling | 0 % | * |
| | Baseline | Reference after piling | 2.8 % | * |
| | Pre-piling | Piling | 4.4 % | * |
| | Pre-piling | Reference after piling | 28.2 % | ns |
| | Piling | Reference after piling | 0 % | * |
| **10-15 km** | 4-sample test for equality of proportions without continuity correction | | X-squared = 51.77; df = 3 p-value = 3.36e-11* | |
| | Baseline | Pre-piling | 4.8 % | * |
| | Baseline | Piling | 0 % | * |
| | Baseline | Reference after piling | 0.1 % | * |
| | Pre-piling | Piling | 2.6 % | * |
| | Pre-piling | Reference after piling | 34.7 % | ns |
| | Piling | Reference after piling | 0 % | * |
| **15-20 km** | 4-sample test for equality of proportions without continuity correction | | X-squared = 4.42; df = 3 *p*-value = 2.19e-01 *ns* | |

***Single OWFs: distances up to 10 km from construction sites***

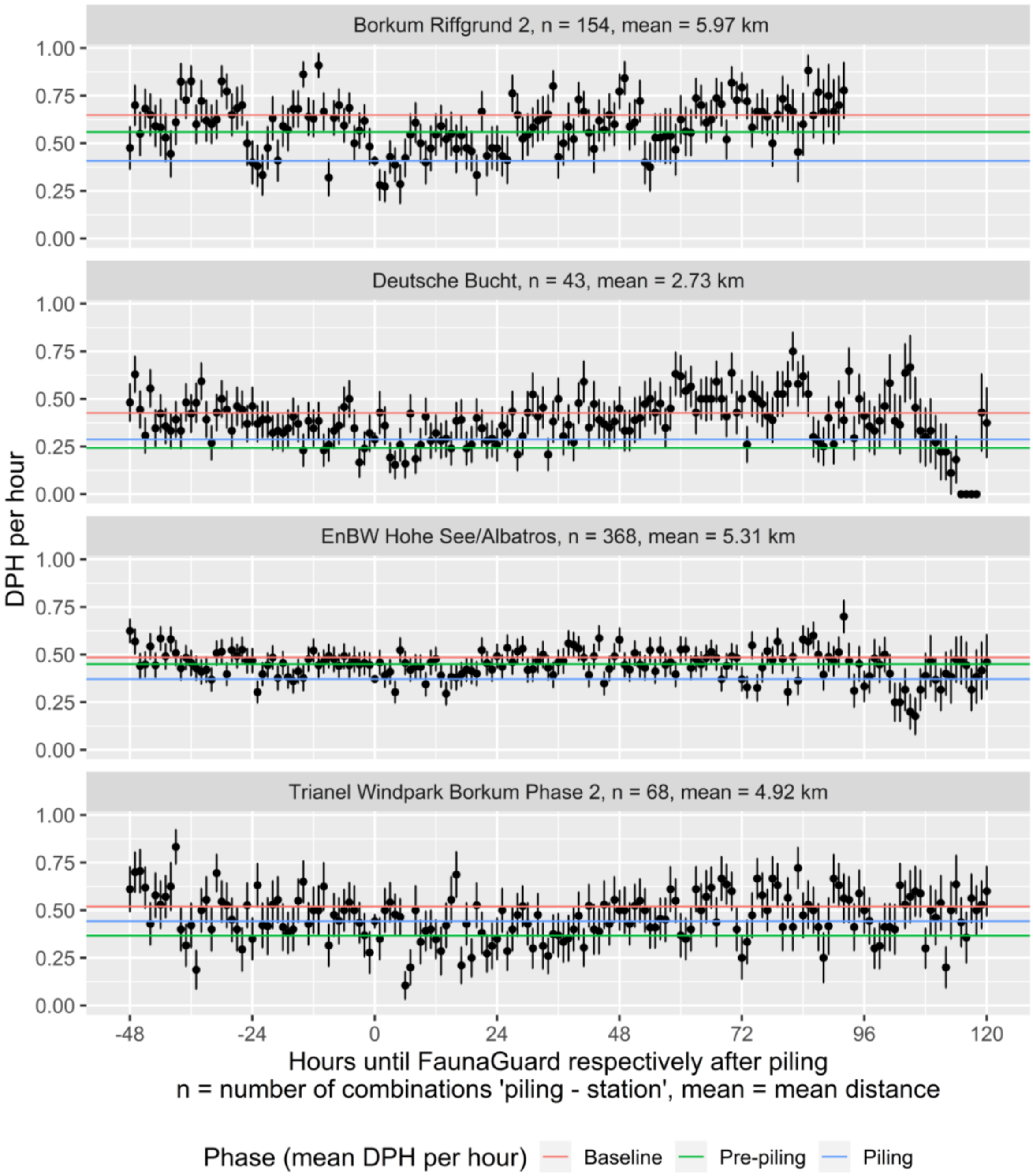


*Figure A.17 Stationary C-PODs from single OWFs: Raw data of DPH per hour (mean and standard error) from 48 daytime hours before the deployment of the FaunaGuard until 120 hours after piling; distance class 0-10 km from piling locations. Mean values for the phases Baseline, Pre-piling and Piling for each distance class are shown as horizontal lines (values from Table A.9).*

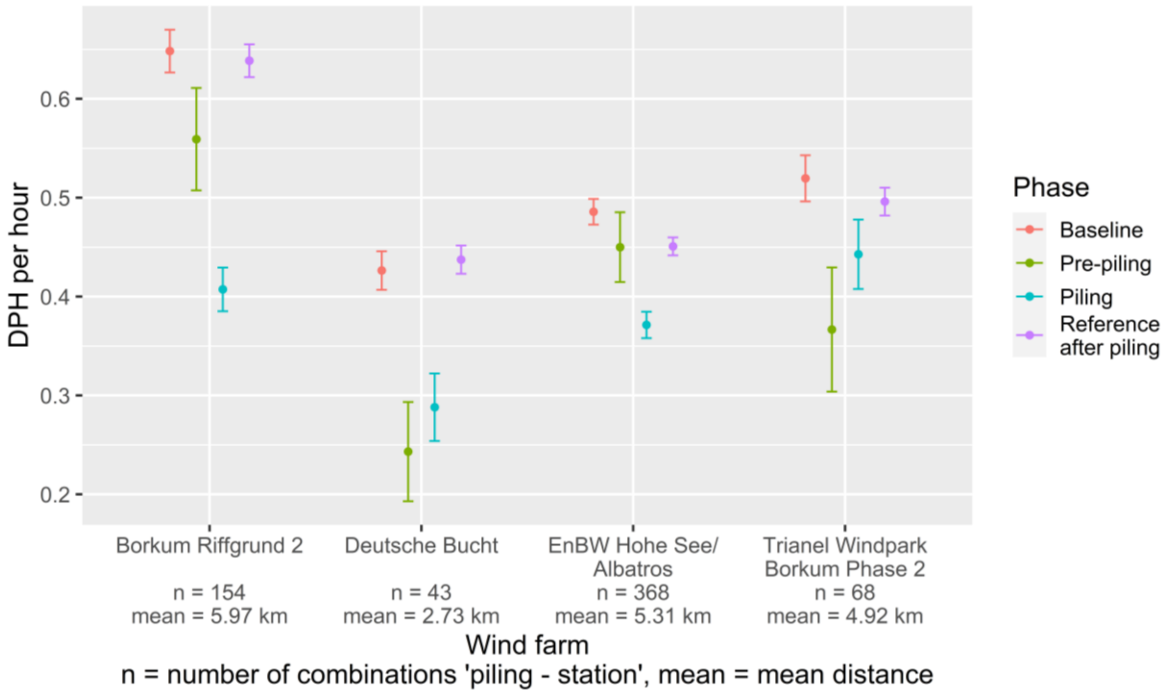


*Figure A.18 Stationary C-PODs from single OWFs: DPH per hour (mean and standard error) during the four investigated phases; distance class 0-10 km from piling locations.*

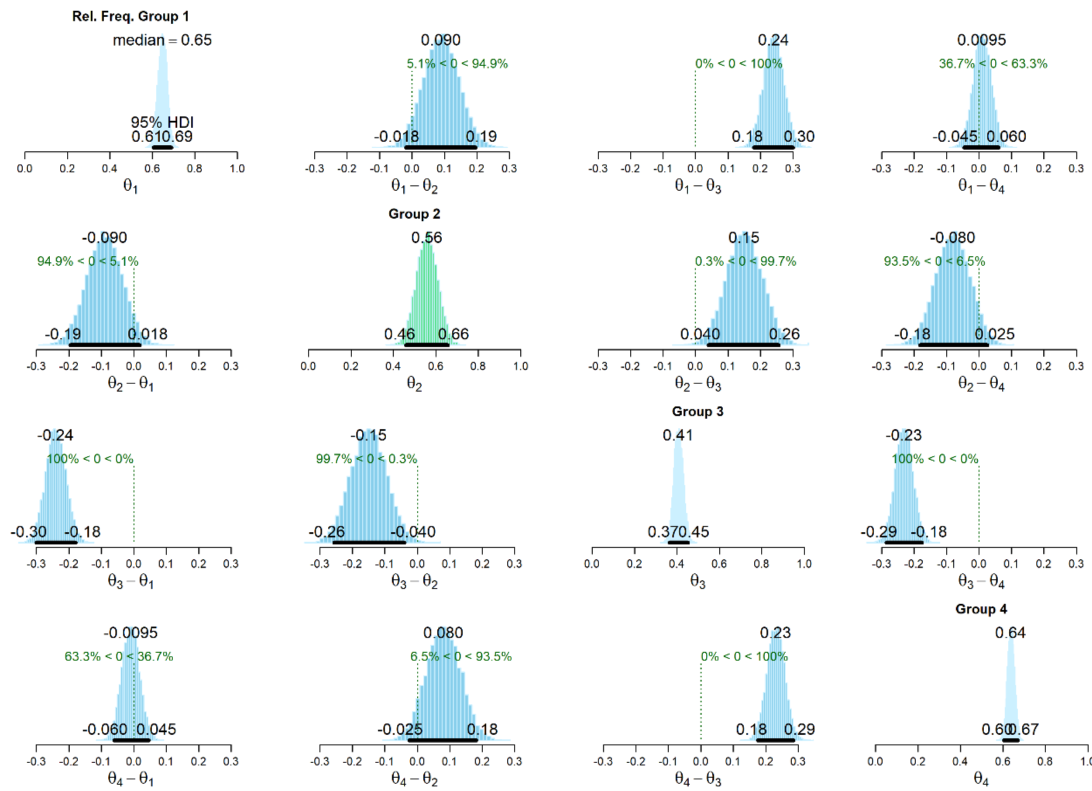


*Figure A.19 Plots of pairwise Bayesian proportion tests for the stationary C-POD dataset from the OWF "Borkum Riffgrund 2", using the parameter DPH per hour; distance class 0-10 km from piling locations; groups in sequence of Table 4.7. Further explanations are given in Figure 4.3; for test results see Table A.11.*

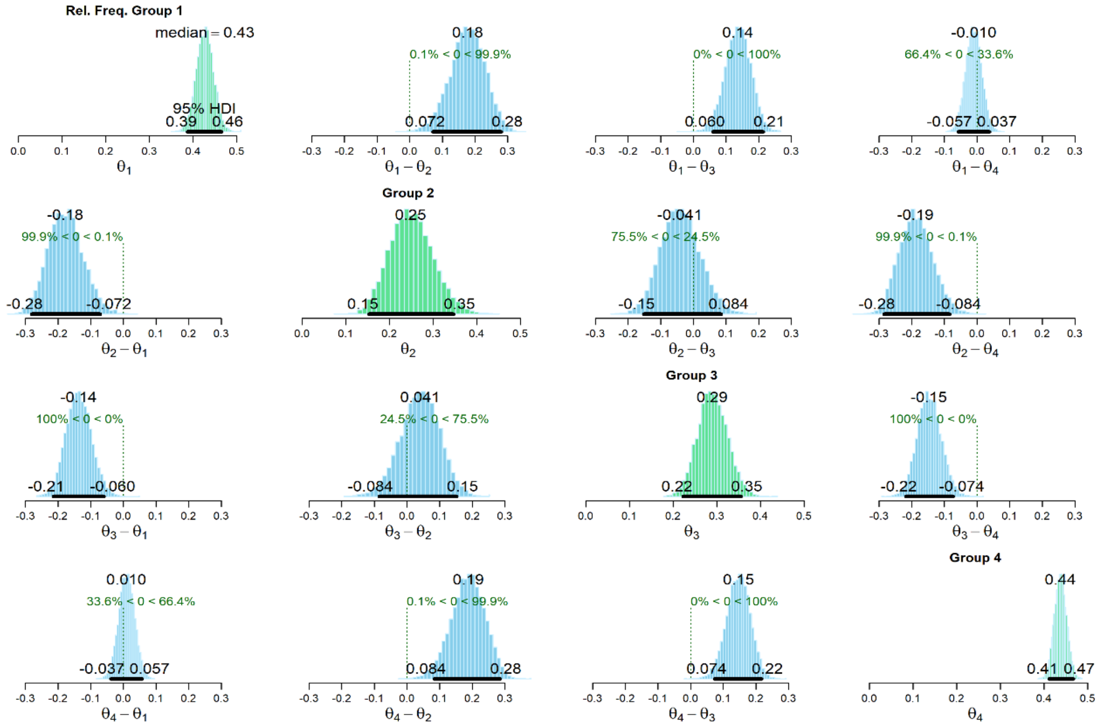


*Figure A.20* *Plots of pairwise Bayesian proportion tests for the stationary C-POD dataset from the OWF “Deutsche Bucht”, using the parameter DPH per hour; distance class 0-10 km from piling locations; groups in sequence of Table 4.7. Further explanations are given in Figure 4.3; for test results see Table A.11.*

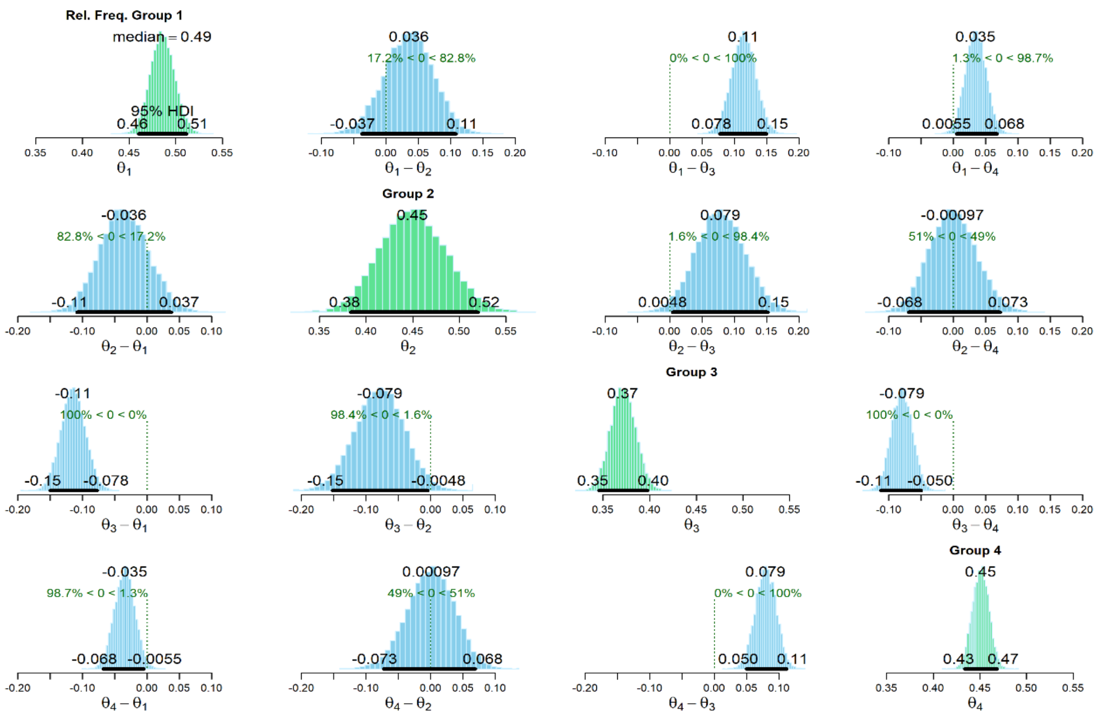


*Figure A.21* *Plots of pairwise Bayesian proportion tests for the stationary C-POD dataset from the OWFs “EnBW Hohe See” and “Albatros”, using the parameter DPH per hour; distance class 0-10 km from piling locations. No plot for the OWF “Trianel Windpark Borkum Phase 2” is shown as the overall test was not significant; groups in sequence of Table 4.7. Further explanations are given in Figure 4.3; for test results see Table A.11.*

*Table A.10 Mean values of DPH per hour (N, mean, standard deviation and error) at the single OWFs for the four investigated phases in the distance class 0-10 km from piling locations.*

| Wind farm (mean distance) | Phase | *DPH per hour* | | | |
|---|---|---|---|---|---|
| | | N (number of hours) | Mean | Standard deviation | Standard error |
| **Borkum Riffgrund 2 (5.97 km)** | Baseline | 489 | 0.65 | 0.48 | 0.022 |
| | Pre-piling | 93 | 0.56 | 0.50 | 0.052 |
| | Piling | 496 | 0.41 | 0.49 | 0.022 |
| | Reference after piling | 841 | 0.64 | 0.48 | 0.017 |
| **Deutsche Bucht (2.73 km)** | Baseline | 645 | 0.43 | 0.49 | 0.019 |
| | Pre-piling | 74 | 0.24 | 0.43 | 0.050 |
| | Piling | 177 | 0.29 | 0.45 | 0.034 |
| | Reference after piling | 1,212 | 0.44 | 0.50 | 0.014 |
| **EnBW Hohe See/Albatros (5.31 km)** | Baseline | 1,478 | 0.49 | 0.50 | 0.013 |
| | Pre-piling | 200 | 0.45 | 0.50 | 0.035 |
| | Piling | 1,306 | 0.37 | 0.48 | 0.013 |
| | Reference after piling | 3,026 | 0.45 | 0.50 | 0.0090 |
| **Trianel Windpark Borkum Phase 2 (4.92 km)** | Baseline | 460 | 0.52 | 0.50 | 0.023 |
| | Pre-piling | 60 | 0.37 | 0.49 | 0.063 |
| | Piling | 201 | 0.44 | 0.50 | 0.035 |
| | Reference after piling | 1,272 | 0.50 | 0.50 | 0.014 |

*Table A.11 Results of the overall and pairwise Bayesian proportion tests for single OWFs; parameter DPH per hour; distance class 0-10 km from piling locations; visualisation of test results in Figure A.19 to Figure A.21.*

| OWF | Comparison | | Probability of equality | Significance |
|---|---|---|---|---|
| **Borkum Riffgrund 2** | 4-sample test for equality of proportions without continuity correction | | X-squared = 81.91; df = 3<br>p-value < 2.2e-16* | |
| | Baseline | Pre-piling | 5.1 % | ns |
| | Baseline | Piling | 0 % | * |
| | Baseline | Reference after piling | 36.7 % | ns |
| | Pre-piling | Piling | 0.3 % | * |
| | Pre-piling | Reference after piling | 6.5 % | ns |
| | Piling | Reference after piling | 0 % | * |
| **Deutsche Bucht** | 4-sample test for equality of proportions without continuity correction | | X-squared = 23.56; df = 3<br>p-value = 3.09e-05* | |
| | Baseline | Pre-piling | 0.1 % | * |
| | Baseline | Piling | 0 % | * |
| | Baseline | Reference after piling | 33.6 % | ns |
| | Pre-piling | Piling | 24.5 % | ns |
| | Pre-piling | Reference after piling | 0.1 % | * |
| | Piling | Reference after piling | 0 % | * |
| **EnBW Hohe See/Albatros** | 4-sample test for equality of proportions without continuity correction | | X-squared = 38.91; df = 3<br>p-value = 1.82e-08* | |
| | Baseline | Pre-piling | 17.2 % | ns |
| | Baseline | Piling | 0 % | * |
| | Baseline | Reference after piling | 1.3 % | * |
| | Pre-piling | Piling | 1.6 % | * |
| | Pre-piling | Reference after piling | 49 % | ns |
| | Piling | Reference after piling | 0 % | * |
| **Trianel Wind-park Borkum Phase 2** | 4-sample test for equality of proportions without continuity correction | | X-squared = 7.20; df = 3<br>p-value = 6.58e-02 *ns* | |