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MASTER THESIS

Response of harbour porpoises (*Phocoena phocoena* L., 1758) to the FaunaGuard and subsequent piling during the construction of offshore wind farms

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In the following text, the FaunaGuard Porpoise module is abbreviated as FaunaGuard. It is not intended to be an advertisement for the company that sells the FaunaGuard. Even though it is a brand name, we declare we have no competing interests. To our knowledge, the FaunaGuard is only marketed by one company as a harbour porpoise scarer and is therefore usually referred to in the scientific community as FaunaGuard. In comparison, the seal scarer is marketed by different companies, so that in this study no brand names were used.

Abstract

To reduce greenhouse gas emissions, an increasing amount of energy is being generated from offshore wind farms. Their construction and operation might cause severe disturbance for the harbour porpoise, the only cetacean species breeding in the German Bight. Offshore wind turbines are hardly audible to harbour porpoises in their vicinity, but during the foundation process considerable noise emissions are produced which can affect the behaviour and – depending on the distance from the sound source – cause temporary hearing threshold shift, permanent hearing threshold shift or even death of harbour porpoises. In order to minimise these effects, noise mitigation systems during pile driving and acoustic harassment devices to drive harbour porpoises out of the endangered area before pile driving were developed.

Until 2017, the seal scarer was mandatory as acoustic harassment device. However, seal scarers led to decreased porpoise detection rates in much larger distances than intended, when 1 km is usually rendered sufficient to avoid temporary and permanent hearing threshold shift. Therefore, the FaunaGuard Porpoise module is now prescribed and used as deterrent device. The development of the FaunaGuard on the one hand aimed at deterring all harbour porpoises from a radius of 1 km around offshore wind farm piling locations before the start of noise-intensive piling. On the other hand, it was intended that deterrence by a FaunaGuard should not lead to such large-scale disturbance as caused by a seal scarer (partly 7 km and more).

Although the respective project-specific evaluations indicated that a FaunaGuard is highly effective, a cross-project analysis and a comparison with data from the previous procedure for piling with previous seal scarer operation were still pending. Thus, this study investigated the following research topic: How do harbour porpoises respond to the FaunaGuard and subsequent piling during the construction of offshore wind farms in the North Sea, in comparison to the seal scarer as acoustic harassment device?

In four offshore wind farm projects, harbour porpoise detection rates were monitored acoustically: (1) Continuously every minute at different distances from the piling, and (2) every minute from a few hours before FaunaGuard operation until a few hours after the piling at 750 m and 1,500 m distance from the piling. Stationary and mobile Cetacean Porpoise Detectors (C-PODs) were used for this purpose. Assuming that the detection

rates indicate the physical presence and absence of harbour porpoises, this study showed the following:

(1) The detection rates of harbour porpoises were decreased by 48 % during FaunaGuard operation at smaller distances up to around 1.5 km, compared to a period of on average six hours before the operation of the device, without leading to long-term deterrence.

(2) During the operation of the FaunaGuard, reduced detection rates were observed only up to a distance of around 2 to 2.5 km, so that in contrast to the seal scarer, obviously no large-scale disturbance occurred.

(3) In spite of environmental differences among the offshore wind farms, detection rates decreased between 37 % and 75 % during FaunaGuard operation in the vicinity of piling locations. Furthermore, no far-reaching disturbance and long-term deterrence were to be expected in any of the wind farms positioned in different regions of the German Bight, North Sea. Therefore, the FaunaGuard appeared to be applicable in various areas in the North Sea for scaring harbour porpoises away from the danger zone around the pile-driving site.

(4) After the first 20 to 25 minutes of FaunaGuard operation, harbour porpoise detection rates nearly declined to zero in the close range of up to 1.25 km distance. Longer operation times of the device seemed to lead only to a small increase in the maximum distance and intensity of deterrence.

(5) At close range, no meaningful differences were found between the FaunaGuard and the seal scarer. However, in 5 to 10 km distance (mean around 8 km), the seal scarer had a much more far-reaching effect than the FaunaGuard. The detection rates during FaunaGuard operation decreased by only 12 % compared to the detection rates in the six hours before, but by 94 % when using a seal scarer. Due to the shorter effect range of the FaunaGuard as well as to improved noise mitigation systems, the response to the FaunaGuard and subsequent pile driving at larger distances seemed to be lower than shown by studies where pilings with a seal scarer as acoustic harassment device were investigated.

The FaunaGuard was assessed as a highly effective acoustic harassment device to displace harbour porpoises from a small-scale area in the short term and thus to prevent a temporary or permanent hearing threshold shift. All results from the present study indicated that a FaunaGuard should be used instead of a seal scarer for future construction of offshore wind farms, assuming there is no habituation effect. Although this study only covers projects in the North Sea, we suppose that the FaunaGuard will also work in the Baltic Sea. The FaunaGuard is an important step forward to a less harmful piling procedure in the North and Baltic Seas.

Zusammenfassung

Um die Treibhausgasemissionen zu reduzieren, wird immer mehr Energie aus Offshore-Windparks erzeugt. Deren Bau und Betrieb kann jedoch Schweinswale beeinträchtigen – die einzige sich in der Deutschen Bucht fortpflanzende Walart. Zwar scheinen Schweinswale sich durch in Betrieb befindliche Offshore-Windenergieanlagen in ihrer Umgebung kaum stören zu lassen, jedoch entstehen während des Fundamentbaus Schallemissionen mit erheblichem Störpotenzial. Diese können das Verhalten beeinflussen und je nach Entfernung zur Schallquelle vorübergehende oder dauerhafte Hörschwellenverschiebungen oder sogar den Tod von Schweinswalen verursachen. Um derartige Auswirkungen zu vermeiden, werden Schallschutzsysteme während sowie akustische Vergrämer vor Rammungen eingesetzt, wobei letztere die Schweinswale bereits vor der lärmintensiven Phase aus dem gefährdeten Gebiet vertreiben sollen.

Bis 2017 war der Sealscarer als akustisches Abschreckungsmittel vorgeschrieben. Der Sealscarer führte jedoch zu geringeren Detektionsraten von Schweinswalen in viel größeren Entfernungen als vorgesehen, denn 1 km reicht üblicherweise aus, um vorübergehende und dauerhafte Hörschwellenverschiebungen zu vermeiden. Daher ist mittlerweile der FaunaGuard (hierbei das Schweinswalmodul) vorgeschrieben und wird als Abschreckungsmittel eingesetzt. Die Entwicklung des FaunaGuards zielte einerseits darauf ab, alle Schweinswale aus einem Radius von 1 km um Baustellen von Offshore-Windparks vor dem Beginn lärmintensiver Rammungen zu vertreiben. Zum anderen sollte die Abschreckung durch den FaunaGuard nicht zu so großflächigen Störungen führen, wie sie durch den Sealscarer verursacht wurden (teilweise 7 km und mehr).

Obwohl die jeweiligen projektspezifischen Auswertungen auf eine hohe Wirksamkeit des FaunaGuards hindeuteten, standen eine projektübergreifende Analyse und ein Vergleich mit Daten aus dem bisherigen Verfahren (Rammung mit vorheriger Vergrämung durch einen Sealscarer) noch aus. Daher untersuchte die vorliegende Studie das folgende Thema: Wie reagieren Schweinswale beim Bau von Offshore-Windparks in der Nordsee auf den Einsatz des FaunaGuards bei Rammungen im Vergleich zu Rammungen mit dem Sealscarer als Vergrämer?

Bei vier Offshore-Windparkprojekten wurde die Schweinswalaktivität akustisch erfasst: (1) Kontinuierlich jede Minute in verschiedenen Entfernungen zum Pfahl und (2) jede

Minute von einigen Stunden vor dem FaunaGuard-Einsatz bis einige Stunden nach der Rammung in 750 m und 1.500 m Entfernung zum Pfahl. Dazu wurden stationäre und mobile Schweinswaldetektoren (C-PODs) eingesetzt. Unter der Annahme, dass die Detektionsraten die physische An- und Abwesenheit von Schweinswalen anzeigen, ergab diese Studie Folgendes:

(1) Die Detektionsraten von Schweinswalen sanken während des FaunaGuard-Einsatzes in Entfernungen bis etwa 1,5 km um 48 % im Vergleich zu einer Phase durchschnittlich sechs Stunden vor dem Einsatz des Gerätes, ohne dass dies zu einer langfristigen Vergrämung führte.

(2) Während des FaunaGuard-Einsatzes wurden verringerte Detektionsraten nur bis zu einer Entfernung von etwa 2 bis 2,5 km beobachtet, sodass im Gegensatz zum Sealscarer offensichtlich keine großflächigen Störungen auftraten.

(3) Trotz der regionalen Umweltunterschieden zwischen den Offshore-Windparks verringerten sich die Detektionsraten während des FaunaGuard-Einsatzes in der Nähe von Baustellen um zwischen 37 % und 75 %. In keinem der Windparks, die in verschiedenen Regionen der Deutschen Bucht in der Nordsee liegen, war nach den Ergebnissen eine weitreichende Störung und langfristige Abschreckung zu erwarten. Daher schien der FaunaGuard in diversen Gebieten der Nordsee anwendbar zu sein, um Schweinswale aus dem Gefahrenbereich um den Rammstandort zu verscheuchen.

(4) Während der ersten 20 bis 25 Minuten des FaunaGuard-Einsatzes sanken die Detektionsraten der Schweinswale im Nahbereich (bis zu 1,25 km Entfernung) auf nahezu Null. Eine längere Einsatzdauer schien nur zu einem geringen Anstieg der maximalen Reichweite und Intensität des Vergrämungseffektes zu führen.

(5) Im Nahbereich wurden keine signifikanten Unterschiede zwischen den Effekten des Sealscarers und des FaunaGuards festgestellt. Allerdings hatte der Sealscarer in 5 bis 10 km Entfernung (Mittelwert etwa 8 km) eine deutlich stärkere Wirkung als der FaunaGuard. Die Detektionsraten während des FaunaGuard-Einsatzes sanken im Vergleich zu den Detektionsraten in den sechs Stunden davor nur um 12 %, beim Einsatz eines Sealscarers jedoch um 94 %. Aufgrund des geringeren Wirkungsbereichs des FaunaGuards sowie verbesserter Schallschutzsysteme schien die Reaktion auf den FaunaGuard und die anschließende Rammung in größeren Entfernungen geringer zu sein

als in anderen Studien, in denen Rammarbeiten mit dem Sealscarer als Vergrämer untersucht wurden.

Der FaunaGuard wurde als hochwirksames akustisches Vergrämungsgerät eingestuft, um Schweinswale kurzfristig aus einem kleinräumigen lärmgefährdeten Gebiet zu vertreiben und damit eine temporäre oder dauerhafte Hörschwellenverschiebung zu verhindern. Die Ergebnisse der vorliegenden Studie zeigten, dass der FaunaGuard beim zukünftigen Bau von Offshore-Windparks anstelle des Sealscarers eingesetzt werden sollte – dies unter der Voraussetzung, dass kein Gewöhnungseffekt eintritt. Obwohl diese Studie nur Windpark-Projekte in der Nordsee umfasst, ist davon auszugehen, dass der FaunaGuard auch in der Ostsee ähnlich effektiv ist. Der Einsatz des FaunaGuards als Vergrämer ist somit als ein wichtiger Schritt hin zu einem den Schweinswal weniger stark beeinträchtigenden Rammverfahren in der Nord- und Ostsee anzusehen.

1. Introduction

Renewable energies: Offshore wind energy

According to the Paris Climate Convention, Germany intends a 55 % reduction in greenhouse gas emissions by 2030 compared to the emissions in 1990 (DEUTSCHER BUNDESTAG 2018). By 2050, the country aims to reduce greenhouse gas emissions by 80 to 95 %, and thus to become almost climate-neutral.

The largest source of anthropogenic greenhouse gas emissions in 2018 was the energy sector accounting for 83.9 % (UMWELTBUNDESAMT 2019). Therefore, to achieve the climate targets, the proportion of renewable energies in electricity consumption has to increase further.

The German Renewable Energy Sources Act (EEG) stated that by 2025 at least 40 to 45 % and by 2050 at least 80 % of the electricity consumed in Germany should be generated from renewable energies (BUNDESMINISTERIUM FÜR WIRTSCHAFT UND ENERGIE 2020b). In 2000, electricity originating from renewable energies amounted to around 6 %, and by 2018 the ratio had already reached 38 % (UBA 2019). 40.9 % of the renewable electricity generation in Germany was generated by onshore wind farms and 8.6 % was produced by offshore wind farms (OWFs).

According to the EEG, it was planned to install 6,500 MW of wind power capacity in German waters by 2020 (BUNDESMINISTERIUM FÜR WIRTSCHAFT UND ENERGIE 2020b). With 7,516 MW and 1,469 turbines being installed until January 2020, the capacity goals have clearly been met (BUNDESVERBAND WINDENERGIE 2020). By now, far more than 20 wind farms in the German parts of the North Sea and Baltic Sea are generating energy. Offshore wind farms provide electricity on about 363 out of 365 days and thus almost the entire year (KNORR et al. 2017). On regular days, Germany needs a capacity of 65 to 70 gigawatts (PRESSE- UND INFORMATIONSAMT DER BUNDESREGIERUNG 2020). Offshore energy thus contributes to about 10 % of the required capacity.

Furthermore, the EEG plans a further expansion of offshore wind energy. Initially, the aim was to install 15,000 MW of wind power capacity by 2030 (BUNDESMINISTERIUM FÜR WIRTSCHAFT UND ENERGIE 2020b). This goal was extended in November 2020 to capacities of 20,000 MW by 2030, respectively 30,000 MW by 2040 (BUNDESMINISTERIUM FÜR WIRTSCHAFT UND ENERGIE 2020a).

When offshore wind farms are in operation, the foundations create a new habitat, and excluding fishing has a positive effect on the local abundance of marine organisms (BERGSTRÖM et al. 2014). At the same time, the electromagnetic fields and the acoustic disturbance may have a negative impact on the ecosystem.

Acoustic disturbances mainly affect marine mammals, which in the German Bight of the North Sea primarily concerns harbour seals (*Phoca vitulina* L., 1758), grey seals (*Halichoerus grypus* Fabricius, 1791) and harbour porpoises (*Phocoena phocoena* L., 1758). Habour seals and grey seals in Europe are classified as "least concern" on the IUCN Red List of Threatened Species (EUROPEAN MAMMAL ASSESSMENT TEAM 2007a; b). However, harbour porpoises in Europe are classified as "vulnerable", having had a declining population trend at that time (SPECIES ACCOUNT BY IUCN SSC CETACEAN SPECIALIST GROUP; REGIONAL ASSESSMENT BY EUROPEAN MAMMAL ASSESSMENT TEAM 2007). Therefore, the two seal species are listed in Annex V of the EU Habitats Directive, so their exploitation is compatible with maintaining them in a favourable conservation status, whereas harbour porpoises are listed in Annex IV, so this species must not be significantly disturbed (EUROPEAN COMMISSION 2007). Consequently, harbour porpoises are used as indicator species and have to be taken into account when authorising the construction of offshore wind farms.

Harbour porpoises as indicator species for the effects of noise pollution during the construction of offshore wind farms

Harbour porpoises are the most common cetaceans in the continental shelf waters of north-western Europe (REID et al. 2003). Approximately 350,000 to 370,000 animals are estimated to live in the North Sea and adjacent waters (HAMMOND et al. 2013, 2017). In particular the German Bight – the present study area – is considered to be an area with relatively high harbour porpoise densities (GILLES et al. 2009; PESCHKO et al. 2016). The porpoise distribution within the German Bight appears to be very heterogeneous, as the MINOS projects (GILLES et al. 2007) and the BfN monitoring (GILLES & SIEBERT 2010; GILLES et al. 2011b, 2013, 2014; VIQUERAT et al. 2015) showed. Certain environmental factors govern this unequal distribution of harbour porpoises, as the animals generally prefer areas with e. g. high chlorophyll concentration, low salinity and steep bottom slopes; such conditions often coincide with an increased food supply, e. g. a high abundance of sand eels (SANTOS et al. 2004; GILLES et al. 2011a; STALDER et al. 2020). However, even though trends vary among sub-regions of the North Sea (NACHTSHEIM et al. 2021) and a high year-to-year variability occurs, the population in the German Bight seems to be rather stable (BIOCONSULT SH ET AL. 2019).

Threats of harbour porpoises include chemical contamination (JOIRIS et al. 1991; KAKUSCHKE & PRANGE 2007; WEIJS et al. 2010; MAHFOUZ et al. 2014), gillnet fishery leading to by-catch (KOCK & BENKE 1996; VINTHER & LARSEN 2004; HERR et al. 2009; BJØRGE et al. 2013; IJSSELDIJK et al. 2020), 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).

Underwater noise in general can affect the individual fitness and structure of ecological communities (SOUTHALL et al. 2007, 2019). The response of marine mammals to underwater 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 source level, frequency and temporal characteristics like the duration and number of pile drivings within a short period of time are crucial. Whether 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 the receiver, in other words the behavioural response of the animal, factors such as hearing ability, behavioural context, distance to the source, previous exposures, demographics and food availability are decisive (ERBE et al. 2016). For example, 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 and it takes longer for animals to return to these areas after noise exposure. Accordingly, each harbour porpoise reacts in its individual context to noise during the construction of offshore wind farms.

Since harbour porpoises use echolocation for orientation, foraging and intraspecific communication regardless of light conditions (KOSCHINSKI et al. 2008; VERFUß et al. 2009), this species has strong hearing abilities: The hearing range extends from below 1 kHz to about 180 kHz (KASTELEIN et al. 2002). The greatest hearing sensitivity is between 100 and 140 kHz, in which case the hearing threshold is about 33 dB re 1 µPa. In this range, namely around 130 kHz, their echolocation click frequencies are centered

(MØHL & ANDERSEN 1973; TEILMANN et al. 2002). Below 16 kHz and above 140 kHz, sensitivity decreases about 10 dB, respectively 260 dB, per octave, and thus the hearing threshold rises sharply (KASTELEIN et al. 2002).

Operating offshore wind turbines are barely audible to harbour porpoises at distances above 70 m from the foundation. Hence, behavioural responses to their noise seem unlikely, except when the animals are very close to the foundation (TOUGAARD et al. 2009b). However, a large proportion of offshore wind farms are built on steel foundations, which in turn are piled into the seabed. This generates considerable noise emissions during construction, which can affect behaviour and lead to a temporary hearing threshold shift (TTS), permanent hearing threshold shift (PTS), or even the death of harbour porpoises depending on the distance towards the sound source (KASTELEIN et al. 2011). Therefore, harbour porpoises have been found often to move away from loud construction activities for offshore wind farms (JOHNSTON 2002; OLESIUK et al. 2002; BRANDT et al. 2013b). Piling is expected to affect the detection rates of harbour porpoises up to distances of around 15 to 20 km during piling, and a negative effect lasting from 28 hours before until 48 hours after piling (CARSTENSEN et al. 2006; TOUGAARD et al. 2009a; BRANDT et al. 2011; DÄHNE et al. 2013; BIOCONSULT SH ET AL. 2019). At the OWF "Horns Rev II" in the Danish North Sea, the detection rates of harbour porpoises were reduced by 100 % during the hour following pile driving at a distance of 2.6 km from the piling location (BRANDT et al. 2011).

In order to minimise the effects of noise emissions during piling, the German Federal Maritime and Hydrographic Agency (BSH) set a dual noise protection criterion (BSH 2013): The upper 5 % percentile of the Sound Exposure Level (SEL_{05}) must stay below 160 dB re 1 µPa² s, and the Peak Level (L_{Peak}) below 190 dB re 1 µPa at a distance of 750 m to pile driving.

As to the first criterion, the Sound Exposure Level (SEL) is a measure of energy that considers the received level as well as the duration of exposure. The SEL_{05} describes the SEL that was exceeded by 5 % of all analysed single strikes over a certain time interval (mostly over the piling strikes for one foundation). Therefore, the SEL_{05} mostly characterises the end of the pile-driving process with the highest blow energy (BELLMANN et al. 2020).

As to the second criterion, the Sound Pressure Level (SPL) is a tool for describing the amplitude of a sound. The Peak Level (L_{Peak}) describes the zero-to-peak SPL for a single strike.

Due to the continuous development of noise mitigation systems (NMS), many construction projects now comply with these two limits or even fall below them (BSH 2013).

Noise mitigation systems during the construction of offshore wind farms

One of the best studied noise mitigation systems (NMS) under offshore conditions is the Big Bubble Curtain (BBC). Here, a perforated pipe ring is located on the seabed and surrounds the foundation structure. Compressors inject air into the perforated nozzle hose, out of which the bubbles rise and form a curtain around the foundation structure. In the Double Big Bubble Curtain (DBBC), two BBCs are positioned one behind another. At a Danish wind farm, the BBC was able to reduce the SEL_{05} by on average 13 dB re 1 µPa² s and the L_{Peak} by on average 14 dB re 1 µPa over a sequence of 95 consecutive pile strikes (LUCKE et al. 2011; BELLMANN & REMMERS 2013; DÄHNE et al. 2017).

Instead of free gas bubbles as with the BBC, Hydro Sound Dampers (HSD) use elastic air-filled balloons or rigid PE foam elements to reduce noise emissions. Here, the SEL_{05} is reduced on average by 10 dB re 1 µPa² s (BELLMANN 2014).

Pile sleeves are another kind of NMS. Here, a steel pipe is placed over the foundation pile. In one particular type of this NMS category – the IHC – the space between the inner and outer cladding tube is filled with air and a bubble curtain is created between the IHC and the pile. Using this technique, the SEL_{05} is reduced by an average of 12 dB re 1 µPa² s (BELLMANN 2014).

Although NMS have been developed further and as a result the noise emission limit values were most often being met or even undercut, the detectable avoidance distance of harbour porpoises did not decrease any further for various wind farms (BIOCONSULT SH ET AL. 2019). Pile driving in a German wind farm in 2014 and 2015 was found to have caused potential TTS after multiple exposure even up to a distance of 5.6 km (SCHAFFELD et al. 2020). This lead to the hypothesis that the range in the animals' response is not only depending on the noise emission during piling, but also possibly on the effects of the acoustic harassment device (AHD) in use.

Acoustic harassment devices during the construction of offshore wind farms

Additionally to noise reduction, the BSH requires a standardised deterrence procedure before the start of pile driving in order to scare all harbour porpoises away from the area where they eventually could suffer TTS or even PTS. For this purpose, acoustic harassment devices are used, which emit acoustic signals before construction works begin.

Until 2017, the seal scarer was mandated as AHD. This device was primarily developed to reduce economic losses at fish farms due to seal predation. It emits pulses with a fundamental frequency of 14.5 kHz and a duration of around 0.55 s with random pauses between the pulses from less than 1 up to 90 s (BRANDT et al. 2013a). However, seal scarers also drive away harbour porpoises and were used accordingly to deter these animals from the endangered area before piling begins.

When using a seal scarer, the sighting rates of harbour porpoises within 1 km distance from the device decreased significantly to only 1 %, but acoustic recordings showed also a significant deterrence effect on harbour porpoises up to 7.5 km distance and thus in a much larger range than intended (BRANDT et al. 2013a; b). The seal scarer alone also appears to have the potential to induce a TTS (SCHAFFELD et al. 2019), so it became questionable whether it is adequate for the desired task.

For the projects “Borkum Riffgrund 2”, “Deutsche Bucht”, “EnBW Hohe See” and “Albatros”, “Trianel Windpark Borkum Phase 2” and “Arkona-Becken Südost”, the FaunaGuard was therefore prescribed and used as AHD. Van Oord and the Dutch company SEAMARCO (Sea Mammal Research Company) developed it a few years ago (VAN DER MEIJ et al. 2015).

Like the seal scarer, the FaunaGuard aims at deterring all harbour porpoises from a radius of 1 km around the piling location before the start of noise-intensive pile driving, but on the other hand was intended not to lead to large-scale disturbance as produced by the seal scarer. In comparison, the FaunaGuard was designed specifically for the deterrence of harbour porpoises and thus emits signals at higher frequencies (40 kHz to 100 kHz,

SEL_{05} = 149 dB re 1 µPa² s at 85 kHz) than a seal scarer (13.5 to 15 kHz, SEL_{05} = 189 dB re 1 µPa² s). In this frequency range, harbour porpoises have better hearing abilities, so that a lower sound volume is necessary for harbour porpoise deterrence. Accordingly, a porpoise response threshold of 86 dB re 1 µPa was observed for acoustic signals from the FaunaGuard (KASTELEIN et al. 2017). At this or a higher SPL, the distance of harbour porpoises from the FaunaGuard was significantly greater than without AHD operation, and the porpoises thus appeared to have swum away. Besides, due to stronger propagation loss of high-frequency signals, the range of the deterrent effect should be significantly smaller than that caused by the seal scarer (ROSEMEYER et al. 2021). By using a "ramp-up" function, the sound power level is gradually increased in the first five minutes after commissioning in order to avoid a sudden exposure of harbour porpoises to the full volume (VAN DER MEIJ et al. 2015). In addition, the FaunaGuard uses eight different complex signal sequences to minimise possible habituation effects.

Passive Acoustic Monitoring as appropriate measure for physical presence and absence

In all OWF projects, harbour porpoise detection rates were monitored acoustically: (1) Continuously every minute at different distances from the piling location, and (2) every minute from a few hours before FaunaGuard operation until a few hours after piling at 750 m and 1,500 m distance from the piling location. Stationary and mobile Cetacean Porpoise Detectors (C-PODs) were used for this purpose.

Detection rates of C-PODs are an approximate device to measure harbour porpoise presence since porpoises use their echolocation system almost continuously (AKAMATSU et al. 2007; WISNIEWSKA et al. 2016). Visual observations showed that there is a strong correlation between C-POD detection rates and harbour porpoise density (DIEDERICHS et al. 2002; KOSCHINSKI et al. 2003; CARSTENSEN et al. 2006; KYHN et al. 2012; WILLIAMSON et al. 2016; JACOBSON et al. 2017). In a study of wild harbour porpoises in Canada, 98 % of all visual observations were also recorded by acoustic data loggers within a distance of 150 m (KOSCHINSKI et al. 2003). In addition, harbour porpoises occur mainly solitary or in groups of two to three animals (SIEBERT et al. 2006), so that acoustic activity may serve as a rough indication for the relative abundance.

Also, the decrease in porpoise clicks when using the seal scarer as AHD and during subsequent piling is not due to a change in echolocation activity but to a displacement of the animals (BRANDT et al. 2013b; HAELTERS et al. 2015; BIOCONSULT SH et al. 2016). Captive harbour porpoises did not change their vocalisation behaviour when different high-frequency sounds were played back, except for the first exposure (TEILMANN et al. 2006). Wild harbour porpoises in Canada even increased echolocation activity when wind turbine sounds were played (KOSCHINSKI et al. 2003).

For the FaunaGuard as AHD, one harbour porpoise specimen in a pool was observed to swim away from the FaunaGuard's location during its operation (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 the environment e. g. whether or not the food situation is attractive (VAN BEEST et al. 2018) which could not be studied in the pool. Therefore, a field study with visual observations and acoustic monitoring was conducted in the tidal bay between Den Helder and Texel, where almost all harbour porpoises seemed to be deterred to a distance of at least 1,000 m during FaunaGuard operation (GEELHOED et al. 2017). Some harbour porpoises dived considerably longer during FaunaGuard operation and were therefore not seen again, but it can be fairly assumed that these animals left the area and did not just dive longer and stay in the area.

Even though a final proof is still lacking that harbour porpoises leave the area during FaunaGuard operation and do not stop echolocation, there is currently no reason to assume that the animals in this study responded completely different to AHD signals and piling than in previous studies. Therefore, it was expected that the number of acoustic detections was a good indication for presence or even relative abundance.

Aim of study

Although former project-specific evaluations during monitoring programmes indicated that the FaunaGuard is highly effective in deterring harbour porpoises, a cross-project analysis and a comparison with data taken during the previous piling procedure with a seal scarer as AHD were still pending. The present master thesis aimed to fill this gap by investigating the following research topic: How do harbour porpoises respond to the FaunaGuard and subsequent piling during the construction of offshore wind farms in the North Sea, in comparison to the seal scarer as acoustic harassment device?

In detail, the following questions had to be answered:

1. How did the detection rates of harbour porpoises change during FaunaGuard operation at smaller distances up to 1.5 km?
2. How did the detection rates of harbour porpoises change during FaunaGuard operation at larger distances up to 20 km?
3. How did the detection rates of harbour porpoises during FaunaGuard operation differ between wind farms at smaller and larger distances?
4. What effect did the duration of operation of the FaunaGuard have on the detection rates during this phase?
5. How did the detection rates of harbour porpoises during FaunaGuard operation differ from those during seal scarer operation?

Data from mobile C-PODs in 750 m and 1,500 m distance, as well as those from stationary C-PODs being deployed at the borders of the wind farms, were evaluated on a cross-project basis regarding the effectiveness of the AHD and thus the deterrence of harbour porpoises.

Our expectations were as follows: It was supposed that the detection rates during the operation of the FaunaGuard decreased considerably up to a distance of at least 1 km. Desirably, the detection rates should not have been lowered in distances of more than 2.5 km, so that far-reaching disturbance is not an issue. Although factors such as previous exposure, age and food availability can also be decisive for the behavioural response of the individual animal (JOHNSTON 2002; OLESIUK et al. 2002; BRANDT et al. 2013b; VAN BEEST et al. 2018), during the construction process the detection rates should have changed in a similar way over all wind farms, meaning that only a small-scale, short-term decrease, and no long-term effects should be observed at each OWF. Therefore, the FaunaGuard should be applicable in various regions in the German North Sea Exclusive Economic Zone (EEZ). The FaunaGuard should best lead to an effective reduction in detection rates during operation times of about 20 to 30 minutes, which would be in accordance with the minimum time span that has been applied in the field so far. Compared to the seal scarer, the FaunaGuard was expected to lead to an at least equally effective decrease in detection rates at distances of up to 1.5 km, but not to a strong decrease beyond this range (BRANDT et al. 2013a; b).

2. Materials and methods

2.1 Study area

For this study, the wind farms “Borkum Riffgrund 2”, “Deutsche Bucht”, “EnBW Hohe See” and “Albatros”, as well as “Trianel Windpark Borkum Phase 2” were analysed (Figure 1). Pile driving took place between March 2018 and April 2019 (Table 1, Figure 2). The wind farm “Arkona-Becken Südost” was excluded as almost no harbour porpoises were recorded in this area and therefore no further conclusions could be drawn about possible effects of the FaunaGuard on the response of harbour porpoises by including these data.

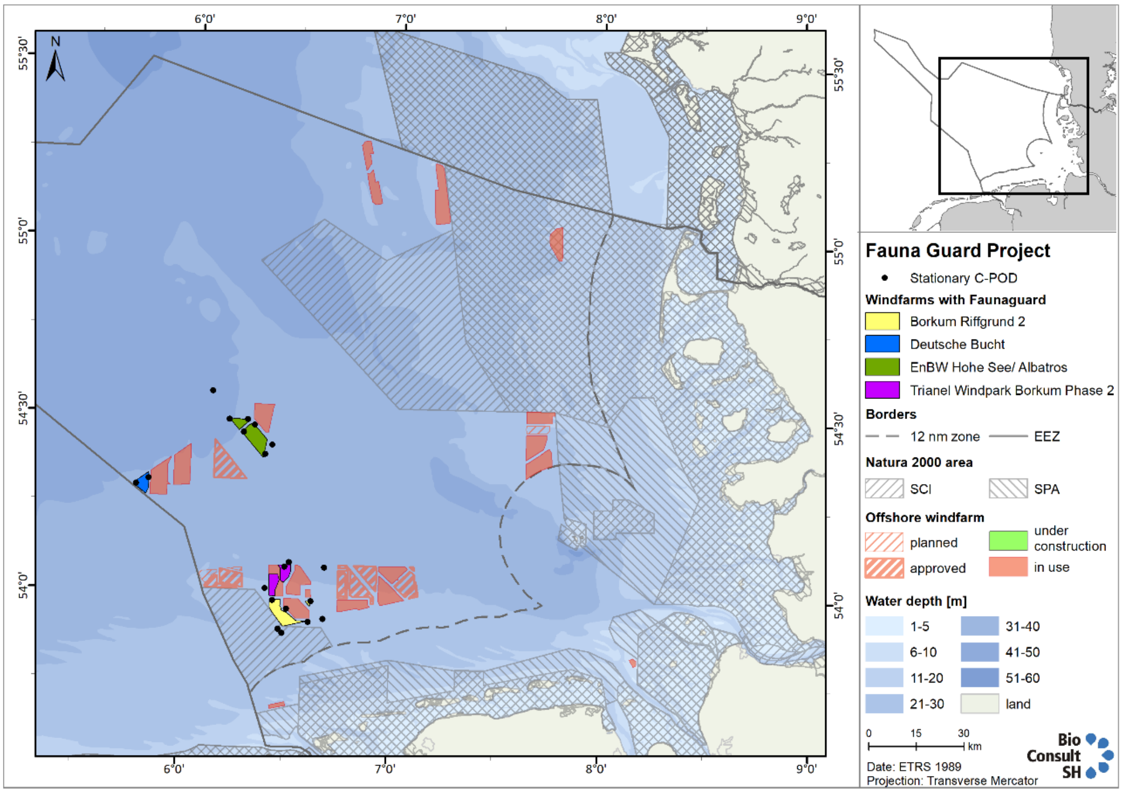

Figure 1: Study area (German Bight, North Sea) with locations of offshore wind farms with FaunaGuard operation and positions of stationary C-PODs.

Table 1: Data sets of the stationary and mobile C-PODs regarding the investigated OWF projects.

	Borkum Riffgrund 2	**Deutsche Bucht**	**EnBW Hohe See/Albatros**	**Trianel Windpark Borkum Phase 2**
Start date	2018-03-01 00:00:00	2018-04-10 00:00:00	2018-04-01 00:00:00	2018-03-01 00:00:00
End date	2018-12-31 23:00:00	2019-01-07 08:00:00	2019-04-28 12:00:00	2018-12-31 23:00:00
Number of total piles	56	32	87	32
Number of analysed piles	35	27	85	29
Number of piles using the FaunaGuard as AHD	35	27	85	26
Number of piles using the seal scarer as AHD	0	0	0	3
Stationary C-PODs: Number of stations	9	2	7	7
Stationary C-PODs: Number of hours	36,021	4,754	36,108	39,674
Mobile C-PODs: Number of stations	58	58	156	62
Mobile C-PODs: Number of hours	911.67	730.10	1,780.58	638.48

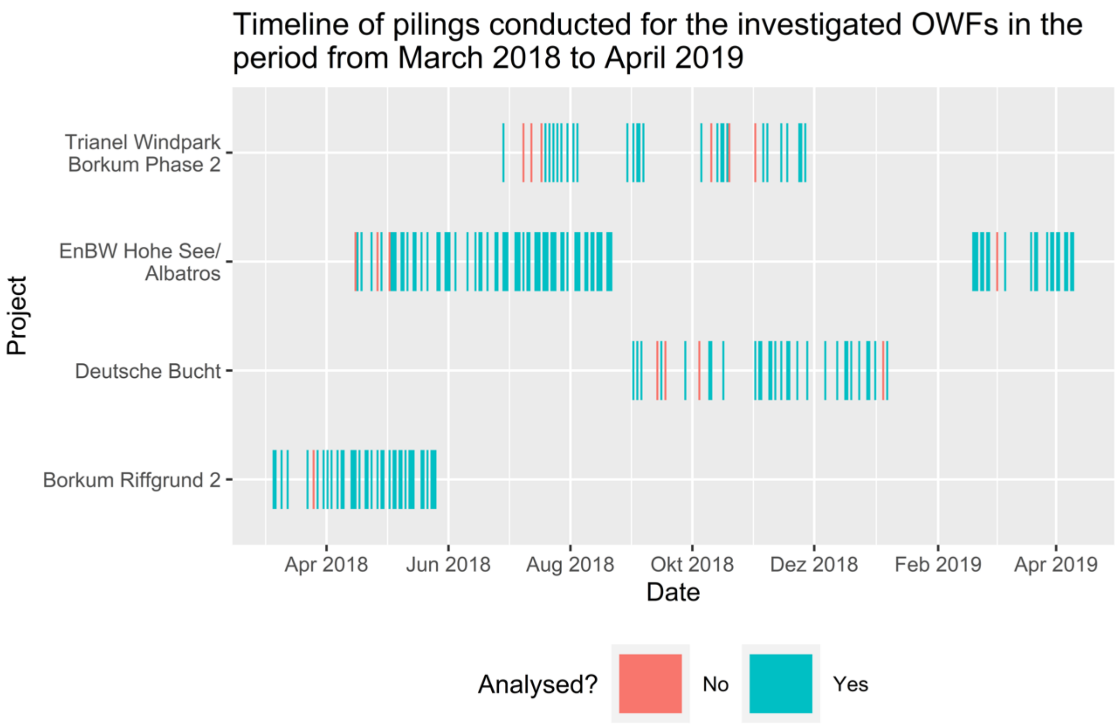

Figure 2: Timeline of pilings conducted for the investigated offshore wind farms (OWF) in the period from March 2018 to April 2019. Pilings with NMS classes "DBBC", "HSD", "IHC", "none", or "unknown" exceeded an SEL_{05} of 160 dB re 1 µPa² s at a distance of 750 m and/or an L_{Peak} of 190 dB re 1 µPa; these failed to meet the dual noise protection criterion defined by the BSH and were excluded from subsequent analyses.

The wind farm "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. For this study, only the data of the monopiles were analysed, so that pile-driving procedure and impact were comparable to those of the other wind farms. Between March and December 2018, nine C-POD stations and 58 mobile C-PODs were deployed, recording around 37,000 hours in total (Table 1). In 2019, the wind farm was officially commissioned and is now able to provide power for around 460,000 households.

The wind farm "Deutsche Bucht" is located in the German EEZ around 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 a water depth 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, recording around 5,500 hours in total (Table 1). All turbines were commissioned in September 2019 and the wind farm is now able to generate electricity for about 300,000 households.

The wind farms "EnBW Hohe See" and "Albatros" are located about 95 km north of Borkum and about 100 km northwest of Helgoland (ENBW ENERGIE BADEN-WÜRTTEMBERG 2020). The water depth in this region is about 40 m. In the wind farm "EnBW Hohe See", 71 wind turbine foundations were piled into the seafloor using monopiles over an area of nearly 42 km². In addition, 16 wind turbines were installed in the wind farm "EnBW Albatros" on a further 11 km². Between April 2018 and April 2019, seven C-POD stations and 156 mobile C-PODs collected data in this area, recording about 38,000 hours in total (Table 1). Since October 2019, this wind farm generates electricity for about 580,000 households.

The wind farm "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). The first construction phase of 40 wind turbines in 2012 is in operation since summer 2015 and not considered here. During the second construction phase between June 2018 and May 2020, 32 further wind turbines were installed on monopiles (Table 1), which had been anchored in the seabed at a water depth between 27 and 33 m. More than 40,000 hours were recorded between March and December 2018 at seven C-POD stations and 62 mobile C-PODs.

2.2 Field methods

In contrast to visual and aerial surveys, Passive Acoustic Monitoring (PAM) provides continuous long-term data on a small-scale basis and thus enables the assessment of short-term fluctuations. Using a network of PAM devices, we were able to study short-term responses of harbour porpoises over a larger area.

Device for Passive Acoustic Monitoring: C-POD

Harbour porpoise detection rates before, during and after the construction of piles for offshore wind farms were monitored acoustically using C-PODs. A C-POD is a hydrophone with a self-contained data logger that recognises odontocete echolocation clicks between 20 and 160 kHz by means of an algorithm that assigns clicks to a so-called train which needs at least five clicks. Thereby, false-positive detections are less likely than when analysing characteristics of individual clicks (CHELONIA LIMITED 2020).

C-PODs are only able to register porpoise clicks if the animals (1) use echolocation, which they do so almost continuously (DIEDERICHS et al. 2002; KOSCHINSKI et al. 2003; AKAMATSU et al. 2007; KYHN et al. 2012; WISNIEWSKA et al. 2016), (2) are facing towards the acoustic data logger as the angular range of porpoise sonar clicks is limited to a maximum of 16.5° (AU et al. 1999), and (3) are within a 400 m radius of the C-POD, which is the maximum detection range (CHELONIA LIMITED 2020).

The false-positive rate of a C-POD appears to be very low (mean 0.003 %) and the hourly detection accuracy very high (mean 99.6 %) (GARROD et al. 2018). Therefore, satellite telemetry and passive acoustic monitoring using a network of C-PODs were found to provide comparable information on the relative distribution patterns of harbour porpoises even in areas of low density (MIKKELSEN et al. 2016). This makes C-PODs reliable indicators of harbour porpoise presence or even relative abundance.

C-PODs record the time of click events, their duration with a resolution of 5 μs (steps of 8 bit) and other features such as intensity, bandwidth and frequency 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 probability by the algorithm. In order to achieve that detection rates are not much influenced by sensitivity differences among C-POD devices, C-PODs were calibrated prior to their first deployment and regularly during the study period. Calibration was conducted according to the main frequency of harbour porpoise click sounds (calibration at 125 kHz; best hearing ability of harbour porpoises at 100 to 140 kHz; KASTELEIN et al. 2002, 2015). In this way, equal sensitivity thresholds (± 3 dB) were obtained.

The data were saved on an SD memory card (maximum 4 GB). A total of ten 1.5 Volt D batteries provided the device with energy for at least six weeks.

Monitoring set up

25 stationary C-PODs were continuously deployed in all four wind farms to record harbour porpoise detection rates at different distances from the pile-driving operations (Figure 1, Table 2). Furthermore, 334 mobile C-PODs were deployed in all four wind farms from a few hours before FaunaGuard operation until a few hours after piling. These always had a distance of either 0.75 km or 1.5 km to the piling location.

All C-PODs were located in the water column 5 to 10 m above the seabed by anchoring the device to the seabed with a mooring system and maintaining it in the water column by a buoy (Figure 3).

Table 2: Time frame in which the mobile and stationary C-PODs were each deployed, and comparison of the analysed variables, their temporal and spatial resolution.

<table>
<tr><th></th><th>Mobile C-PODs</th><th colspan="2">Stationary C-PODs</th></tr>
<tr><td>Operation</td><td>Short-term: From a few hours before start of FaunaGuard operation until a few hours after end of piling</td><td colspan="2">Long-term: Continuous data acquisition</td></tr>
<tr><td>Variable</td><td>DPM per minute</td><td>DPM per minute</td><td>DPH per hour</td></tr>
<tr><td>Evaluation</td><td>To the minute</td><td>To the minute</td><td>To the hour</td></tr>
<tr><td>Scan limit</td><td>Mostly no</td><td colspan="2">Mostly yes (4,096 clicks per minute)</td></tr>
</table>

Criteria for which the data were excluded	• Pilings with NMS classes “DBBC”, “HSD”, “IHC”, “none”, or “unknown” • Pilings with seal scarer as AHD (except for data analysis in 2.3.5)		
	• Minutes in which the scan limit was reached	• Minutes in which the scan limit was reached	• Hours with more than 100,000 recorded clicks • Hours with more than 2 minutes in which the scan limit was reached • Less than 72 hours passed between two piling events
Excluded percentage of data in which the scan limit was reached	5.76 %	1.90 %	7.94 %
Distance to FaunaGuard/ piling	0.75 and 1.5 km	0 to 10 km analysed	0 to 20 km analysed
Advantage of variable	• Exactly analysing the impact of the FaunaGuard and subsequent piling	• Exactly analysing the impact of the FaunaGuard and subsequent piling • Making the results compara-ble to the mobile C-POD data	• Making the results compara-ble to the Gescha 2 study (BioConsult SH et al. 2019)

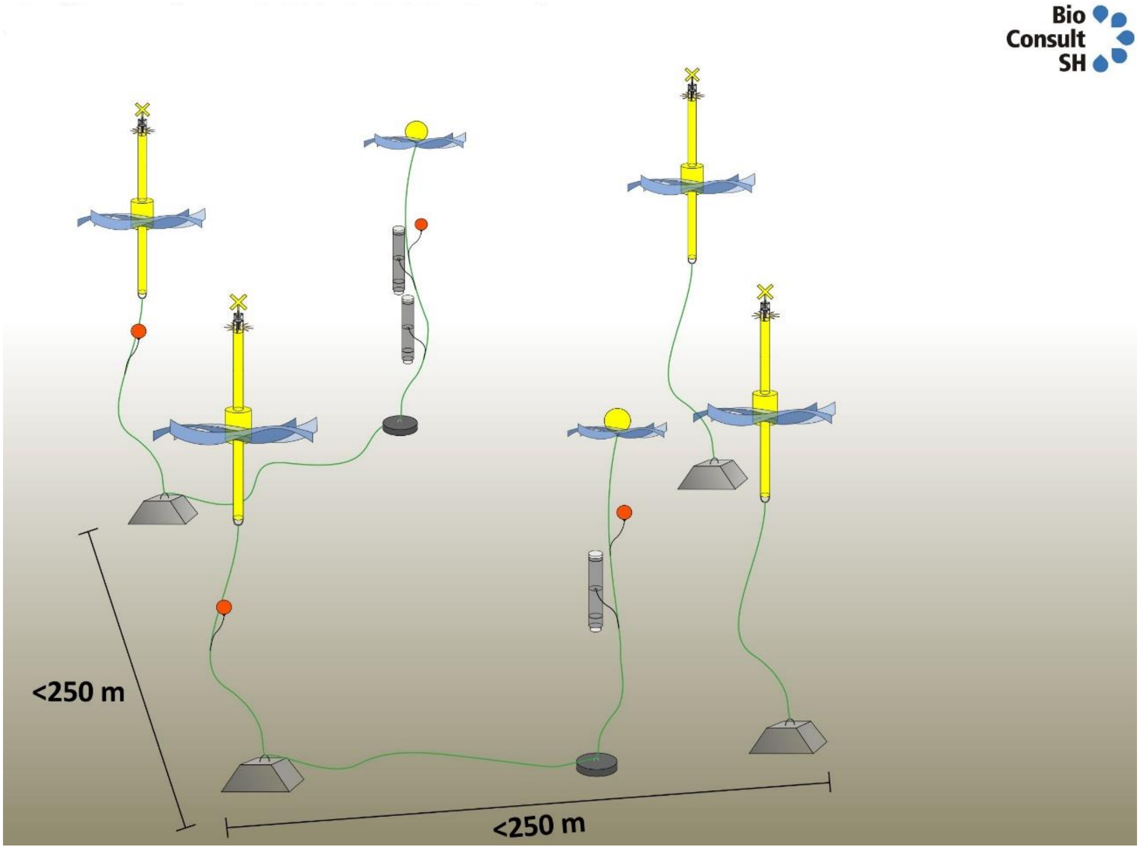

Figure 3: C-POD anchoring system used by BioConsult SH GmbH & Co. KG. All C-PODs were located in the water column 5 to 10 m above the seabed by anchoring the device to the seabed with a mooring system and maintaining it in the water column by a buoy.

Settings of the C-PODs

C-PODs record all clicks, including background noise, during deployment. The algorithm for recognising harbour porpoise clicks is only used when the memory card is read out in the software CPOD.exe. This means that the memory card can fill up quickly when there is a lot of background noise. Therefore, scan limits have been set.

For the stationary C-PODs, the scan limit was mostly set to 4,096 clicks per minute. Once this value was reached by an excess of background noise, like for example noise from wind-induced waves, the C-POD did not record any further clicks in the remaining seconds of this minute and did not register clicks again until the next minute. This was done to prevent memory from filling up with background noise before the next service took place.

For the mobile C-PODs, mostly no scan limit was set, as these were only used for a few hours and were intended to detect all sounds during this period.

Some mobile and stationary C-PODs had different scan limits for unknown reasons. For the mobile C-PODs, a scan limit of 4,095 (1.47 % of all data), 8,191 (3.17 % of all data) or 65,536 (1.12 % of all data) was incorrectly specified. For the stationary C-PODs, a scan limit of 4,095 (1.76 % of all data) or 65,536 respectively no scan limit (0.13 % of all data) was wrongly specified. However, minutes in which the scan limit was reached were excluded from the data analyses. Therefore, these discrepancies from the intended methodology were not expected to have any implications for the results, considering that the discrepancies only accounted for a small percentage of the data sets.

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

2.3 Data analysis

Statistical analyses were conducted using the software R (version 4.0.2). Mobile C-POD data were used for the questions 1, 3, 4 and 5 (see Introduction; description of data analyses in 2.3.1 and 2.3.3 to 2.3.5), stationary C-POD data were used for the questions 2, 3, 4 and 5 (description of data analyses in 2.3.2 to 2.3.5).

In the following, information applicable to all analyses is presented: (1) The three procedures used to analyse the raw data are described, (2) the statistical test to investigate whether there were significant differences among phases is explained (Bayesian proportion test), and (3) the criteria for which the data were excluded are listed.

Three procedures used to analyse the raw data

Mobile and stationary C-PODs were deployed in all wind farms. The mobile C-PODs were evaluated with the detection parameter “DPM per minute”; the stationary C-PODs were evaluated with the detection parameters “DPM per minute” and “DPH per hour” (Table 2). In the following, the different methodologies are described in more detail:

(1) Mobile C-POD data using DPM per minute

Mobile C-PODs recorded the number of minutes with porpoise clicks, or in other words the “Detection Positive Minutes” (DPM), at distances of either 750 or 1,500 m to the piling locations. This indicator described whether echolocation clicks were recorded and identified during a certain minute (1) or not (0) and was thus a binary variable. Phase 1 described the hours before FaunaGuard operation, Phase 2 covered the FaunaGuard operation, Phase 3 was defined as the time of piling, and Phase 4 described the hours after piling (Table 3). Since the duration of the phases differed, the number of clicks per phase was scaled down to a standardised time axis using DPM per minute. This variable was calculated by dividing the sum of DPM per phase by the duration of the phase in minutes. As an example, 20 minutes with porpoise clicks (in other words 20 DPM) in 3 hours (thus 180 minutes) equals 0.11 DPM per minute.

(2) Stationary C-POD data using DPM per minute

Stationary C-POD data were divided into the same phases as mobile C-POD data and again, the variable "DPM per minute" was used in order to allow for comparability. Again, Phase 1 described the hours before FaunaGuard operation, Phase 2 covered the FaunaGuard operation, Phase 3 was defined as the time of piling and Phase 4 described the hours after piling (Table 3).

Since stationary C-PODs continuously collected data, the average duration of Phase 1 and Phase 4 of the mobile C-POD data was calculated and transferred. Thus, Phase 1 of the stationary C-POD data was defined as the six hours before FaunaGuard operation, and Phase 4 was defined as the three hours after piling.

Besides, a further phase could be added due to the continuous data acquisition of stationary C-PODs compared to mobile C-PODs: Phase Reference was defined as the reference before and after piling being based (1) on 48 to 48' records before FaunaGuard operation with the condition that the last piling ended at least 72 hours ago, and (2) on 48 to 72 hours' records after piling with the condition that the next FaunaGuard operation will start after 72 hours at the earliest.

(3) Stationary C-POD data using DPH per hour

The parameter "Detection Positive Hours" (DPH) was used to investigate harbour porpoise detection rates on an hourly basis in order to make results comparable to those of the Gescha 2 study (BIOCONSULT SH ET AL. 2019). This indicator described whether echolocation clicks were recorded and identified during a certain hour (1) or not (0) and was thus also a binary variable. Based on the Gescha 2 study, the stationary C-POD data were divided into the following different phases: Baseline (hours -48 to -25 before the FaunaGuard), Pre-piling (down to 3 hours before FaunaGuard operation), Piling (at least 1 minute of FaunaGuard operation or piling) and Reference after piling (hours +49 to +120 after piling) (Table 3). Accordingly, the duration of the phases differed again, so the number of clicks per phase was scaled down to a standardised time axis using DPH per hour in this case.

In the Gescha 2 study, the phase covering the three hours prior to AHD operation was called Traffic, because at that time vessel traffic in preparation for the NMS and the upcoming pile driving already increases. For example, anchors are placed with the help of anchor tugs and until the anchor reaches the seabed, it drags over the bottom. Generally, the presence of marine mammals and especially harbour porpoises might be reduced by construction-related vessel traffic (CULLOCH et al. 2016; NEHLS et al. 2016). The animals either respond directly to this type of noise or associate it with subsequent piling noise, in this way being conditioned (DIEDERICHS et al. 2010; HERMANNSEN et al. 2014; DYNDO et al. 2015; OAKLEY et al. 2017; WISNIEWSKA et al. 2018). Harbour porpoises show their response by altered diving and echolocation behaviour as well as by displacement (WISNIEWSKA et al. 2018). However, since even individual responses to similar noise levels seem to differ, more studies are needed to further evaluate the effect of increased vessel traffic a few hours before pile driving on porpoise detection rates. Therefore, in this study the phase Traffic was retained for consistency, but renamed as Pre-piling in order to avoid confusion (Table 3).

Table 3: Definition of the individual phases in the analyses of the variables (1) DPM per minute of the mobile C-PODs, (2) DPM per minute of the stationary C-PODs, and (3) DPH per hour of the stationary C-PODs.

Name of phase	**Definition**	**Reason for classification**
	Mobile C-PODs: DPM per minute	
Phase 1	On average 6.20 hours before FaunaGuard operation	• Only short-term operation, no further data
Phase 2	Exact time during FaunaGuard operation	• Analysing the impact of the AHD
Phase 3	Exact time during piling	• Analysing the impact of the piling
Phase 4	On average 3.02 hours after piling	• Only short-term operation, no further data
	Stationary C-PODs: DPM per minute	
Phase 1	Exactly 6 hours before FaunaGuard operation	• Based on availability of mobile C-POD data for making the results comparable

Phase 2	Exact time during FaunaGuard operation	• Analysing the impact of the AHD
Phase 3	Exact time during piling	• Analysing the impact of the piling
Phase 4	Exactly 3 hours after piling	• Based on availability of mobile C-POD data for making the results comparable
Phase Reference	Hours -48 to -25 before FaunaGuard operation and hours +49 to +72 after piling	• Analysing the extent to which Phase 1 and Phase 4 reflect the usual detection rates of harbour porpoises
Stationary C-PODs: DPH per hour		
Baseline	Hours -48 to -25 before FaunaGuard operation	• Reference level • Based on Gescha 2 study for making the results comparable
Pre-piling	Down to 3 hours before FaunaGuard operation	• Analysing the impact of the presumed increased vessel traffic for preparing the NMS and upcoming pile driving • Based on Gescha 2 study for making the results comparable • Name in Gescha 2 study: Traffic
Piling	At least 1 minute of FaunaGuard operation or piling	• Analysing the impact of the AHD and subsequent piling • Based on Gescha 2 study for making the results comparable
Reference after piling	Hours +49 to +120 after piling	• Analysing long-term deterrence • Based on Gescha 2 study for making the results comparable

Statistical test to investigate whether there were significant differences among phases: Bayesian proportion test

A Bayesian proportion test was chosen in order to look for significant differences among phases due to the following desirable properties: (1) Neither the user nor the test makes any prior assumptions about the distribution of the data. (2) Multiple testing in this case does not lead to significances by chance (false positives) instead of actual significances – this means that a correction for multiple comparisons is generally not necessary when building multilevel models (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; SJÖLANDER & VANSTEELANDT 2019): For each group, or in this case for each phase, it was tested whether a sample from a population represents the true proportion of the entire population. In other words, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. If the sample size of a phase was small, the uncertainty and therefore the confidence interval was high.

In all cases, the null hypothesis was rejected for p-values less than 0.05 and a post-hoc analysis was conducted. A significant difference was observed between two phases if the probability was below 5 % that the median of one phase was within the 95 % confidence interval of another phase (KRUSCHKE 2011).

Criteria for which the data were excluded

In order to obtain a homogeneous data set, the following data were excluded from the analyses:

(1) Several noise mitigation systems

Different NMS were used during pile driving in order to reduce noise emissions and to minimise negative effects on the marine fauna. Noise mitigation was mostly quite effective; however, pilings with NMS classes “DBBC”, “HSD”, “IHC”, “none”, or “unknown” exceeded an SEL_{05} of 160 dB re 1 µPa² s at a distance of 750 m and/or an

L_{Peak} of 190 dB re 1 µPa², and thus failed to meet the dual noise protection criterion defined by the BSH (Figure 4, Table A.1; see Introduction for explanation of the criteria).

In order to investigate how porpoise detection rates changed from during FaunaGuard operation to pile driving in compliance with BSH thresholds, pilings with the mentioned NMS classes were excluded from analyses. This concerned only eleven piles as in most pilings the well-working NMS "BBC", "DBBC & HSD" or "IHC & BBC" were used as NMS (Figure A.1, Table A.2). In this way, data sets were kept consistent and not influenced by outliers in terms of piling noise.

The excluded pilings affected data sets from different wind farms (Figure A.2, Table A.3 to Table A.4).

(2) Pilings with seal scarer as AHD

A seal scarer was used as AHD during three pile-driving operations in the wind farm "Trianel Windpark Borkum Phase 2" (Table 1). These pile-driving operations were excluded from analyses except for comparisons with the FaunaGuard as AHD in question 5 (description of data analysis in 2.3.5).

(3) Special criteria for analyses using DPM per minute

Since some mobile C-PODs had a scan limit set, minutes in which this scan limit was reached were excluded from the analyses (Table 2). Consequently, only complete minutes were evaluated and thus a consistent data set was produced. To maintain consistency between the mobile and stationary C-PODs (when using DPM per minute), minutes in which the scan limit was reached were also excluded from the analyses of the stationary C-PODs.

(4) Special criteria for analyses using DPH per hour

To minimise the impact of background noise on the detection of porpoise clicks and to make the results comparable to the Gescha 2 study (BioConsult SH et al. 2019), hours with more than 100,000 recorded clicks and/or more than 2 minutes in which the scan limit was reached were excluded from the analyses of the stationary C-PODs (when using

DPH per hour). Furthermore, in order to exclude effects on harbour porpoise detection rates other than those investigated, at least 72 hours had to pass between two piling events.

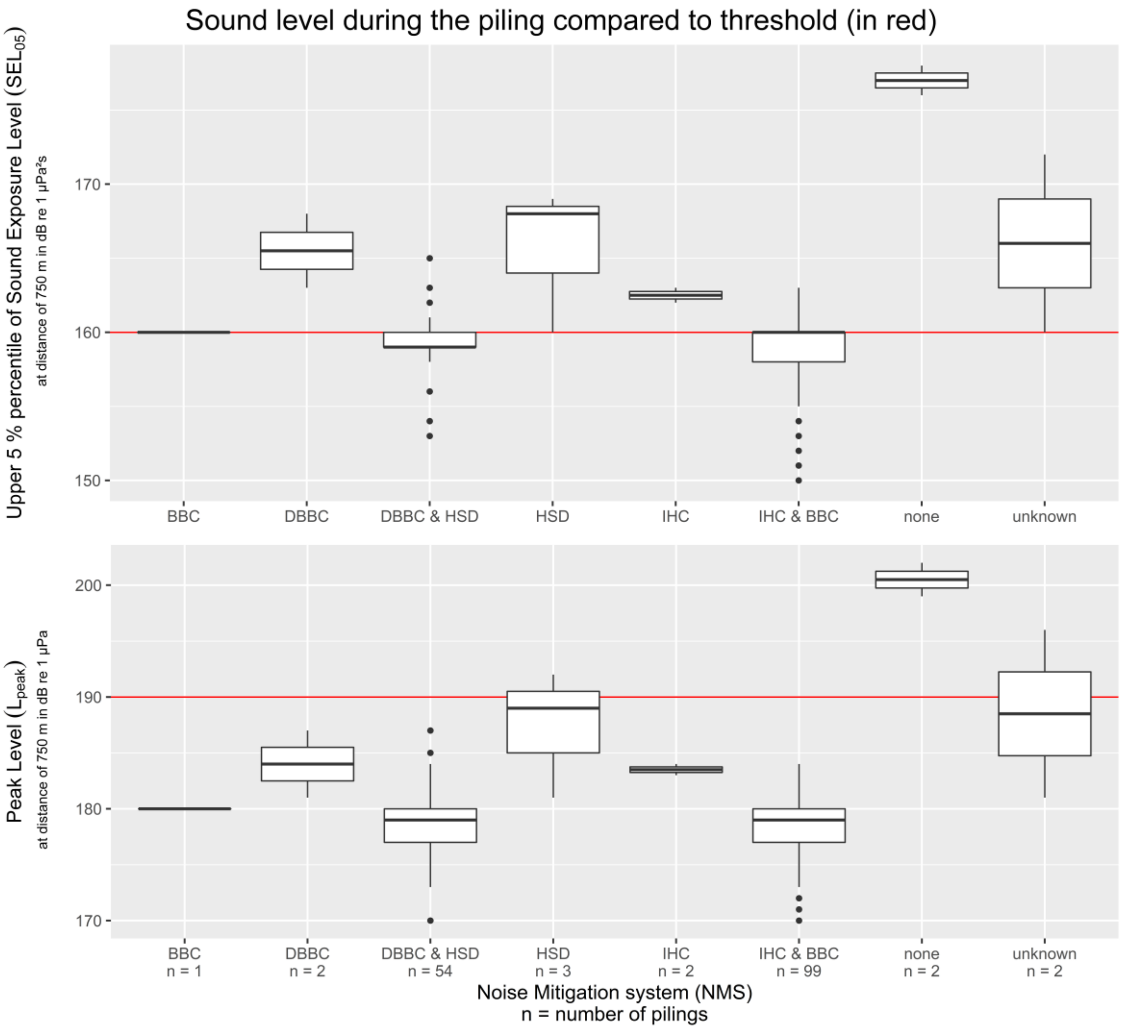

Figure 4: Upper 5 % percentile of Sound Exposure Level (SEL_{05}) as well as Peak Level (L_{Peak}) at a distance of 750 m to piling location in relation to the dual noise protection criterion of the German Federal Maritime and Hydrographic Agency, BSH (in red). Pilings with the NMS classes "DBBC", "HSD", "IHC", "none", and "unknown" did not comply with the thresholds for SEL_{05} and L_{Peak} and were thus excluded from subsequent analyses.

2.3.1 How did the detection rates of harbour porpoises change during FaunaGuard operation at smaller distances up to 1.5 km?

To answer this question, the mobile C-POD data were analysed at distances of either 750 or 1,500 m from the pile-driving sites. Bayesian proportion tests were performed to investigate the following two questions: Did DPM per minute differ significantly among phases up to a distance of 1.5 km? And did DPM per minute differ significantly among phases of both distance categories – 0.75 as well as 1.5 km?

2.3.2 How did the detection rates of harbour porpoises change during FaunaGuard operation at larger distances up to 20 km?

For this topic, stationary C-POD data were analysed (1) on a per-minute basis (using DPM per minute) in order to allow for comparability with the mobile C-POD data and (2) on an hourly basis (using DPH per hour) in order to make results comparable to those of the Gescha 2 study (BIOCONSULT SH ET AL. 2019).

Analysis using DPM per minute

The distance towards the piling location was divided into four categories: 0 to 2.5 km, 2.5 to 5 km, 5 to 7.5 km, and 7.5 to 10 km. A Bayesian proportion test was performed for each distance category to answer the question: Did DPM per minute differ significantly among phases of each distance category?

Analysis using DPH per hour

Mean DPH per hour of the different phases was calculated for several distance categories (0 to 5 km, 5 to 10 km, 10 to 15 km and 15 to 20 km distance from the piling location). These values were compared to the DPH rates at hours relative to piling ranging from 48 hours before FaunaGuard operation until 120 hours after piling. Hour 0 was defined as the daytime hour during which the FaunaGuard was in operation and/or piling activities took place for at least 1 minute. A Bayesian proportion test was performed for each distance category to answer the question: Did DPH per hour differ significantly among phases of each distance category?

2.3.3 How did the detection rates of harbour porpoises during FaunaGuard operation differ between wind farms at smaller and larger distances?

To investigate whether the FaunaGuard had a similar effect in different areas of the North Sea, harbour porpoise detection rates during FaunaGuard operation were compared between wind farms at both smaller and larger distances. Therefore, the following data were separated by wind farm: (1) For smaller distances: Mobile C-POD data using DPM per minute, (2) for larger distances: Stationary C-POD data using DPM per minute as comparison to the mobile C-POD data, and (3) also for larger distances: Stationary C-POD data using DPH per hour as comparison to the Gescha 2 study (BIOCONSULT SH ET AL. 2019).

There were not enough data available to model harbour porpoise response for each wind farm with, for example, Generalised Additive Models.

Smaller distances: Mobile C-POD data using DPM per minute

DPM per minute were calculated for the different phases at a distance of up to 1.5 km for each wind farm. Bayesian proportion tests were performed to investigate the following question: Did the DPM per minute of the phases differ significantly up to a distance of 1.5 km at each wind farm?

Larger distances: Stationary C-POD data using DPM per minute

DPM per minute of the different phases at the distance class of 0 to 5 km, respectively 5 to 10 km, to the piling location were calculated for each wind farm. Since the number of observations was too small for each category, no statistical test was performed to investigate whether or not the effects of a FaunaGuard and subsequent pile driving on porpoise detection rates differed between the wind farms at greater distances compared to the mobile C-POD data sets.

Larger distances: Stationary C-POD data using DPH per hour

Mean DPH rates of the different phases with a distance of up to 10 km to the piling location were calculated for each wind farm. Again, these values were compared to DPH rates for each wind farm at hours relative to piling ranging from hour -48 before FaunaGuard operation until hour +120 after piling. A Bayesian proportion test was performed for each wind farm to answer the question: Did DPH per hour of the phases differ significantly up to a distance of 10 km at each wind farm?

2.3.4 What effect did the duration of operation of the FaunaGuard have on the detection rates during this phase?

Depending on the project, a minimum duration of 20 or 30 minutes was prescribed for the FaunaGuard operation. In some cases, the FaunaGuard was also activated for a longer time, so that sufficient data were available for analyses up to a runtime of 43 minutes.

To investigate the influence of the duration of operation of a FaunaGuard on the detection rates during this phase, the mobile and stationary C-POD data were combined. Different types of modelling were performed: (1) Analysis of the raw data, (2) a Generalised Additive Model, and (3) Boosted Regression Trees.

In all cases, the response variable was “DPM_min_rate”, which was binary and indicated the presence-absence response on a one-minute basis. Furthermore, one of the predictor variables was always “A_min_FaunaGuard” and described the minute of FaunaGuard operation ranging from the start of the FaunaGuard (minute +1) until the start of piling, or if the FaunaGuard was switched off before, until the end of the FaunaGuard operation. So even if the FaunaGuard was activated for a few more minutes during pile driving, these minutes were not taken into account in the analyses, as piling probably masks the sound of a FaunaGuard (ROSEMEYER et al. 2021). Therefore, the FaunaGuard is assumed to be barely audible during pile driving, potentially leading to distorted results. Instead, solely the detections during FaunaGuard-only operation were considered.

Raw data

When analysing the raw data, the distance towards the piling location was divided into five categories: 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. For a reliable sample size, two minutes of the response variable "DPM_min_rate" were always combined, e. g. minute 1 and minute 2 during FaunaGuard operation were combined to minute 1. Only if at least 50 minutes were recorded in this class of the response variable for the corresponding distance class, the mean and standard error were calculated.

Generalised Additive Model

A Generalised Additive Model (GAM) was chosen because GAMs do not require a normal distribution of data points compared to e. g. Generalised Linear Models (GLM) 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.

The GAM utilised a tensor product of the variables "A_min_FaunaGuard" and "A_dist". The variable "A_dist" described the distance to the FaunaGuard.

The GAM included 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 were considered, as only for this range sufficient data were available. No further models could be created for the individual wind farms due to limited availability of data.

Different piling- and noise-related, time-related, environmental, as well as POD-related variables were available (Table 4). 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 was on a minute-by-minute basis and the time-related variables were 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.3). For variables with high collinearity, the biologically more reasonable variable was retained and the other eliminated (Figure 5). In the case of sand eels, the average value of three different species was considered first and then the best model was used to see 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 must be investigated whether the smooth function of one variable can be created by combining the smoothings of the other variables in the model, and thus leading to concurvity (AMODIO et al. 2015). Although GAMs have some degree of built-in amplification against multicollinearity, it should still be tested whether the data are affected by multicollinearity and therefore 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 5) 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 GAM. Furthermore, this study aimed to make only estimates and predictions, but not to interpret individual regression coefficients, so that multicollinearity needs less consideration (MURRAY et al. 2012).

Furthermore, random effects were included into the model: (1) The name of the wind farm (variable "project"), (2) the name of the C-POD station (variable "station", only one data set 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 special characteristics of the piling. However, since a GAM is often faster and more reliable when the number of random effects is modest (WOOD 2017), only one random effect per GAM was used and it was tested which of the random effects mentioned was the most suitable.

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 a previous time step should be included as a variable. In this analysis, the variable “DPMt”, which describes the 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 this analysis, 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 this analysis by using the select argument. The gamma value was set to 1.4 as recommended (WOOD 2017).

To find the best explanatory GAM, the Akaike Information Criterion (AIC) was used: 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 differ by less than 2, the model with the higher AIC value can also be considered to be 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 2, otherwise the inclusion was considered poorly justified.

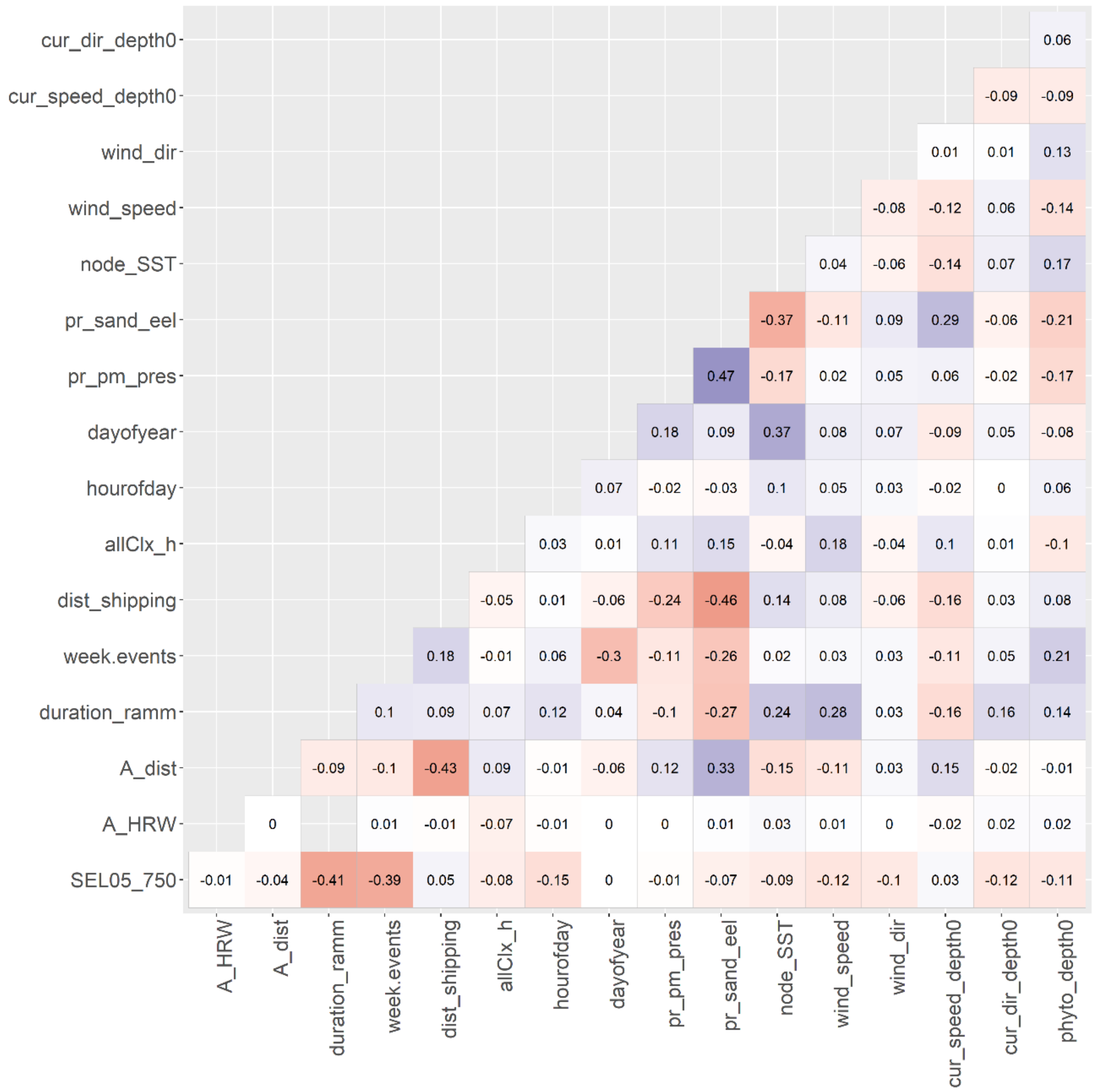

Figure 5: Pearson correlation coefficients of all combinations of the finally used variables except factors. Red boxes show a negative, blue boxes a positive r-value. For these variables, the correlation coefficients were below 0.7 and collinearity therefore could not greatly distort model estimates and predictions (DORMANN et al. 2013).

Table 4: List of all variables considered for the Generalised Additive Model and Boosted Regression Trees analysing the effect of the duration of FaunaGuard operation on the detection rates (adapted from BIOCONSULT SH 2019).

Variable	Type	Description
Response variable		
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 FaunaGuard operation ranging from +1 (start of FaunaGuard operation) to +43 (start of pile driving, or end of FaunaGuard operation if the FaunaGuard was switched off before)
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 species *Pomatoschistus minutus* per station
pr_sand_eel	continuous	Average probability of presence of sand eel species *Hyperoplus lanceolatus*, *Ammodytes marinus* and *Pomatoschistus minutus* per station
pr_am_pres	continuous	Probability of presence of sand eel species *Ammodytes marinus* per station
pr_at_pres	continuous	Probability of presence of sand eel species *Ammodytes tobianus* per station

pr_hl_pres	continuous	Probability of presence of sand eel species *Hyperoplus lanceolatus* 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 and continuous	Wind direction in degree on a 6 hours basis
cur_speed_depth0	continuous	Speed of currents in m/s at surface on an hourly basis
cur_dir_depth0	circular and 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

Boosted Regression Trees

Boosted Regression Trees (BRT) were created since this kind of modelling is stochastic and thus improving the prediction performance (ELITH et al. 2008). Data of all wind farms were combined. The following settings were used:

(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 this data set 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 therefore set at 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 was unknown, it was set to 5. This number was used as a trade-off, because a tree complexity of 1, for example, generally shows an excessive prediction deviation, and a very high tree complexity makes 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 a harbour porpoise 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 1,000 trees (ELITH et al. 2008) and this rule of thumb was followed in this study.

On the one hand, a three-dimensional BRT model was created solely using the variables "A_min_FaunaGuard" and "A_dist" (description of variables in Table 4).

On the other hand, BRTs were created for different distance classes containing several other variables such as environmental variables. Therefore, the distance towards the piling location was again divided into five categories: 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 and two minutes of the response variable "DPM_min_rate" were always combined. As with the raw data, only those data were used in the analysis if at least 50 minutes were recorded in this class of the response variable for the corresponding distance class.

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

The results for each distance class were presented in Partial Dependence Plots (PDP). These indicate changes in the predicted mean value when one parameter, and in this case "A_min_FaunaGuard", varies while the other parameters remain constant. The mean value of the data distribution is always centred on zero. Positive values on the y-axis therefore indicate that the detection rates increase compared to the mean value. Negative values indicateda decrease in detection rates. In addition, the relative contribution of each variable to the BRT was shown for each distance class in order to better classify the influence of the variable "A_min_FaunaGuard" on the model.

2.3.5 How did the detection rates of harbour porpoises during FaunaGuard operation differ from those during seal scarer operation?

To investigate how harbour porpoise detection rates differed between seal scarer and FaunaGuard operation, two comparisons were conducted: (1) Comparison of FaunaGuard and seal scarer operation at OWF "Trianel Windpark Borkum Phase 2": Mobile and stationary C-POD data using DPM per minute, as both AHDs were deployed in this wind farm, and (2) cross-project comparison: Stationary C-POD data of all wind farms up to 10 km distance to the piling location using DPH per hour in order to compare with the Gescha studies (BIOCONSULT SH et al. 2016; BIOCONSULT SH ET AL. 2019).

Comparison of FaunaGuard and seal scarer operation at OWF "Trianel Windpark Borkum Phase 2"

At OWF "Trianel Windpark Borkum Phase 2", the FaunaGuard was not working during three pile drivings, so that the seal scarer had to be used. These pilings were excluded from all other analyses despite this section.

Using both AHDs in the same wind farm provided the chance to directly compare the effect of the FaunaGuard to the effect of the seal scarer. As the data were collected from one wind farm and over a similar period of time (Table 5), it was assumed that the environmental parameters like sandeel density, phytoplankton density, salinity, or wind conditions were similar. Furthermore, the piling conditions like the piling duration, SEL_{05} and L_{Peak} were similar despite the low number of observations, and thus it was assumed that differences in detection rates of harbour porpoises would probably be caused by the two AHDs.

First, the mobile C-POD data were analysed using DPM per minute and dividing the data by distance to the piling location (either 0.75 or 1.5 km).

Second, the stationary C-POD data were analysed using DPM per minute in order to render the results comparable to the mobile C-POD data. As the stationary C-PODs were only deployed at a distance of 5 to 10 km from the seal scarer, only data in this distance category were selected for the FaunaGuard as well.

The data were explored visually. Statistical tests were not feasible for comparing the AHDs since the seal scarer was only used during three pile drivings, hence the number of samples was too low.

Table 5: Comparing the information of the pilings between pilings using the FaunaGuard and pilings using the seal scarer as AHD. Despite the low number of observations, the data of the pilings were similar, and thus it was assumed that differences in detection rates of harbour porpoises would probably be caused by the two AHDs.

AHD	**Variable**	**N (number of pilings)**	**Mean**	**Standard error**	**Standard deviation**
FaunaGuard	Period of time	June to November 2018 (Figure A.4)			
	Time of piling	All times of day and night (Figure A.5)			
	Piling duration in minutes	24	84.75	27.97	5.71
	Number of piling events occurring during seven days before a given piling event in a 40 km radius	24	2.75	1.03	0.21
	Upper 5 % percentile of Sound Exposure Level at a distance of 750 m	21	159.38	4.59	1.00
	Peak Level at a distance of 750 m	21	178.38	5.71	1.25
Seal scarer	Period of time	July 2018 (Figure A.4)			
	Time of piling	All times of day and night (Figure A.5)			
	Piling duration in minutes	4	78.38	38.13	19.07
	Number of piling events occurring during seven days before a given piling event in a 40 km radius	4	2.00	0.82	0.41
	Upper 5 % percentile of Sound Exposure Level at a distance of 750 m	4	158.25	0.50	0.25
	Peak Level at a distance of 750 m	4	177.75	1.50	0.75

Cross-project comparison to Gescha studies: Stationary C-POD data using DPH per hour up to 10 km distance to the piling location

Mean DPH per hour of the different phases (Table 3) were calculated for a distance of up to 10 km. A Bayesian proportion test was performed to answer the question: Did DPH per hour differed significantly among phases up to a distance of 10 km? Mean DPH per hour of the different phases were compared to the results of the Gescha studies (BIOCONSULT SH et al. 2016; BIOCONSULT SH ET AL. 2019).

3. Results

3.1 How did the detection rates of harbour porpoises change during FaunaGuard operation at smaller distances up to 1.5 km?

Data of the mobile C-PODs, which were operating only for a few hours around piling and in fixed distances of 0.75 and 1.5 km to the piling locations, were used to answer this question.

Phase 1 comprised on average of 6.20 hours of mobile C-POD data before FaunaGuard operation. During this phase, which should not be considered as an undisturbed reference since most pre-piling activities fell into it, highest DPM per minute of all four phases were registered (Figure 6, Table 6).

During Phase 2, which described the application of a FaunaGuard and lasted on average 0.55 hours, lowest DPM per minute were recorded. In comparison to Phase 1, DPM per minute dropped a 48 % during Phase 2.

Phase 3 marked the period of pile driving, which took on average 1.72 hours. DPM per minute increased again and reached a similar level as during Phase 1. However, when considering the distance classes, the following stood out: At a distance of 0.75 km, DPM per minute decreased a 30 % during Phase 3 compared to Phase 1, whereas at a distance of 1.5 km, DPM per minute increased an 18 %.

After piling and thus during Phase 4, which covered an average of 3.04 hours after piling, DPM per minute stayed on a similar level and only decreased a 7 % from Phase 1 to Phase 4.

DPM per minute were higher at a distance of 1.5 km compared to 0.75 km at all wind farms except for “Borkum Riffgrund 2” (Figure A.6, Table A.5). Furthermore, DPM per minute of the individual phases differed significantly (Figure A.7, Table A.6). This difference was also observed separately at both distances – 0.75 km as well as 1.5 km (Figure A.8 to Figure A.9, Table A.6). In all cases, DPM per minute were lowest during Phase 2 and differed significantly from Phase 1, Phase 3 and Phase 4. Therefore, detection rates during the FaunaGuard were significantly reduced prior to piling at distances of at least 1.5 km. Besides, detection rates during the FaunaGuard were significantly more reduced than during the actual piling.

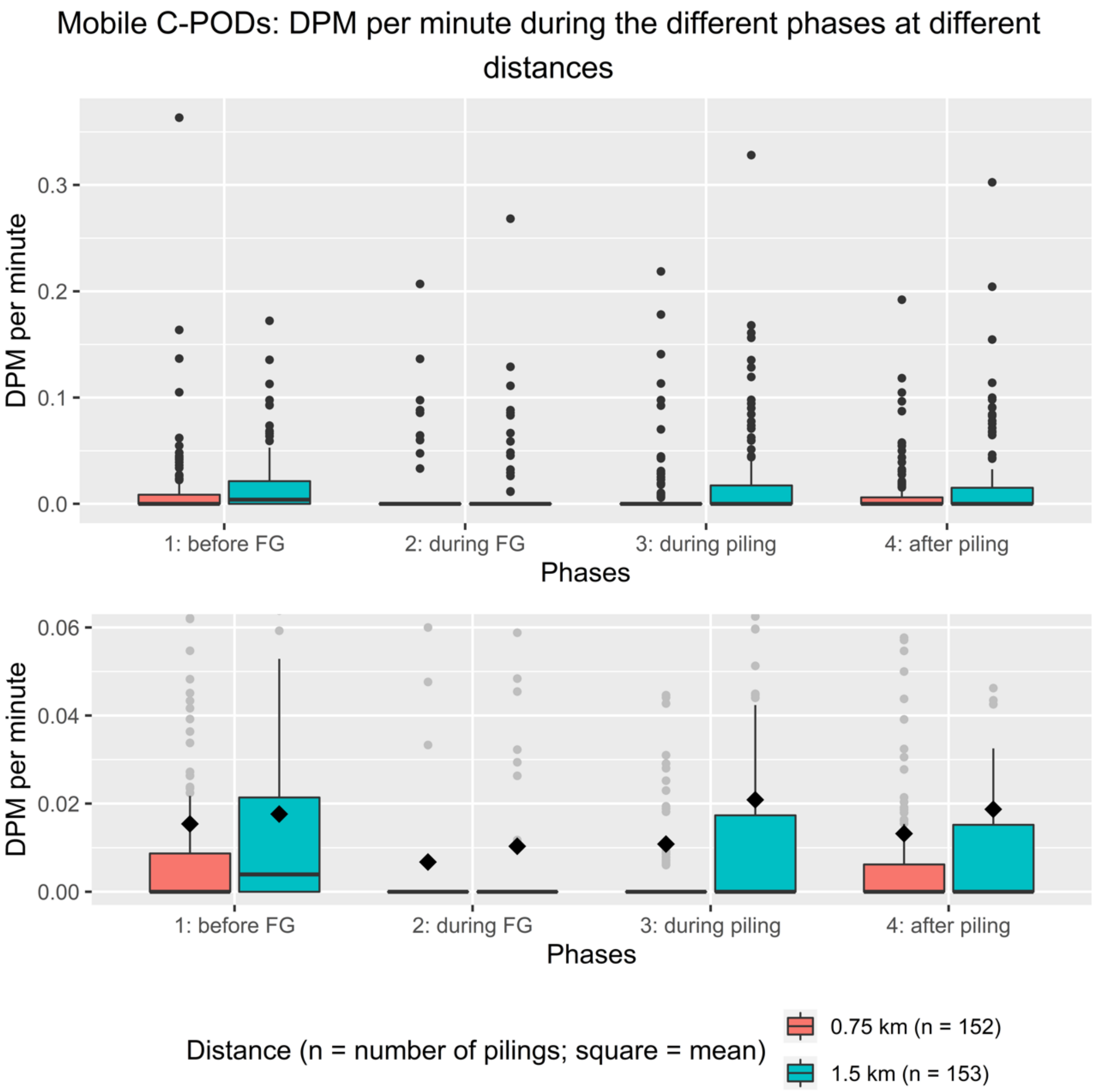

Figure 6: Mobile C-PODs: DPM per minute during the different phases at a distance of 0.75 respectively 1.5 km to the FaunaGuard and subsequent piling (upper boxplots with all outliers, lower boxplots as zoom in quantile range). At both distances, DPM per minute were highest in Phase 1 (on average 6.20 hours before the FaunaGuard), lowest in Phase 2 (during the FaunaGuard, on average 0.55 hours), increased again in Phase 3 (during piling, on average 1.72 hours), and in Phase 4 (on average 3.04 hours after piling), DPM per minute remained close to the level of Phase 1.

Table 6: Mobile C-PODs: DPM per minute during the different phases at a distance of 0.75 respectively 1.5 km to the FaunaGuard and subsequent piling. At both distances, DPM per minute were highest in Phase 1 (on average 6.20 hours before the FaunaGuard), lowest in Phase 2 (during the FaunaGuard, on average 0.55 hours), increased again in Phase 3 (during piling, on average 1.72 hours), and in Phase 4 (on average 3.04 hours after piling), DPM per minute remained close to the level of Phase 1.

Distance	**Phase**	**N (number of minutes)**	**DPM per minute**		
			Mean	**Standard deviation**	**Standard error**
0.75 km	1: Before FaunaGuard	51,497	0.015	0.12	0.00054
	2: During FaunaGuard	5,178	0.0068	0.082	0.0011
	3: During piling	17,171	0.011	0.10	0.00079
	4: After piling	25,588	0.013	0.11	0.00071
1.5 km	1: Before FaunaGuard	52,298	0.018	0.13	0.00058
	2: During FaunaGuard	5,036	0.010	0.10	0.0014
	3: During piling	17,296	0.021	0.14	0.0011
	4: After piling	26,164	0.019	0.14	0.00084

3.2 How did the detection rates of harbour porpoises change during FaunaGuard operation at larger distances up to 20 km?

Data of the stationary C-PODs, which were operating continuously and in various distances to piling locations, were used to answer this question. These were analysed on a minute-by-minute and on an hourly basis.

Analysis using DPM per minute

When analysing the rate DPM per minute at the distance class of 0 to 2.5 km to the piling location, the highest mean value was found for the phase Reference, ranging from 48 to 24 hours before FaunaGuard operation started and from 48 to 72 hours after piling ended (Figure 7, Table 7). In comparison, the detection rates decreased during Phase 1 describing the six hours before FaunaGuard operation, and reached their lowest point during Phase 2 and thus during FaunaGuard operation. During the piling and thus in Phase 3, DPM per minute increased again, but decreased again in Phase 4 describing the three hours after piling. Furthermore, the phases differed significantly: During Phase 2 (During FaunaGuard), DPM per minute were significantly lower than during Phase 1 (Before FaunaGuard), Phase 3 (During piling) and phase Reference (Figure A.10, Table A.7).

At distances between 2.5 to 7.5 km from the piling location, the detection rates were mainly at a similar level in all phases. At a distance of 2.5 to 5 km, lower detection rates were only observed in Phase 4 (After piling), whereas at a distance of 5 to 7.5 km, lower detection rates were only observed in Phase 2 (During FaunaGuard) and Phase 3 (During piling). Therefore, no clear trends were observed in this distance range (Figure A.11 to Figure A.12, Table A.7).

In contrast to distances below 7.5 km, for distances of 7.5 to 10 km lowest detection rates were observed during the phase Reference. In the other phases the detection rates were above the level of the phase Reference and were highest during Phase 2 (During FaunaGuard). Again, the phases differed significantly: During Phase 2 (During FaunaGuard), DPM per minute were significantly higher than during phase Reference (Figure A.13, Table A.7).

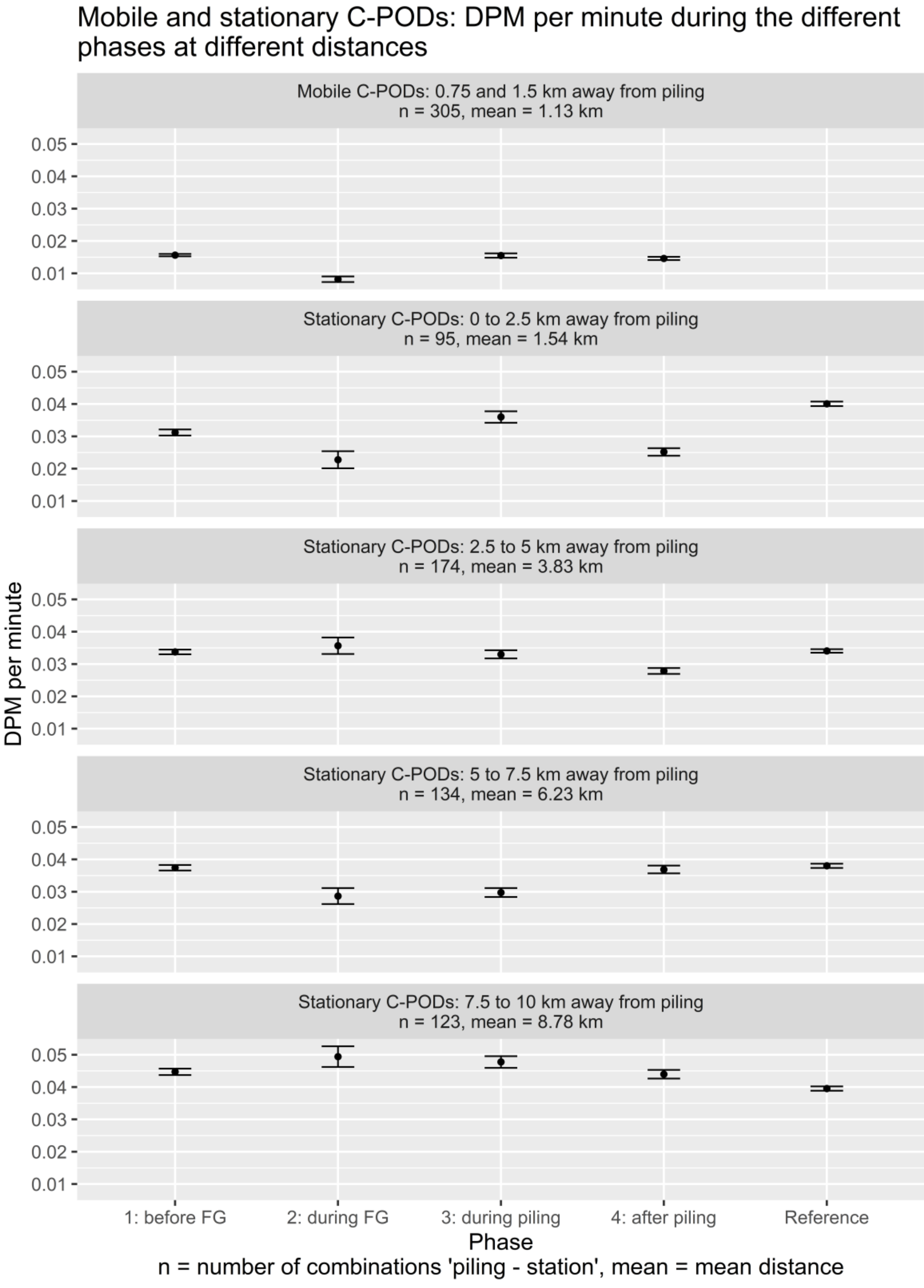

Figure 7: Mobile and stationary C-PODs: DPM per minute (mean and standard error) during the different phases at different distances. At a distance of 0 to 2.5 km to the piling location, values were highest during phase Reference (hours -48 until -25 before the FaunaGuard, as well as +49 until +72 after piling) and lowest during Phase 2 (During FaunaGuard). At distances between 2.5 to 7.5 km from the piling location, the detection rates were mainly at a similar level in all phases. In contrast, detection rates for distances between 7.5 and 10 km were lowest during phase Reference and highest during Phase 2.

Table 7: Mobile and stationary C-PODs: DPM per minute during the different phases at different distances. At a distance of 0 to 2.5 km to the piling location, values were highest during phase Reference (hours -48 until -25 before the FaunaGuard, as well as +49 until +72 after piling) and lowest during Phase 2 (During FaunaGuard). At distances between 2.5 to 7.5 km from the piling location, the detection rates were mainly at a similar level in all phases. In contrast, detection rates for distances between 7.5 and 10 km were lowest during phase Reference and highest during Phase 2.

Distance (mean) in km	**Phase**	**DPM per minute**			
		N (number of minutes)	**Mean**	**Standard deviation**	**Standard error**
0.75 and 1.5 (1.13)	1: Before FaunaGuard	109,814	0.016	0.12	0.00037
	2: During FaunaGuard	10,635	0.0082	0.090	0.00087
	3: During piling	35,262	0.016	0.12	0.00066
	4: After piling	56,749	0.015	0.12	0.00050
	Reference	NA	NA	NA	NA
0 – 2.5 (1.54)	1: Before FaunaGuard	33,359	0.031	0.17	0.00095
	2: During FaunaGuard	3,205	0.023	0.15	0.0026
	3: During piling	10,974	0.036	0.19	0.0018
	4: After piling	18,026	0.025	0.16	0.0012
	Reference	79,510	0.040	0.20	0.00070
2.5 – 5 (3.83)	1: Before FaunaGuard	62,081	0.034	0.18	0.00072
	2: During FaunaGuard	5,300	0.036	0.19	0.0025
	3: During piling	20,153	0.033	0.18	0.0013
	4: After piling	31,939	0.028	0.16	0.00092
	Reference	115,867	0.0348	0.18	0.00053
5 – 7.5 (6.23)	1: Before FaunaGuard	49,029	0.037	0.19	0.00086
	2: During FaunaGuard	4,571	0.029	0.17	0.0025
	3: During piling	15,392	0.030	0.17	0.0014
	4: After piling	24,889	0.037	0.19	0.0012
	Reference	84,946	0.038	0.19	0.00066
7.5 – 10 (8.78)	1: Before FaunaGuard	44,177	0.045	0.21	0.00098
	2: During FaunaGuard	4,573	0.049	0.22	0.0032
	3: During piling	13,901	0.048	0.21	0.0018
	4: After piling	23,699	0.044	0.21	0.0013
	Reference	87,164	0.040	0.19	0.00066

Analysis using DPH per hour

In general, detection rates up to a distance of at least 20 km decreased a few hours before pile driving and increased again a few hours after pile driving (Figure 8). This trend was best visible for distances between 0 and 5 km to the pile-driving site and became less visible with increasing distance.

In all four distance categories, DPH per hour were highest during the phase Baseline, which included hours -48 to -25 before FaunaGuard operation (Figure 9, Table A.8). DPH per hour were slightly lower in the phase Reference after piling, and thus in hours +49 to +120 after piling. Lowest DPH per hour were always observed during the phase Piling, meaning in the hours in which the FaunaGuard was activated and/or piling took place for at least one minute. In the phase Pre-piling, defined as hours -3 to -1 before FaunaGuard operation, detection rates varied according to the distance category: For distances between 0 and 5 km, the detection rate was similar to that from phase Piling, and for distances between 15 and 20 km, the detection rate was similar to that from the phases Baseline and Reference after piling.

Furthermore, in all distance categories up to 15 km from the piling location, the phases differed significantly (Figure A.14 to Figure A.16, Table A.7). DPH per hour during the phase Piling were always significantly lower than during the other three phases. Besides, for distances up to 5 km, DPH per hour during the phase Pre-piling were significantly lower than during the phase Baseline.

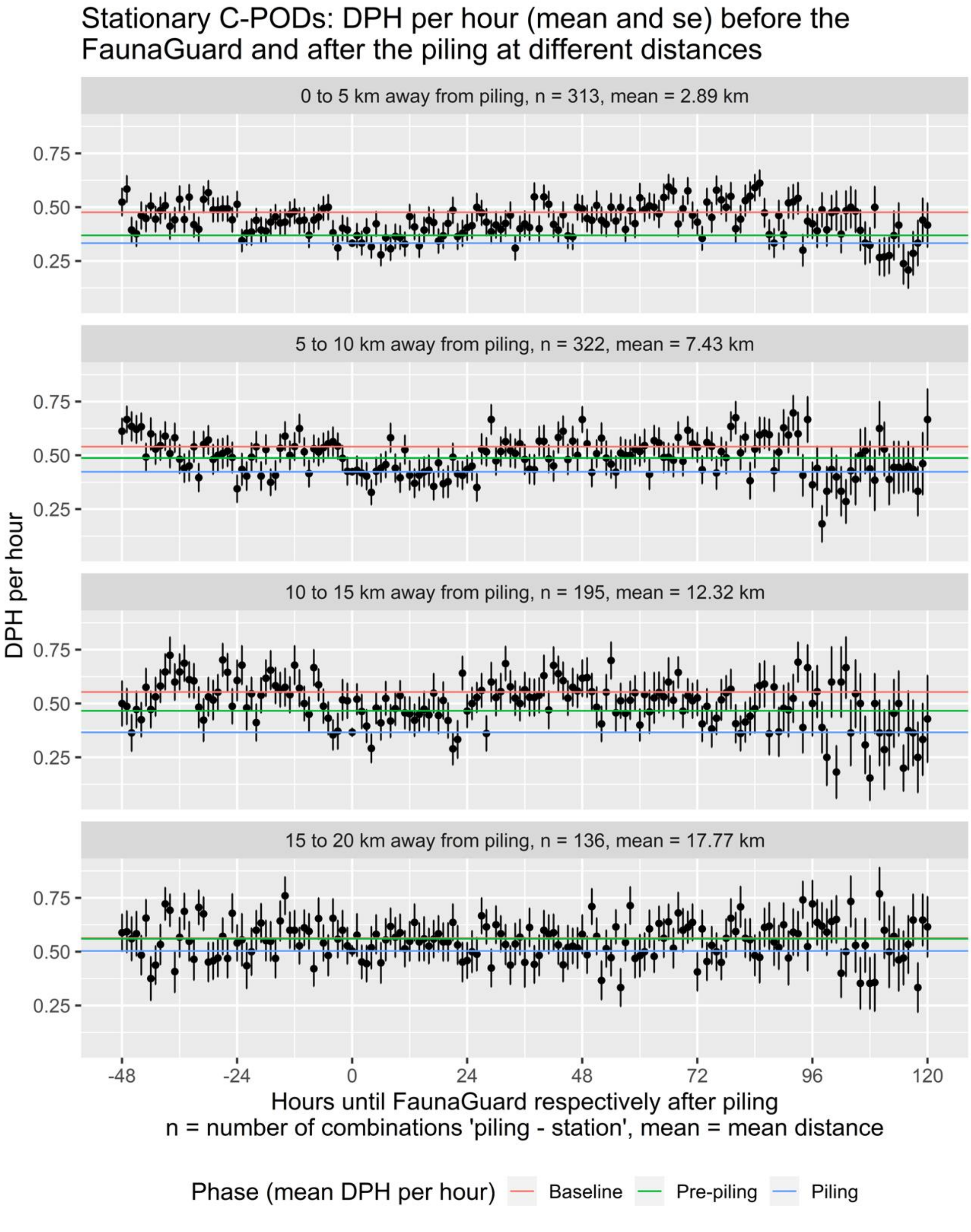

Figure 8: Stationary C-PODs: DPH per hour (mean and standard error) from 48 hours before FaunaGuard operation until 120 hours after piling at different distances. In general, detection rates up to a distance of at least 20 km decreased a few hours before pile driving and increased again a few hours after pile driving; this trend was best visible for distances between 0 and 5 km to the pile-driving site and worst for distances between 15 and 20 km.

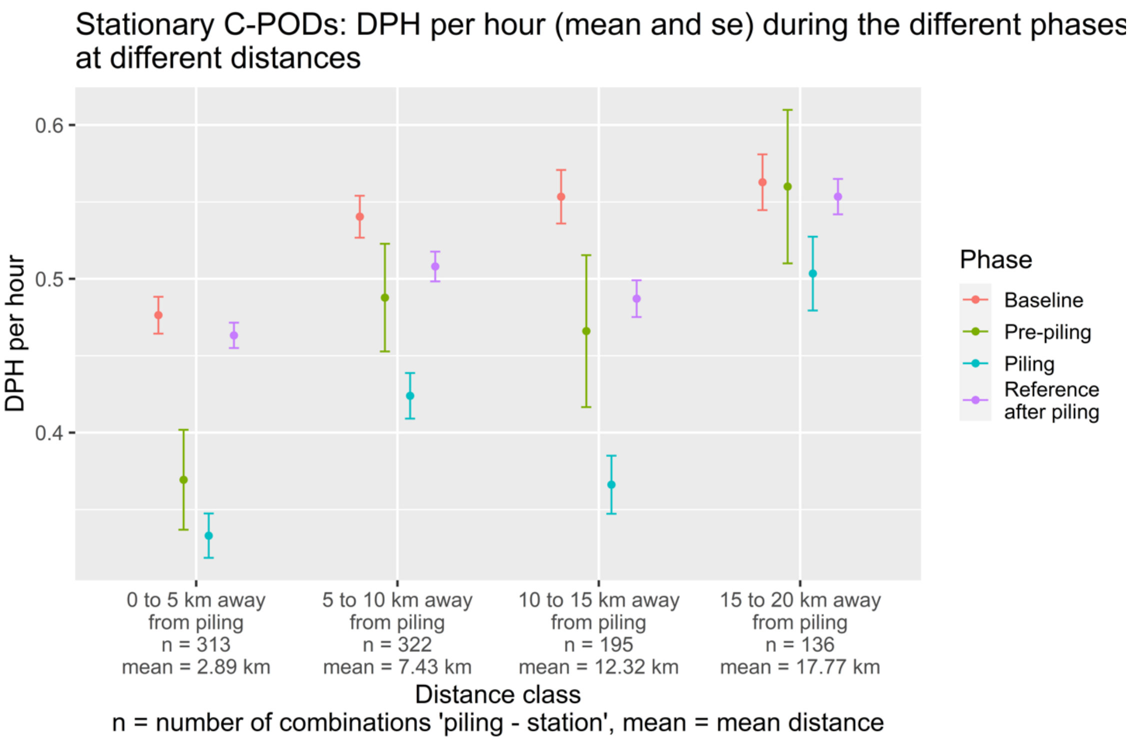

Figure 9: Stationary C-PODs: DPH per hour (mean and standard error) during the different phases at different distances. DPH per hour for the distance categories up to 20 km from the piling location were highest during the phases Baseline (hours -48 to -25 before FaunaGuard operation) and Reference after piling (hours +49 to +120 after piling), in the intermediate range during the phase Pre-piling (down to 3 hours before FaunaGuard operation) and lowest during the phase Piling (at least 1 minute of FaunaGuard operation or piling).

3.3 How did the detection rates of harbour porpoises during FaunaGuard operation differ between wind farms at smaller and larger distances?

Data of the mobile as well as stationary C-PODs were separated by wind farm in order to answer this question for smaller as well as larger distances.

Smaller distances: Mobile C-POD data

Data of the mobile C-PODs, which were operating only for a few hours around piling and in fixed distances of 0.75 and 1.5 km to the piling locations, were used to answer this question. Again, Phase 1 comprised on average of 6.20 hours of mobile C-POD data before FaunaGuard operation. Phase 2 described the application of a FaunaGuard and lasted on average 0.55 hours, whereas Phase 3 marked the period of pile driving, which took on average 1.72 hours. The time after piling was defined as Phase 4 and covered an average of 3.04 hours after piling.

In all four wind farms, DPM per minute decreased from Phase 1 to Phase 2, namely between 37 % and 75 % (Figure 10, Table 8). Furthermore, detection rates always already increased again in Phase 3 and Phase 4. In comparison to Phase 1, DPM per minute reached 84 % to 93 % during Phase 4. In this context, the wind farm "Trianel Windpark Borkum Phase 2" was not taken into account because Phase 4 lasted only 0.41 hours on average and should therefore not be compared with the same phase in other wind farms. Moreover, detection rates were highest in the wind farm "Borkum Riffgrund 2" and lowest in the wind farm "Trianel Windpark Borkum Phase 2".

DPM per minute differed significantly for each particular wind farm (Figure A.17 to Figure A.20, Table A.6). In all cases, DPM per minute were lowest during Phase 2 (During FaunaGuard) and differed significantly from Phase 1, Phase 3 and Phase 4 (except for the wind farm "Trianel Windpark Borkum Phase 2"). Therefore, detection rates during the FaunaGuard were significantly reduced prior to piling for all wind farms at distances of at least 1.5 km. Besides, detection rates during the FaunaGuard were always significantly more reduced than during the actual piling.

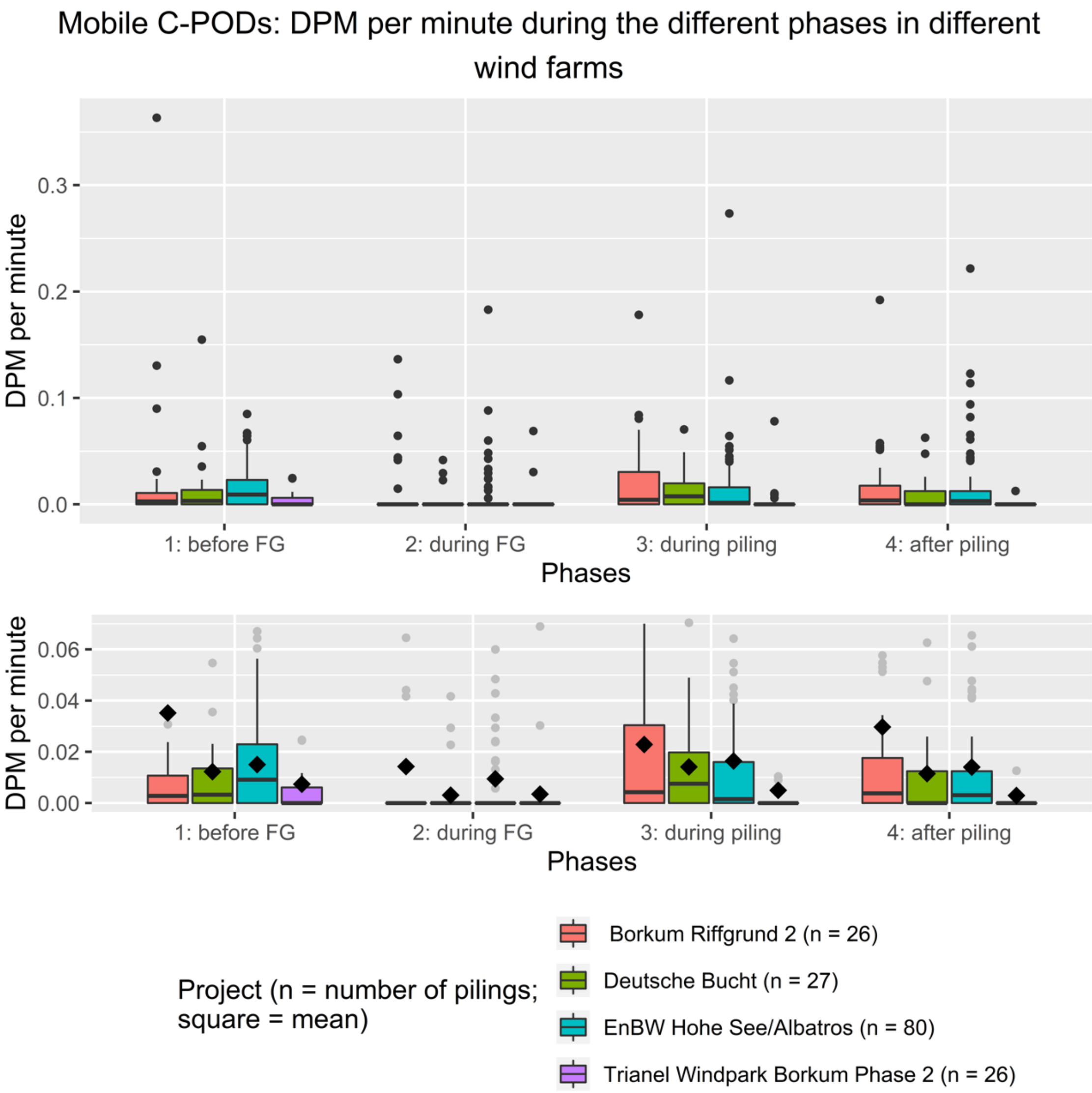

Figure 10: Mobile C-PODs: DPM per minute during the different phases in different wind farms (upper boxplots with all outliers, lower boxplots as zoom in quantile range). At all wind farms, DPM per minute were highest in Phase 1 (on average 6.20 hours before the FaunaGuard), lowest in Phase 2 (during the FaunaGuard, on average 0.55 hours), increased again in Phase 3 (during piling, on average 1.72 hours), and in Phase 4 (on average 3.04 hours after piling), DPM per minute remained close to the level of Phase 1.

Table 8: Mobile C-PODs: DPM per minute during the different phases in different wind farms. At all wind farms, DPM per minute were highest in Phase 1 (on average 6.20 hours before the FaunaGuard), lowest in Phase 2 (during the FaunaGuard, on average 0.55 hours), increased again in Phase 3 (during piling, on average 1.72 hours), and in Phase 4 (on average 3.04 hours after piling), DPM per minute remained close to the level of Phase 1.

Wind farm	**Phase**	**DPM per minute**			
		N (number of minutes)	**Mean**	**Standard deviation**	**Standard error**
Borkum Riffgrund 2	1: Before FaunaGuard	17,705	0.035	0.18	0.0014
	2: During FaunaGuard	1,820	0.014	0.12	0.0028
	3: During piling	5,250	0.023	0.15	0.0021
	4: After piling	8,687	0.030	0.17	0.0018
Deutsche Bucht	1: Before FaunaGuard	17,893	0.012	0.11	0.00082
	2: During FaunaGuard	1,292	0.0031	0.056	0.0015
	3: During piling	7,083	0.014	0.12	0.0014
	4: After piling	7,483	0.011	0.11	0.0012
EnBW Hohe See/Albatros	1: Before FaunaGuard	48,354	0.015	0.12	0.00055
	2: During FaunaGuard	5,377	0.0095	0.097	0.0013
	3: During piling	18,929	0.016	0.13	0.00092
	4: After piling	34,217	0.014	0.12	0.00064
Trianel Windpark Borkum Phase 2	1: Before FaunaGuard	19,843	0.0074	0.086	0.00061
	2: During FaunaGuard	1,725	0.0035	0.059	0.0014
	3: During piling	3,205	0.0050	0.070	0.0012
	4: After piling	1,365	0.0029	0.054	0.0015

Larger distances: Stationary C-POD data using DPM per minute

For distances up to 5 km from piling locations, two patterns were observed (Figure 11, Table A.9):

(1) At the wind farms “Borkum Riffgrund 2” and “Deutsche Bucht”, highest DPM per minute were measured in the phase Reference. In Phase 1 (Before FaunaGuard), DPM per minute already decreased and then continued to decrease during Phase 2 (During the FaunaGuard). In Phase 3 (During piling) and Phase 4 (After piling) they continued to decrease or slightly increased, but did not reach the level of the phase Reference.

(2) At the wind farms “EnBW Hohe See” and “Albatros”, as well as “Trianel Windpark Borkum Phase 2”, the detection rates were mainly at a similar level in all phases, and no clear trends were observed.

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 (Figure 11, Table A.9). Three patterns were observed:

(1) For the lowest average distance in this distance category (observed at the wind farm “Deutsche Bucht”: 5.17 km), a similar pattern as in the distance category 0 to 5 km was observed. More precisely, highest DPM per minute were measured in the phase Reference. In Phase 1 (Before FaunaGuard), DPM per minute already decreased and then continued to decrease during Phase 2 (During the FaunaGuard). In Phase 3 (During piling), DPM per minute remained at the level of the previous phase and in Phase 4 (After piling), DPM per minute reached the reference level again.

(2) For the intermediate average distances in this distance category (observed at the wind farms “EnBW Hohe See” and “Albatros”, as well as “Borkum Riffgrund 2”: 7.37 km respectively 7.73 km), DPM per minute were at a similar level in all phases, and no clear trends were observed.

(3) For the largest average distance in this distance category (observed at the wind farm “Trianel Windpark Borkum Phase 2”: 8.34 km), DPM per minute were mainly above the level of the phase Reference and highest during Phase 3 (During piling).

Accordingly, project-specific as well as distance-specific differences in detection rates were observed between the wind farms.

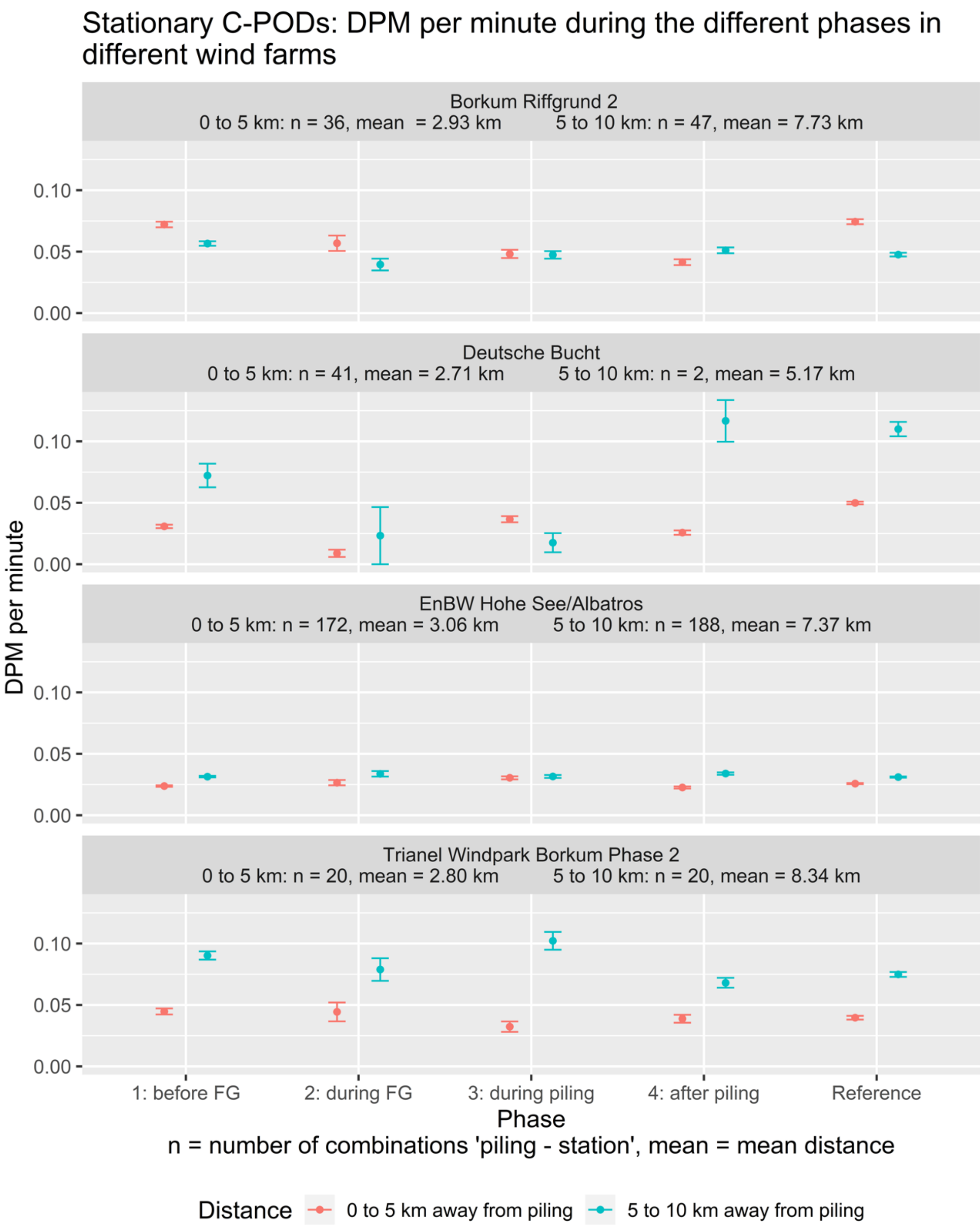

Figure 11: Stationary C-PODs: DPM per minute (mean and standard error) during the different phases in different wind farms at different distances. For distances up to 5 km from piling locations, detection rates either decreased during Phase 1 (Before FaunaGuard), Phase 2 (During FaunaGuard) and Phase 3 (During piling) or were mainly 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.

Larger distances: Stationary C-POD data using DPH per hour

In general, DPH per hour at the OWFs “Borkum Riffgrund 2”, and “Deutsche Bucht” decreased a few hours before the FaunaGuard operation started and increased again a few hours after piling (Figure 12). This trend was less noticeable at the wind farms “EnBW Hohe See” and “Albatros”, as well as “Trianel Windpark Borkum Phase 2”.

As with the four distance categories, DPH per hour for all wind farms up to 10 km were highest during the phase Baseline (hours -48 to -25 before FaunaGuard operation) and slightly lower in the phase Reference after piling (hours +49 to +120 after piling) (Figure 13, Table A.10). Lowest DPH per hour were observed in different phases in accordance with the average distance: For the wind farms with higher average distance during the phase Piling, meaning in the hours in which the FaunaGuard was activated and/or piling took place for at least one minute (“Borkum Riffgrund 2”: 5.97 km, “EnBW Hohe See” and “Albatros”: 5.31 km) and for the wind farms with lower average distance during the phase Pre-piling and thus in the hours -3 to -1 before FaunaGuard operation (“Deutsche Bucht”: 2.73 km, “Trianel Windpark Borkum Phase 2”: 4.92 km).

Besides, project-specific differences in detection rates were observed between the wind farms. The differences in DPH per hour among the individual phases were smallest for “EnBW Hohe See” and “Albatros”. Furthermore, generally higher DPH per hour were recorded at “Borkum Riffgrund 2” compared to the other wind farms.

At all wind farms except for “Trianel Windpark Borkum Phase 2”, the phases differed significantly (Figure A.21 to Figure A.23, Table A.7). In the wind farms “Borkum Riffgrund 2” as well as “EnBW Hohe See” and “Albatros”, DPH per hour were significantly lower during the phase Piling than during the other three phases. Besides, in the wind farm “Deutsche Bucht”, DPH per hour were significantly lower during the phase Pre-piling than during the phases Baseline and Reference after piling.

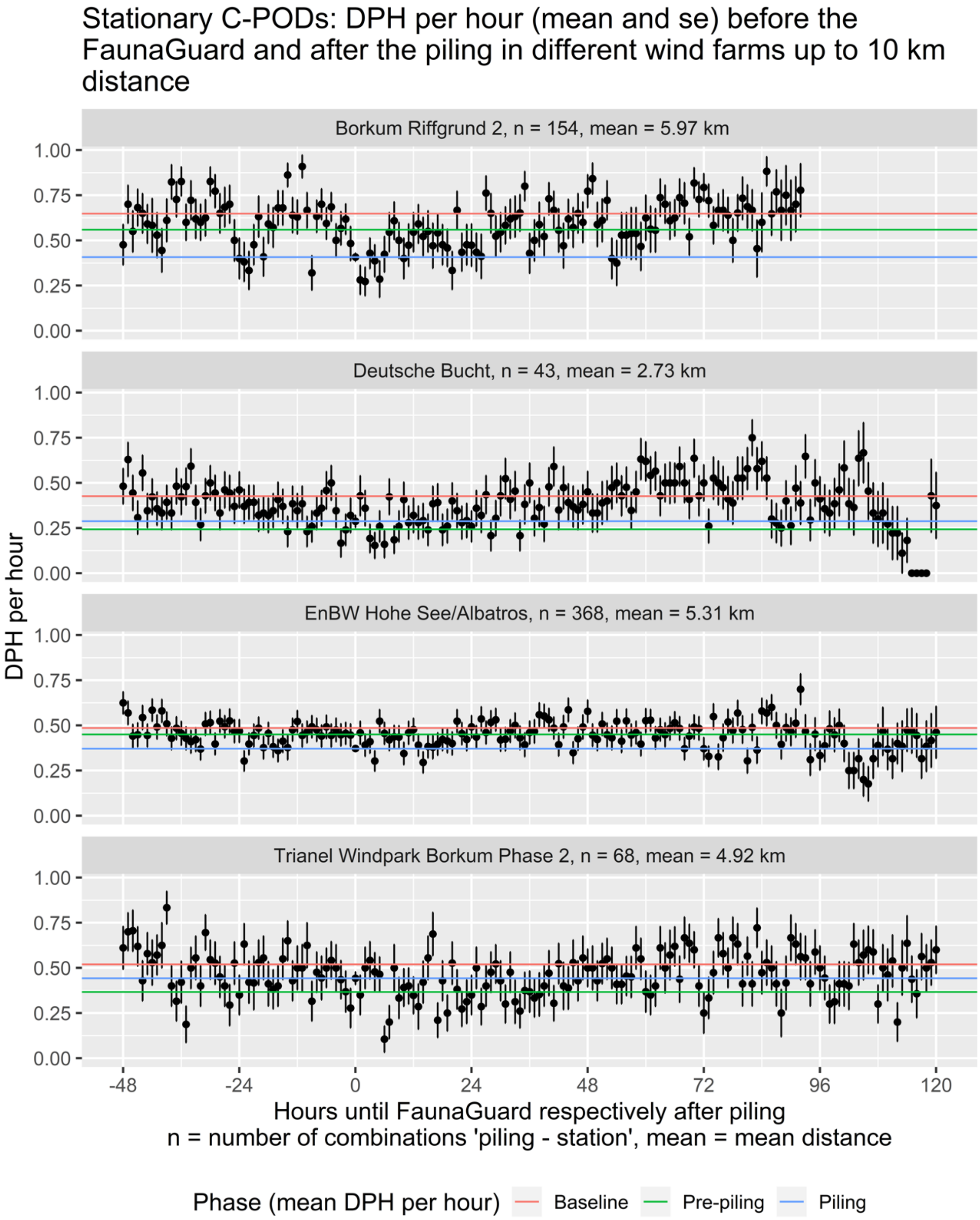

Figure 12: Stationary DPH per hour (mean and standard error) from 48 hours before FaunaGuard operation until 120 hours after piling in the different wind farms up to 10 km distance towards the piling location. DPH per hour at the OWFs “Borkum Riffgrund 2”, and “Deutsche Bucht” decreased a few hours before the FaunaGuard operation started and increased again a few hours after piling; this trend was less noticeable at the wind farms “EnBW Hohe See” and “Albatros”, as well as “Trianel Windpark Borkum Phase 2”.

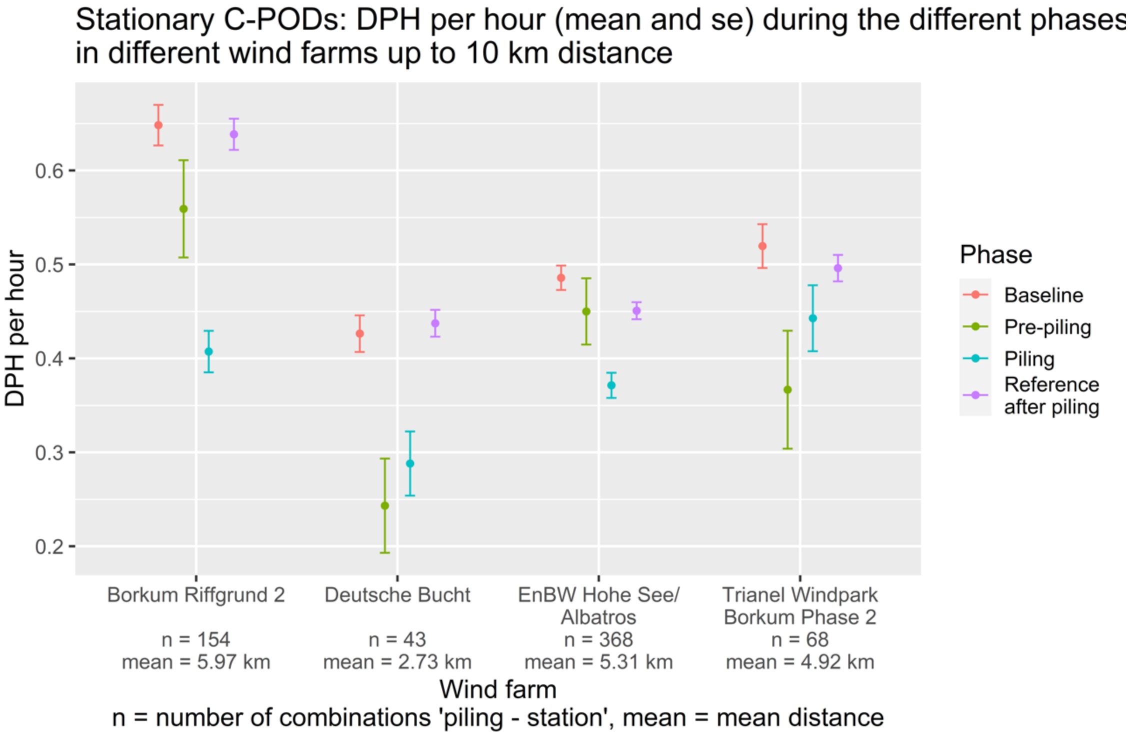

Figure 13: Stationary C-PODs: DPH per hour (mean and standard error) during the different phases in the different wind farms up to 10 km distance from the piling location. At all wind farms, DPH per hour were highest during the phases Baseline (hours -48 to -25 before FaunaGuard operation) and Reference after piling (hours +49 to +120 after the piling); at the wind farms "Borkum Riffgrund 2" as well as "EnBW Hohe See" and "Albatros", DPH per hour were lowest during the phase Piling (at least 1 minute of FaunaGuard operation or piling) and at the wind farms "Deutsche Bucht" and "Trianel Windpark Borkum Phase 2", DPH per hour were lowest during the phase Pre-piling (down to 3 hours before FaunaGuard operation).

3.4 What effect did the duration of operation of the FaunaGuard have on the detection rates during this phase?

To investigate the influence of the duration of operation of a FaunaGuard on the detection rates during this phase, the mobile and stationary C-POD data were combined and different types of modelling were performed.

Raw data

When looking at the raw data, higher detection rates were generally observed further away from the pile-driving site (Figure 14, Table A.11). As soon as the FaunaGuard operation started, detection rates between distances of 0 to 1.25 km to the pile-driving site decreased further with increasing duration of operation, and near-zero detection rates were observed from minute 23. No clear trends could be detected at larger distances.

Generalised Additive Model

When using a Generalised Additive Model, even before the FaunaGuard operation started, reduced detection rates were calculated up to a distance of about 1.5 km (Figure 15, Table 9). The use of the FaunaGuard further reduced the detection rates. The longer the FaunaGuard was used, the stronger and further away the detection rates decreased. After about 20 minutes of FaunaGuard operation, a decrease in detection rates was recorded up to a distance of about 2 km. If the FaunaGuard was applied for 20 further minutes, and thus for a total of 40 minutes, the detection rates decreased up to a distance of about 2.5 km.

Boosted Regression Trees

When using Boosted Regression Tree (BRT) models, the results were similar. The three-dimensional BRT model without any environmental parameters or random effects showed that the detection rates generally increased with increasing distance to the pile-driving site, irrespective of the duration of the FaunaGuard (Figure 16). While at the beginning individual detections were simulated in the vicinity of the piling locations, after about 20 minutes of using the FaunaGuard no more detections up to a distance of about 2 km were calculated.

Moreover, the Partial Dependence Plots showed that detection rates between distances of 0 to 1.25 km to the pile-driving site decreased with increasing duration of the FaunaGuard (Figure 17). However, after about 20 minutes of operation the detection rates did not change any further. Simultaneously, increased detection rates were simulated for distances between 1.25 and 2.5 km.

No clear trends could be observed for larger distance categories, e. g. in 2.5 to 5 km distance there was an apparent contradiction between the raw data showing particular high detection rates from minute 33 of FaunaGuard operation (though only few data in the latter time classes; Figure 14) and the BRT model indicating a decrease from minute 26 (Figure 17). Contradictions were due to the inclusion of covariates in the BRT models; effects in distance classes from 2.5 km upwards (Figure 17) were thus probably prone to a higher heterogeneity within those datasets which were based on only a few C-POD stations at various positions and no mobile C-POD data.

Besides, not the variable describing the duration of FaunaGuard operation ("A_min_FaunaGuard") had the highest explanatory power in the BRTs, but the total number of clicks ("allClx_min"), 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 always ranked fourth regarding its relative importance (Figure 17).

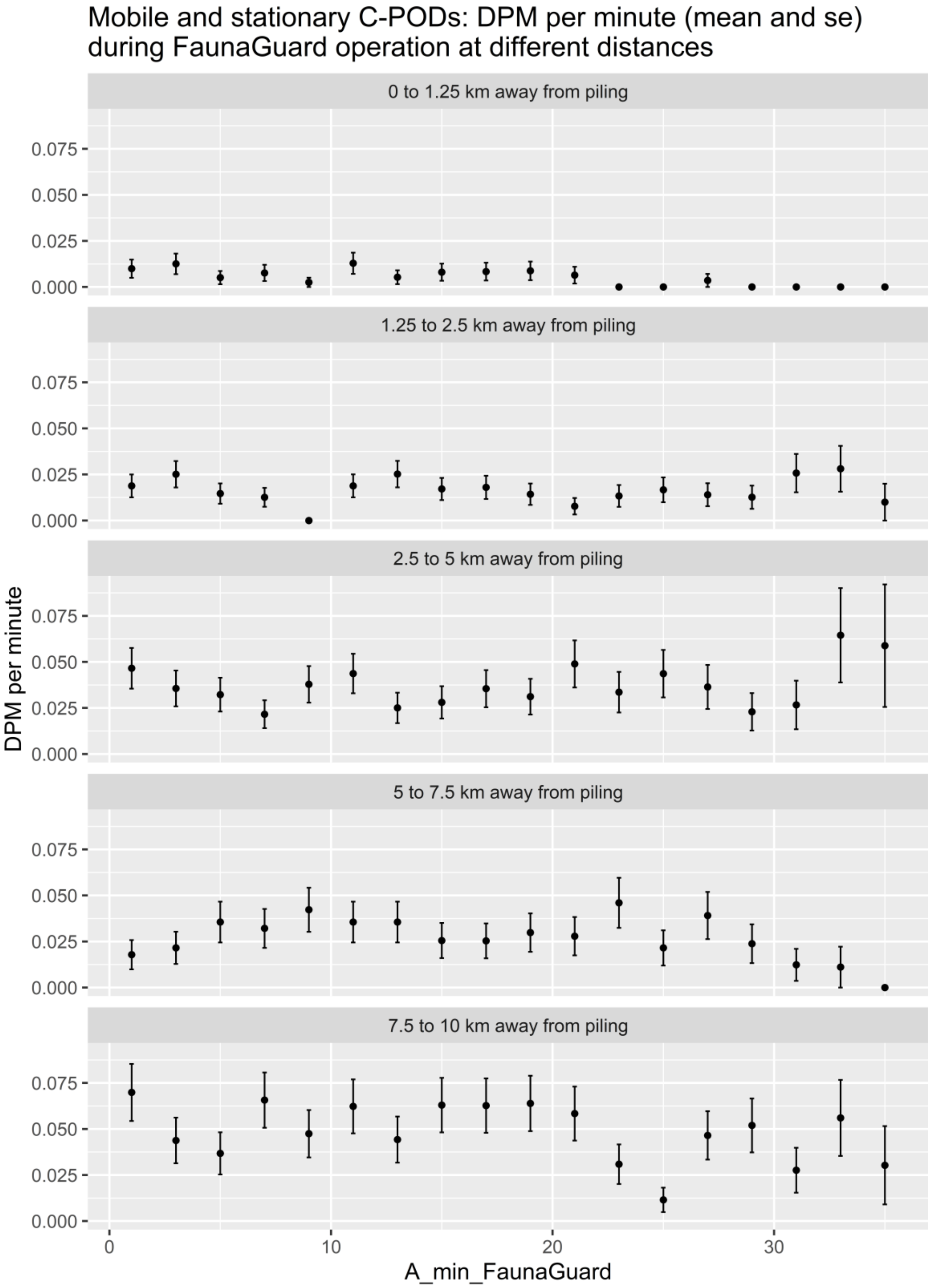

Figure 14: Mobile and stationary C-PODs: DPM per minute (mean and standard error) during FaunaGuard operation at different distances. Higher detection rates were generally observed further away from the pile-driving site. In addition, detection rates in the distance class 0 to 1.25 km to the pile-driving site continued to decrease as the duration of use of the FaunaGuard increased; no clear trends could be identified for larger distances.

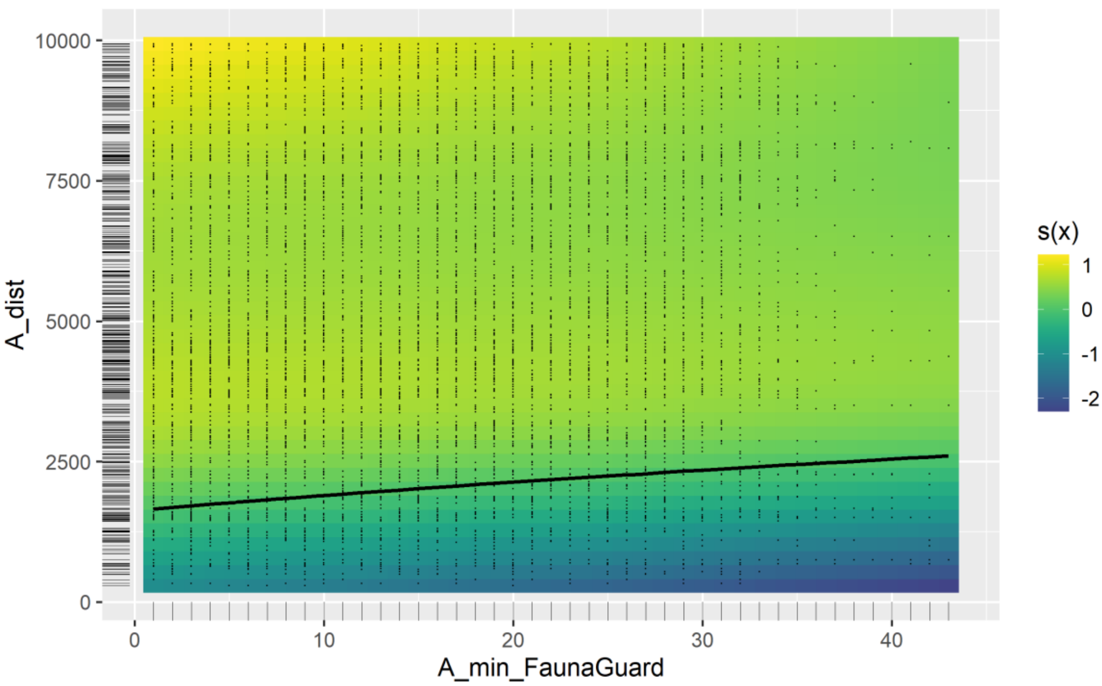

Figure 15: Effect of the duration of FaunaGuard operation on the spatial extent and intensity of decrease for all wind farms using a Generalised Additive Model. The variable "A_dist" described the distance to the FaunaGuard; the variable "A_min_FaunaGuard" described the minute of FaunaGuard operation 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. The black line is the zero line, which means that even before the FaunaGuard was used, reduced detection rates were observed in the vicinity of the piling location. Depending on how long the FaunaGuard was used, reduced detection rates were simulated up to a distance of about 2.5 km from the pile-driving site.

Table 9: Effect of the duration of FaunaGuard operation on the spatial extent and intensity of decrease for all wind farms using a Generalised Additive Model. For the best explanatory model, the p-value for all variables and additionally the indices of the model were given.

	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	pr_at_pres: < 2e-16 (***)
N (number of analysed hours)	26,796
R-squared (adjusted)	0.286
Deviance explained	40.2 %

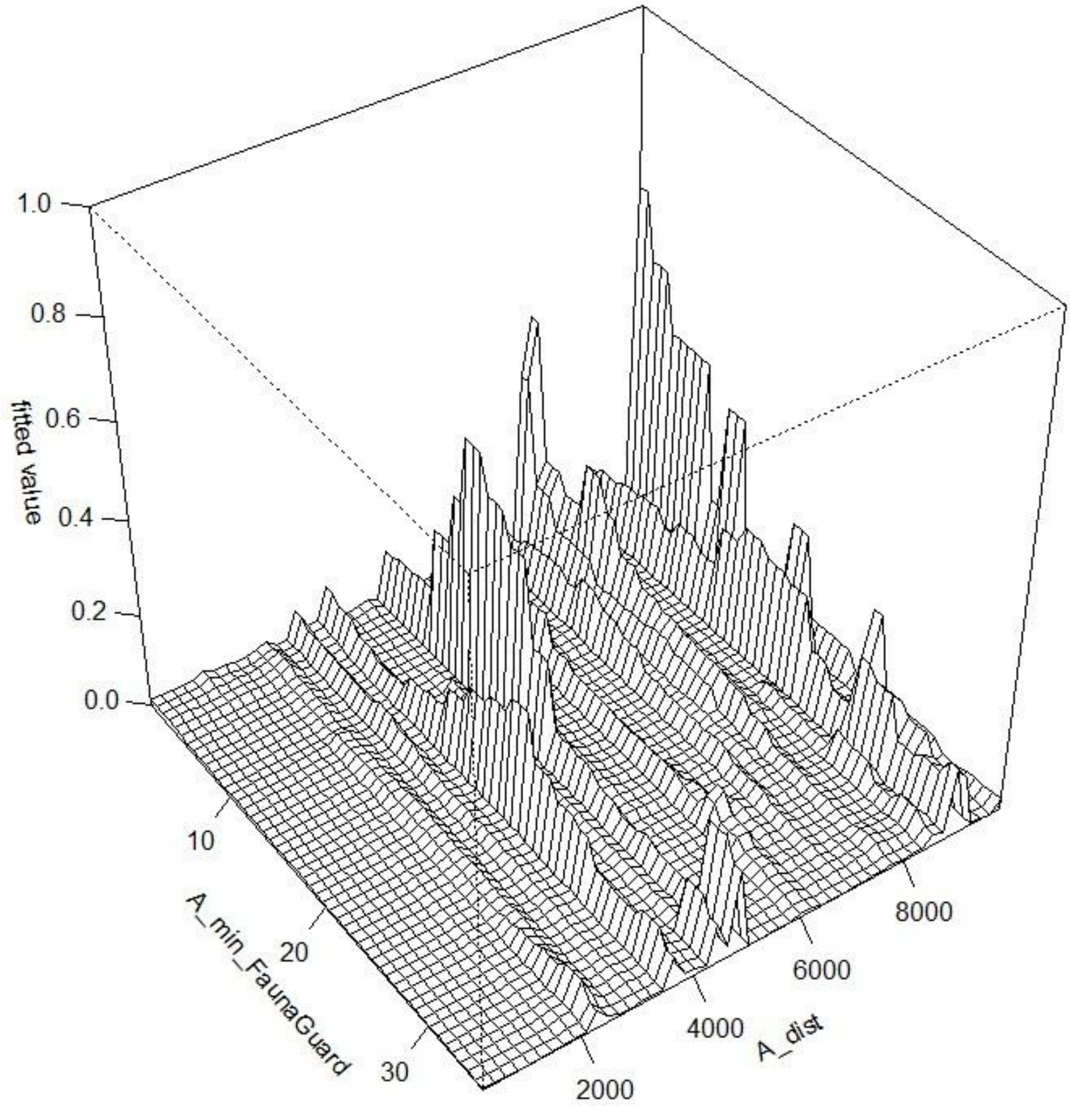

Figure 16: Effect of the duration of FaunaGuard operation on the spatial extent and intensity of decrease for all wind farms using a three-dimensional Boosted Regression Tree model without any environmental parameters or random effects. The variable "A_dist" described the distance to the FaunaGuard; the variable "A_min_FaunaGuard" described the minute of FaunaGuard operation 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. The fitted values represent the probability of a DPM. Accordingly, the detection rates generally increased with increasing distance to the pile-driving site, irrespective of the duration of the FaunaGuard. While at the beginning individual detections were simulated in the vicinity of the piling locations, after about 20 minutes of using the FaunaGuard no more detections up to a distance of about 2 km were calculated.

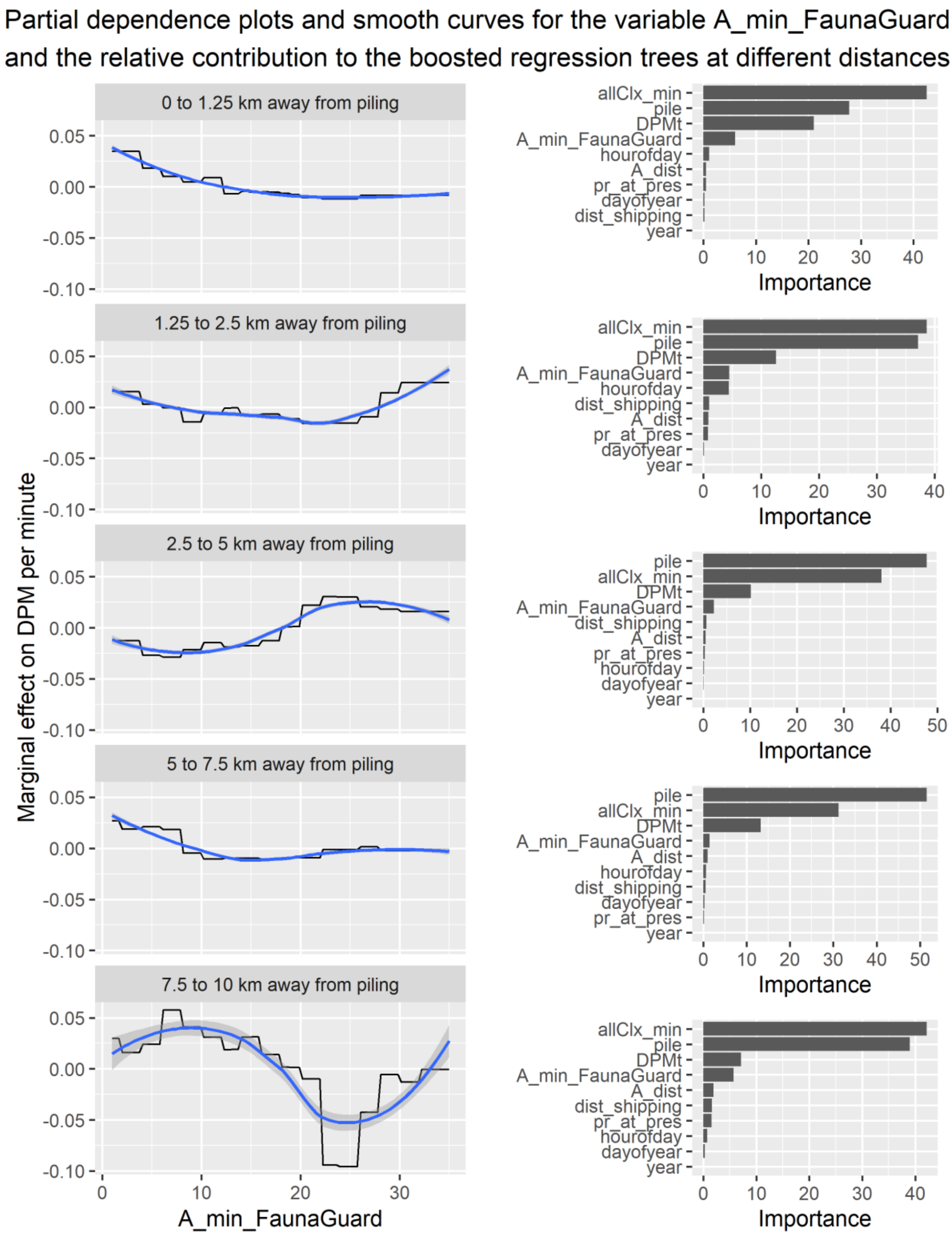

Figure 17: Effect of the time of the FaunaGuard operation on the spatial extent and intensity of decrease for all wind farms using Boosted Regression Tree models at different distances and including environmental parameters and random effects. The variable “A_min_FaunaGuard” described the minute of FaunaGuard operation 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. Left panel: Partial Dependence Plots (PDP) indicate changes in the predicted mean value when one parameter, and in this case “A_min_FaunaGuard”, varies while the other parameters remain constant. Therefore, positive values on the y-axis indicate that the detection rates increase compared to the mean value; negative values indicate a decrease in detection rates. Right panel: The relative contribution of each variable to the BRT was shown for each distance class in order to better classify the influence of the variable “A_min_FaunaGuard” on the model.

3.5 How did the detection rates of harbour porpoises during Fauna-Guard operation differ from those during seal scarer operation?

For the comparison at the OWF “Trianel Windpark Borkum Phase 2”, data of the mobile as well as stationary C-PODs were used; in contrast, for the comparison with the Gescha studies, only stationary C-POD data were used.

Comparison at the OWF “Trianel Windpark Borkum Phase 2”

The mobile C-POD data in the wind farm “Trianel Windpark Borkum Phase 2” showed generally low detection rates in all phases (Figure 18, Table A.12). DPM per minute rates were higher at a distance of 1.5 km compared to 0.75 km, irrespective of using a FaunaGuard or seal scarer as AHD. Due to the generally low detection rates, no difference could be detected between the FaunaGuard and the seal scarer at distances up to 1.5 km.

In comparison, the stationary data showed a difference between the AHDs at distances of 5 to 10 km from the piling location (Figure 19, Table A.13). When using a FaunaGuard as AHD, DPM per minute were similar during all phases. Mean DPM per minute decreased during Phase 2 (During AHD) by only 12 % compared to Phase 1 (Before AHD). However, when using the seal scarer as AHD, mean DPM per minute were considerably lower in Phase 2 compared to the other phases and decreased by 94 % compared to Phase 1.

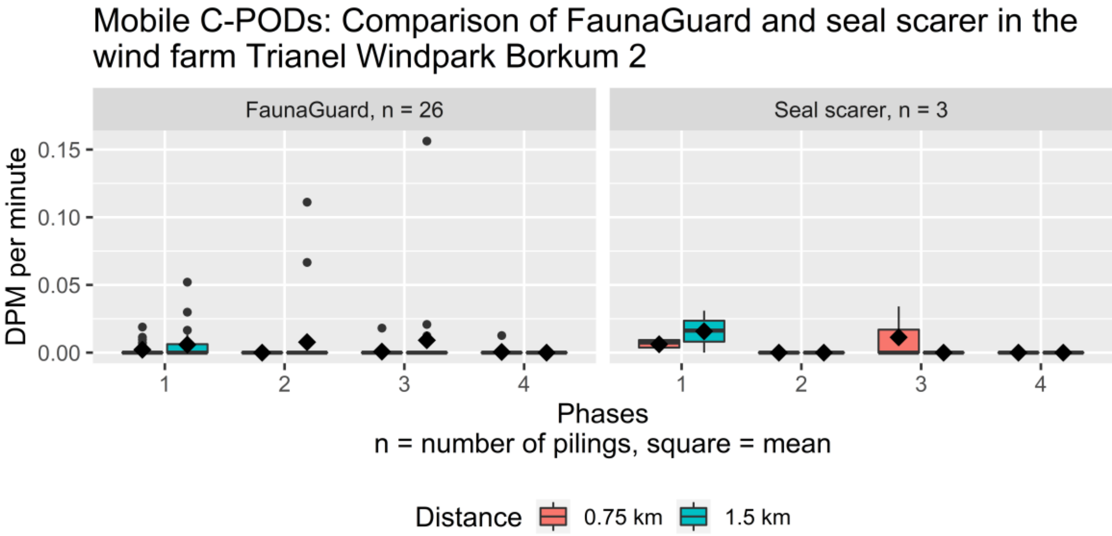

Figure 18: Mobile C-PODs: Comparison of FaunaGuard and seal scarer in the wind farm "Trianel Windpark Borkum Phase 2". DPM per minute were highest in Phase 1 (on average 6.20 hours before AHD operation), lowest in Phase 2 (during AHD operation, on average 0.55 hours), increased again in Phase 3 (during piling, on average 1.72 hours), and in Phase 4 (on average 3.04 hours after piling), DPM per minute remained close to the level of the previous phase. Due to the generally low detection rates, no difference could be detected between the FaunaGuard and the seal scarer as AHD at distances up to 1.5 km.

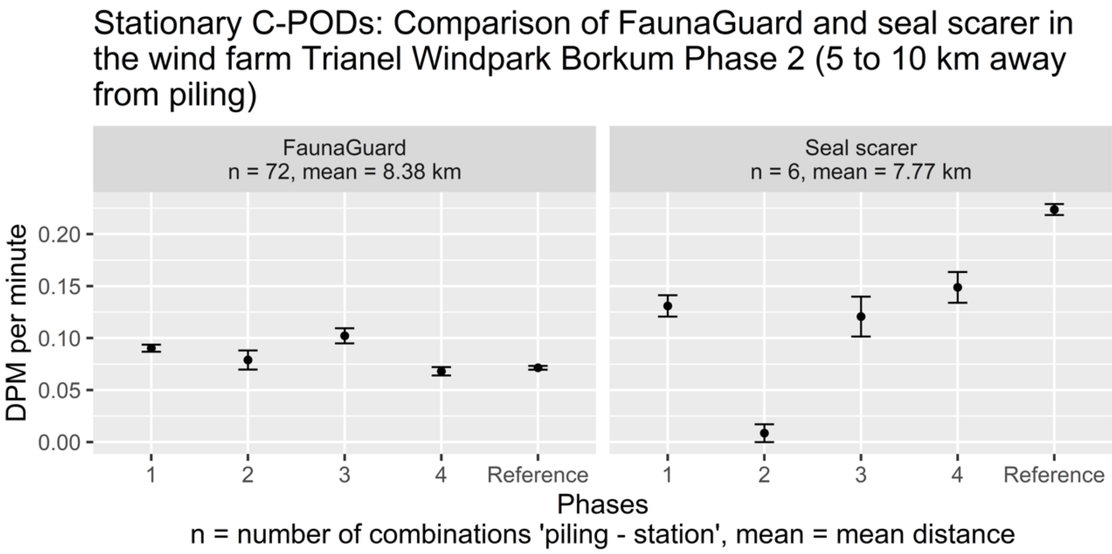

Figure 19: Stationary C-PODs: Comparison of FaunaGuard and seal scarer in the wind farm "Trianel Windpark Borkum Phase 2" (5 to 10 km away from piling). When using the FaunaGuard as AHD, DPM per minute were similar during all phases (Phase 1: Before AHD/ Phase 2: During AHD/ Phase 3: During Piling/ Phase 4: After piling/ Reference); however, when using the seal scarer as AHD, DPM per minute were considerably lower in Phase 2, meaning during the use of the seal scarer, compared to the other phases.

Cross-project comparison to Gescha studies: Stationary C-POD data with DPH per hour up to 10 km distance from the piling location

In this study, DPH per hour up to a distance of 10 km were highest during the phases Baseline (hours -48 to -25 before FaunaGuard operation) and Reference after piling (hours +49 to +120 after piling) having a mean value of 0.50 respectively 0.48 (Figure 20, Table 10). Lowest DPH per hour were recorded during the phase Piling (at least 1 minute of FaunaGuard operation or piling) having a mean value of 0.37. The DPH rate of the phase Pre-piling (hours -3 to -1 before the FaunaGuard operation) was in the intermediate range and had a mean value of 0.41.

In addition, each phase was significantly different from every other (Figure A.24, Table A.7). Therefore, the influencing factors of each individual phase seemed to have a significant effect on the detection rate of the phase.

In the Gescha 1 and Gescha 2 studies (BIOCONSULT SH et al. 2016; BIOCONSULT SH ET AL. 2019), DPH per hour up to a distance of 10 km were also highest during the phases Baseline and Reference after piling and lowest during the phase Piling (Figure 20, Table 10). The DPH per hour were similar in most phases; however, in this study the detection rates decreased less during the phase Piling than in the Gescha studies. Namely, DPH per hour decreased from the phase Baseline to the phase Piling by 25 % in this study, whereas DPH per hour declined by 39 to 41 % in the Gescha 1 and Gescha 2 studies.

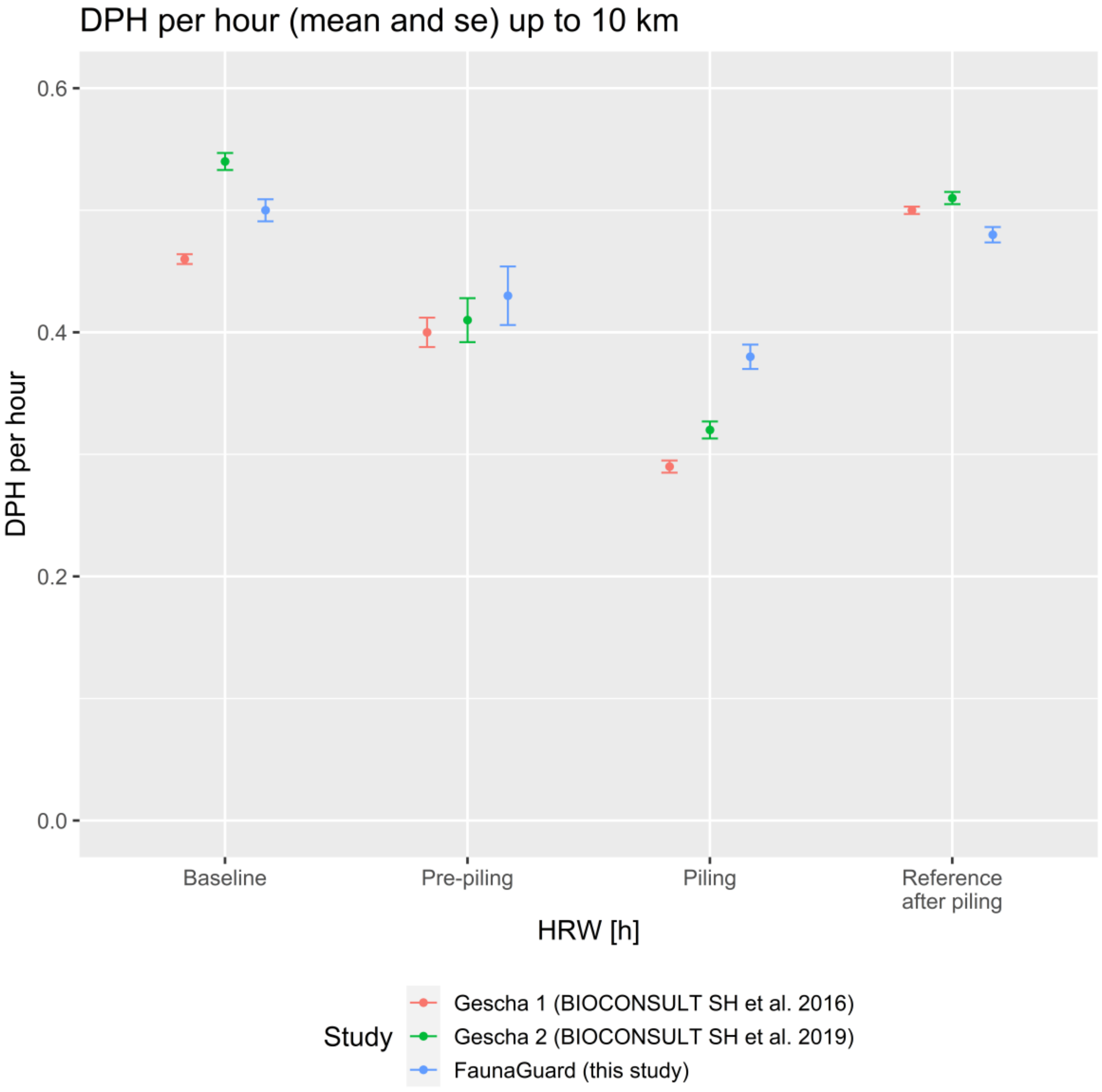

Figure 20: Stationary C-PODs: DPH per hour during the different phases up to 10 km distance from the piling location (mean of this study = 4.90 km) compared to results of the Gescha studies (BIOCONSULT SH et al. 2016; BIOCONSULT SH ET AL. 2019). DPH per hour were always highest during the phases Baseline (hours -48 to -25 before AHD operation) and Reference after piling (hours +49 to +120 after piling), in the intermediate range during the phase Pre-piling (down to 3 hours before FaunaGuard operation) and lowest during the phase Piling (at least 1 minute of FaunaGuard operation or piling); in this study, detection rates decreased less during the phase Piling than in the Gescha studies.

Table 10: Stationary C-PODs: DPH per hour during the different phases up to 10 km distance from the piling location (mean of this study = 4.90 km) compared to results of the Gescha studies (BioConsult SH et al. 2016; BioConsult SH et al. 2019). DPH per hour were always highest during the phases Baseline (hours -48 to -25 before AHD operation) and Reference after piling (hours +49 to +120 after piling), in the intermediate range during the phase Pre-piling (down to 3 hours before FaunaGuard operation) and lowest during the phase Piling (at least 1 minute of FaunaGuard operation or piling); in this study, detection rates decreased less during the phase Piling than in the Gescha studies.

Phase	**Definition**	**Study**	**DPH per hour**			
			N (number of hours)	**Mean**	**Standard deviation**	**Standard error**
Baseline	Hours -48 to -25 before AHD	Gescha 1	13,703	0.46	0.50	0.0040
		Gescha 2	4,864	0.54	0.50	0.0070
		FaunaGuard	3,027	0.50	0.50	0.0090
Pre-piling	Down to 3 hours before AHD	Gescha 1	1,542	0.40	0.49	0.012
		Gescha 2	714	0.41	0.49	0.018
		FaunaGuard	427	0.43	0.50	0.024
Piling	At least 1 minute of AHD or piling	Gescha 1	8,043	0.29	0.45	0.0050
		Gescha 2	5,052	0.32	0.47	0.0070
		FaunaGuard	2,180	0.38	0.49	0.010
Reference after piling	Hours +49 to +120 after piling	Gescha 1	23,389	0.50	0.50	0.0030
		Gescha 2	8,732	0.51	0.47	0.0050
		FaunaGuard	6,351	0.48	0.50	0.0063

4. Discussion

To reduce greenhouse gas emissions, the proportion of renewable energies in electricity consumption has to increase further. Therefore, among other things, more offshore wind farms are planned to be built (BUNDESMINISTERIUM FÜR WIRTSCHAFT UND ENERGIE 2020a; b). However, offshore wind farms generate noise and underwater noise in general can affect the individual fitness and structure of ecological communities (SOUTHALL et al. 2007, 2019). Acoustic disturbances mainly affect marine mammals, which in the German Bight of the North Sea primarily concerns harbour porpoises – the only cetacean species breeding in this area. Although operating offshore wind turbines are barely audible to harbour porpoises at distances above 70 m from the foundation (TOUGAARD et al. 2009b), construction creates significant noise emissions, which can affect behaviour and lead to a temporary hearing threshold shift (TTS), permanent hearing threshold shift (PTS), or even the death of harbour porpoises depending on the distance towards the sound source (KASTELEIN et al. 2011). In order to minimise the effects of noise emissions during piling, the German Federal Maritime and Hydrographic Agency (BSH) set a dual noise protection criterion and prescribes the use of noise mitigation systems (BSH 2013). Additionally, acoustic harassment devices have to be used before the start of pile driving in order to scare all harbour porpoises away from the area where they eventually could suffer TTS or even PTS. Until 2017, the seal scarer was mandated as AHD. However, the seal scarer showed a significant deterrence effect on harbour porpoises in a much larger range than intended (BRANDT et al. 2013b) and appeared to have the potential to induce a TTS (SCHAFFELD et al. 2019). Therefore, the FaunaGuard was developed a few years ago by Van Oord and the Dutch company SEAMARCO (Sea Mammal Research Company) (VAN DER MEIJ et al. 2015) and is now prescribed and used as a deterrent device. The FaunaGuard also aims at deterring all harbour porpoises from a radius of 1 km around piling locations before the start of the noise-intensive piling, but should not lead to large-scale disturbance as caused by the seal scarer.

Although former OWF-specific monitorings indicated that a FaunaGuard is highly effective in deterring harbour porpoises, a cross-project analysis and comparison with data regarding the previous procedure with seal scarer operation before piling were still pending. Therefore, the present master thesis aimed to fill this gap.

This study showed that the FaunaGuard is highly effective in decreasing the detection rates of harbour porpoises in the vicinity of piling locations, but that it does not cause negative effects that are ranging further than necessary. Referring to the initial research questions, the study produced the following main results which are discussed in more detail in sections 4.2 to 4.6:

(1) How did the detection rates of harbour porpoises change during FaunaGuard operation at smaller distances up to 1.5 km? (See section 4.2)

The detection rates of harbour porpoises decreased by 48 % during FaunaGuard operation at smaller distances up to around 1.5 km, compared to a period of on average six hours before the operation of the device. Detection rates during FaunaGuard operation were thus lower than during piling itself. Moreover, the detection rates returned to a baseline level in the hours following pile driving.

(2) How did the detection rates of harbour porpoises change during FaunaGuard operation at larger distances up to 20 km? (See section 4.3)

During operation of a FaunaGuard, reduced detection rates were observed only up to a distance of around 2 to 2.5 km.

(3) How did the detection rates of harbour porpoises during FaunaGuard operation differ between wind farms at smaller and larger distances? (See section 4.4)

In all offshore wind farms positioned in different regions of the German Bight, detection rates decreased between 37 % and 75 % during FaunaGuard operation in up to 1.5 km distance, and returned to a baseline level in the hours following pile driving. In addition, harbour porpoise detections during FaunaGuard operation, as well as during pile driving, achieved the reference level at different distances from the sound source depending on the OWF.

(4) What effect did the duration of operation of the FaunaGuard have on the detection rates during this phase? (See section 4.5)

The detection rates decreased up to a distance of about 2 km when the FaunaGuard was in operation for about 20 to 25 minutes. At this duration of operation, harbour porpoise detection rates nearly declined to zero in the close range of up to 1.25 km distance. A longer operation seemed to lead to a slightly further increasing effect intensity and distance (then up to 2.5 km).

(5) How did the detection rates of harbour porpoises during FaunaGuard operation differ from those during seal scarer operation? (See section 4.6)

At the wind farm "Trianel Windpark Borkum Phase 2", the data from mobile C-PODs (up to a distance of 1.5 km) showed no difference in effects of a seal scarer and FaunaGuard on detection rates. However, in 5 to 10 km distance (mean around 8 km), the detection rates during FaunaGuard operation decreased by only 12 % compared to the detection rates in the six hours before, but rates declined by 94 % when using a seal scarer. A cross-project comparison showed that in this study, detection rates during AHD operation and subsequent piling decreased less than in studies where pilings with different noise mitigation systems and a seal scarer as AHD were investigated.

The chosen method of passive acoustic monitoring was appropriate for this research project, as the porpoise detections not only show the presence of animals but also may serve as a rough indication for the relative abundance of harbour porpoises. This aspect is discussed in detail in section 4.1.

4.1 Passive Acoustic Monitoring as appropriate measure to analyse the effect of the FaunaGuard and subsequent piling on harbour porpoise response

Outline

In OWF construction projects, acoustic monitoring of harbour porpoise activity using C-PODs is mandatory. This methodology is more suitable than visual and aerial surveys to investigate the effects of the FaunaGuard and subsequent piling on the response of harbour porpoises because (1) visual observations are limited by light, weather conditions, and visibility, (2) harbour porpoises in particular are difficult to observe visually, and (3) in this study, the temporal and spatial resolution of the FaunaGuard effect was mainly important, but with aerial surveys, construction sites are only briefly overflown, so analysing the temporal resolution of the FaunaGuard effect would not have been possible, and with the line transect method from the vessel, the spatial resolution would have been lower.

Therefore, PAM was chosen in this cross-project analysis. Harbour porpoises are particularly suitable for PAM, as they use their echolocation system almost continuously (AKAMATSU et al. 2007; LINNENSCHMIDT et al. 2013). Accordingly, detection rates of C-PODs are an approximate device to measure harbour porpoise presence or absence. Also during wind farm construction with seal scarer operation and piling (KOSCHINSKI et al. 2003; TEILMANN et al. 2006; BRANDT et al. 2013b; HAELTERS et al. 2015; BIOCONSULT SH et al. 2016) as well as FaunaGuard operation (GEELHOED et al. 2017; KASTELEIN et al. 2017) – the echolocation activity of individuals does not change considerably, but rather indicates a displacement of the animals.

When using PAM, there are mainly two sources of error: (1) The passive acoustic loggers themselves, namely the C-PODs used here – for example a low maximum detection range, background noise, the internal sensitivity of the C-PODs, false-positive detections or the angular range of harbour porpoise echolocation, and (2) other factors affecting harbour porpoise echolocation activity in general – such as time of day, season, habitat conditions, tide and lunar cycle. However, both sources of error were considered low in this study and thus the reliability of the results was considered high.

Even though a final proof is still lacking that the observed decrease in detection rates during FaunaGuard operation was mainly due to a physical absence of harbour porpoises and not to a reduction in echolocation activities, there was no reason to assume that the animals in this study responded completely different to FaunaGuard signals and piling than in previous studies. Therefore, it was expected that the number of acoustic detections was a good indication for presence or even relative abundance.

Using Passive Acoustic Monitoring instead of visual and aerial surveys

Visual and aerial surveys can provide a large-scale study on the presence and absence of marine mammals. However, three points argue against visual and aerial observations as suitable method for OWF construction projects and in particular for this study:

First, visual observations are limited to light, weather conditions and visibility and are thus only possible to a limited extent, mostly in summer and not continuously (SIMON et al. 2010; HAMMOND et al. 2013). For this study, however, a continuous data set was needed.

Second, harbour porpoises in particular are difficult to observe visually for the following reasons: (1) Because of their small size of only up to 1.70 m, their inconspicuous blow and their shy behaviour, they are often overlooked and difficult to detect. (2) Different observers and platforms can influence the results considerably. (3) The diving patterns can vary depending on the time of day, season, habitat condition, tide and lunar cycle, so that these factors must be taken into account when calculating the detection function. (4) Harbour porpoises dive more often during the day than at night – thus in the time in which visual observations are feasible – and can stay under water for over 5 minutes (WESTGATE et al. 1995). (5) Harbour porpoises can only be observed up to a Beaufort Sea State of 2 (TEILMANN 2003). For these reasons, it is particularly difficult for harbour porpoises to calculate detection functions and estimate density from visual observations alone. Especially in low-density areas, there is high variability, causing unreliable results (BACH et al. 2000; GALLUS et al. 2012). However, this study included some low-density areas.

Third, the temporal and spatial resolution of the FaunaGuard effect was mainly important in this study. In the case of aerial surveys, the construction sites are only flown over briefly, so that no temporal resolution of the FaunaGuard effect would have been possible, while the line transect method from the vessel would have been less accurate in terms of spatial resolution.

Therefore, for this study, Passive Acoustic Monitoring (PAM) of harbour porpoises seemed to be more suitable than visual and aerial surveys. PAM provides continuous long-term data on a small-scale basis and thus enables the assessment of short-term fluctuations. Using a network of PAM devices, we were able to study short-term responses of harbour porpoises over a larger area. Additional visual observations would have been beneficial, but were not feasible due to cost constraints.

Passive Acoustic Monitoring as suitable method for harbour porpoises

PAM is a non-invasive and at the same time cost-effective method for the continuous acquisition of homogeneous data on a long-term basis, independent of weather, visibility and daylight. Thus, the detection function is better developed for acoustic than visual surveys (BUCKLAND et al. 2004).

Harbour porpoises are particularly suitable for PAM, as their signals are stereotypical and easily recognisable (VERFUß et al. 2007; KYHN et al. 2008; BRANDT et al. 2011). Furthermore, they use their echolocation system almost continuously (AKAMATSU et al. 2007; LINNENSCHMIDT et al. 2013) because echolocation is used for orientation, foraging and intraspecific communication, regardless of light conditions (KOSCHINSKI et al. 2008; VERFUß et al. 2009). Wild individuals in Danish waters were tagged and produced sonar clicks every 12.30 seconds on average (AKAMATSU et al. 2007). Furthermore, the inter click-train intervals were no longer than 20 seconds in 90 % of the cases. In our study, detections were determined on a minutely and hourly basis and the temporal range is thus many times greater than the reported average inter click-train interval. Although no clicks were recorded in three free-ranging harbour porpoises during maximum periods of 99 to 1,300 seconds, meaning that they were either silent or the clicks were below 142 dB and thus outside the threshold of the A-tag used, these periods of silence were rare and it is therefore assumed that harbour porpoises echolocate almost continuously (LINNENSCHMIDT et al. 2013).

Decrease in detection rates as indication of physical absence

Various studies show that the acoustically estimated porpoise density coincides well with the visually estimated porpoise density (DIEDERICHS et al. 2002; KOSCHINSKI et al. 2003; CARSTENSEN et al. 2006; KYHN et al. 2012; WILLIAMSON et al. 2016; JACOBSON et al. 2017). Even in low-density areas, the comparison from satellite telemetry and PAM using a network of C-PODs showed that both methods provide comparable information on the relative distribution patterns of harbour porpoises (MIKKELSEN et al. 2016). Since harbour porpoises occur mainly solitary or in groups of two to three animals (SIEBERT et al. 2006), the number of acoustic detections seems to be a rough indication of relative abundance.

The echolocation activity and thus the detection rate of harbour porpoises does not change during wind farm construction, but rather indicates displacement of the animals: Several studies showed that the decrease in clicking sounds of wild harbour porpoises during the use of seal scarers as AHD and subsequent piling is due to displacement of the animals and not to a decrease in echolocation activity (BRANDT et al. 2013b; HAELTERS et al. 2015; BIOCONSULT SH et al. 2016). For example, captive harbour porpoises did not change their vocal behaviour when different high-frequency sounds were played back, except for the first exposure (TEILMANN et al. 2006). Wild harbour porpoises in Canada even increased echolocation activity when wind turbine sounds were played (KOSCHINSKI et al. 2003).

For the FaunaGuard as AHD, one harbour porpoise in a pool was observed to swim away from the FaunaGuard’s location during its operation (KASTELEIN et al. 2017). A field study with visual observations and acoustic monitoring in the tidal bay between Den Helder and Texel affirmed this result: Almost all harbour porpoises seemed to be deterred to a distance of at least 1,000 m during FaunaGuard operation (GEELHOED et al. 2017).

The behavioural response to noise obviously also depends on the environment, e. g. whether the foraging situation is attractive or not (VAN BEEST et al. 2018). Future experiments may provide final proof that an observed decrease in detection rates during FaunaGuard operation is mainly due to the physical absence of harbour porpoises and not to a reduction in echolocation. However, there is currently no reason to assume that the animals in this study responded completely different to FaunaGuard signals and piling than to deterrence in previous studies.

Error source no. 1 of PAM: Reliability of C-PODs

Even though PAM was a suitable tool to investigate the research questions of this study, passive acoustic loggers themselves, such as the C-PODs used here, also have disadvantages and can thus influence the results. The following restrictions were tried to be kept to a minimum, if possible.

(1) Low maximum detection range resulting in a small-scale resolution: Even though the manufacturer of the C-POD states that these data loggers can record clicks of harbour porpoises up to a range of 400 m (CHELONIA LIMITED 2020), the effective detection radius is rather smaller. For example, in a field study with the predecessor model, the T-POD, only clicks up to a distance between 22 and 104 m were effectively recorded (KYHN et al. 2012), while in another field study a detection range of about 170 m was observed (KOSCHINSKI et al. 2003). The respective detection radius depends on the POD type, POD sensitivity, train classification settings and duration of snapshots, as well as sea state, wind, current speed and sediment type which affect the background noise level. In this study, the C-PODs were always installed, calibrated and evaluated in the same way. Nevertheless, the area covered by an individual C-POD is unknown, may vary within a study and generally covers a limited area. Due to this small-scale resolution (KOSCHINSKI et al. 2003), a network of C-PODs was used. Thereby, even areas with low harbour porpoise densities can be realistically estimated (KYHN et al. 2012). Data from C-PODs are not strongly correlated, because harbour porpoises swim at an average speed of $1.5\ \mathrm{m\ s^{-1}}$ (TEILMANN 2000), so that they can cover about 900 m in 10 minutes though they may swim much faster when being startled. In this study, two stationary C-PODs were always positioned at least 1.75 km apart from each other within a wind farm project. The mobile C-PODs were always installed at least about 0.75 km apart from each other. Therefore, the acoustic data loggers were considered to detect mainly independent of each other due to their low maximum detection range.

(2) Background noise: Even though dominated by lower frequencies, pile driving provides broadband noise, so that it may mask harbour porpoise clicks. The same is true for wind and wave noise. Thus, minutes and hours with a particularly high number of clicks were not included in the analyses, as they indicate loud background noise, and thus porpoise clicks may no longer have been adequately recognised. However, some clicks may have been missed during the remaining analysed time.

(3) C-PODs' internal sensitivity: The sensitivity of the POD versions, the training algorithms or even the POD itself can differ and thus influence the results of a study based on PAM, especially if earlier versions are used (KYHN et al. 2008; BAILEY et al. 2010). In this study, however, C-PODs instead of the previous T-PODs were installed. Additionally, the current version of CPOD.exe (version 2.045) and thus an algorithm with several improvements was used to detect harbour porpoise clicks (DÄHNE et al. 2013; NUUTTILA et al. 2013). The internal sensitivity of the C-PODs is analogous to the different abilities of observers during visual surveys (KYHN et al. 2012). To keep these differences as small as possible, all C-PODs in this study were calibrated in the same way before first use and afterwards regularly over the study period. By this procedure, these acoustic data loggers are an efficient tool for PAM of harbour porpoises, despite their minor differences in sensitivity (KYHN et al. 2008).

(4) False-positive detections: The algorithm of the acoustic data loggers might classify sounds from other sources as harbour porpoise detections. For example, dolphin echolocation signals may have energy within the harbour porpoise frequency range (KAMMINGA 1988). However, with the C-POD as used in this study, these false positive rate appears to be very low (mean 0.003%) and the hourly detection accuracy very high (mean 99.6%) (GARROD et al. 2018). Therefore, in a high-density area, all click-train categories can be used and false-positive detections may safely be ignored (KYHN et al. 2012). But this is not recommended for low-density areas, as the inclusion of false positives would have a much higher effect on the outcome. In these areas, a conservative approach should thus be taken, meaning that only porpoise clicks classified as "high" or "moderate" quality should be included into analyses. As harbour porpoise densities in this study differed significantly among the OWF areas and comparability was demanded, only harbour porpoise clicks in the two highest C-POD click categories ("high" and "moderate") were evaluated with all wind farms. The false-positive rate in this study should therefore not have had any influence on the results.

(5) Angular range of porpoise echolocation sounds: In order for the C-POD to detect harbour porpoise clicks, the animals must swim in the direction of the acoustic data logger, because the angular range of porpoise sonar clicks is limited to a maximum of 16.5° (AU et al. 1999). Therefore, the recorded echolocation activity may underestimate the actual echolocation activity, especially when "bottom grubbing" behaviour is taken into account. In this case, harbour porpoises swim for extended periods in a near-vertical

position close to the bottom, pointing with their head downwards to search for prey (LOCKYER et al. 2001). Then, the C-POD records no clicks or only single buzzes, which are either reflected from the bottom or caused by the porpoise's sudden change of orientation while chasing prey when it may briefly turn towards the acoustic device (KOSCHINSKI et al. 2008). However, the algorithm usually does not recognise these buzzes as harbour porpoise clicks, even if, as in this study, the C-PODs were attached near the ground. This source of error cannot be avoided in a study with harbour porpoises and PAM; however, as this error would have been the same over the whole data set it was assumed that it did not significantly influence the results. Although food availability and thus presumably also the frequency of this behaviour may have differed among the investigated OWFs, detection rates were always investigated within an OWF or across projects with all OWFs. Therefore, this source of error may have led to an overall underestimation of detection rates, and perhaps greater in some OWFs than in others, but the ratios among phases, e. g. the comparison before and during and after pile driving, should have been unaffected.

According to the chosen procedure, the influence of these five factors was considered to be low in the present study and the reliability of the C-PODs accordingly as high. Even though it has to be taken into account that e. g. no information about the algorithm is available and the performance of the C-PODs was not tested in this project with the help of simulated data, C-PODs are generally considered to be a suitable tool for acoustic surveys of harbour porpoises and due to their proper use in this study there were no indications to consider the results as being unreliable.

Error source no. 2 of PAM: Further factors that generally influence porpoise echolocation activity

Not only passive acoustic loggers like the C-POD can influence the results of a study using PAM, but also aspects that generally influence porpoise echolocation activity. In the following, these are presented and it is explained why porpoise echolocation activity in this study was nevertheless assumed to be continuous, as well as why these factors did not bias the results.

(1) Time of day: A large proportion of studies observed significantly higher echolocation activity at night compared to daytime (CARLSTRÖM 2005; TODD et al. 2009; SCHAFFELD

et al. 2016; OSIECKA et al. 2020). Other studies observed an opposite diurnal rhythm with higher activity during the day (MIKKELSEN et al. 2013), or no differences at all in echolocation activity based on time of day (GALLUS et al. 2012; LINNENSCHMIDT et al. 2013). The observed increase in acoustic activity during night could compensate for the loss of visual cues (CARLSTRÖM 2005), indicate greater foraging activity during darkness due to the vertical migration of their prey (CARLSTRÖM 2005; TODD et al. 2009; LINNENSCHMIDT et al. 2013; SCHAFFELD et al. 2016), and/or suggest an intrinsic circadian rhythm of harbour porpoises (OSIECKA et al. 2020). In all wind farms of this study, pile driving took place during all times of day and night (Figure A.25), and the reference periods as well as the phases before using the AHD and after piling always covered different daytime hours. Therefore, the time of day should not have severely biased the results in this study.

(2) Seasons: Harbour porpoises not only have seasonal shifts of distribution, but also of their acoustic activity (SCHAFFELD et al. 2016; ZEIN et al. 2019; OSIECKA et al. 2020). This could be related to the mating season, when harbour porpoises produce frequent social calls (OSIECKA et al. 2020), as well as to seasonally available prey resources and the resulting change in foraging activity (SANTOS et al. 2004; SCHAFFELD et al. 2016; ZEIN et al. 2019). In this study, pilings were spread over 3 to 12 months with all wind farms. Detection rates to be compared were always taken from shortly before to shortly after pile driving, so that phenology should not have severely affected the present results.

(3) Habitat conditions: Vocal behaviour can differ depending on artificial structures or natural habitat (TODD et al. 2009; MIKKELSEN et al. 2013; BRANDT et al. 2014), sediment (WILLIAMSON et al. 2017) and depth (BRANDT et al. 2014; WILLIAMSON et al. 2017). These habitat conditions also affect the diurnal pattern, e. g. a greater increase in echolocation activity during the night was observed in areas with mud when compared to areas with sand (WILLIAMSON et al. 2017). Such observed patterns seemed to be related to temporal changes in food availability and composition within a habitat, as for example harbour porpoises in a study in the Baltic Sea alternated between feeding on benthic prey in shallow waters during the day and on pelagic prey in deeper waters at night (SCHAFFELD et al. 2016). In this study, however, habitat conditions of the OWF areas were similar in terms of e. g. substrate (sand and muddy sand), salinity (fully marine), biozone (circalittoral or infralittoral) and depth ("Borkum Riffgrund 2" and "Trianel Windpark Borkum Phase 2": between 24 and 34 m; "EnBW Hohe See" and "Albatros"

and "Deutsche Bucht": between 39 and 41 m). Therefore, the results regarding echolocation activity were not expected to be biased by abiotic factors among the OWFs. At the same time, areas of varying importance for harbour porpoises were included in this study to nevertheless investigate whether FaunaGuard operation had a similar effect in all wind farms despite differences in biotic factors like food availability.

(4) Tides: Numerous studies show that tides influence echolocation activity of harbour porpoises (GOODWIN 2008; PIERPOINT 2008; MARUBINI et al. 2009; EMBLING et al. 2010; ISOJUNNO et al. 2012; IJSSELDIJK et al. 2015; NUUTTILA et al. 2017). Tides affect vertical migration as well as schooling patterns in many prey fish species (CARDINALE 2003; NILSSON 2003; NEAT et al. 2006; BENOIT-BIRD et al. 2009; ISOJUNNO et al. 2012; GRABOWSKI et al. 2015). As pilings evaluated in this study were conducted independently of the tides and furthermore as this cross-project study covers a relatively large sample size of 176 analysed piles, effects of the tide on harbour porpoise vocal behaviour should not have biased the results.

(5) Lunar cycles: The echolocation activity of harbour porpoises may be related to the lunar phase, but in some areas it is difficult to distinguish this factor from the influence of the tides because of the strong inter-relationship of both factors (OSIECKA et al. 2020). As described under the previous point, harbour porpoises could either respond to vertical migration and behaviour of prey fish species, which may depend on the phase of the moon (CARDINALE 2003; NILSSON 2003; NEAT et al. 2006; BENOIT-BIRD et al. 2009; GRABOWSKI et al. 2015), or respond to the change in light conditions and thus visibility which may cause a change in echolocation activity (OSIECKA et al. 2020). All pilings evaluated in this study were conducted independently of the lunar phase, and due to the large sample size detection rates were not expected to be biased in terms of lunar cycles.

Accordingly, these five aspects were assumed not to have significantly influenced the echolocation activity of harbour porpoises in the present study and thus not to have biased the results.

4.2 How did the detection rates of harbour porpoises change during FaunaGuard operation at smaller distances up to 1.5 km?

Outline

As expected, harbour porpoise detection rates decreased when using a FaunaGuard as AHD. Namely, the detection rates declined by 48 % during FaunaGuard operation at smaller distances up to around 1.5 km, compared to on average six hours before operation of the device. When compared with the seal scarer as AHD, the FaunaGuard showed a slightly stronger negative effect on porpoise detection rates in the vicinity of piling locations.

The actual decrease is likely to be higher than 48 % as the hours prior to the use of the FaunaGuard cannot be seen as a true unaffected reference value: Vessel traffic for preparing the NMS and for the upcoming pile driving increases in the hours before piling and thus a decrease in detection rates already some hours before FaunaGuard operation was probable. Nevertheless, the detection rates showed an additional decrease during FaunaGuard operation. This decrease was detectable up to a distance of about 2 to 2.5 km around piling locations. Assuming that the detection rates correlate with the physical presence or even relative abundance, the FaunaGuard seemed to have successfully scared the animals safely out of the danger zone of about 1 km around piling locations and thus had the potential to prevent animals from TTS or PTS. Hence, the FaunaGuard was highly effective in deterring animals from the endangered zone.

However, after detection rates had dropped to almost zero in the course of FaunaGuard operation, the rates increased again significantly at close range during pile driving. Interestingly, sound emissions of noise-reduced pile driving were obviously perceived as less disturbing as the AHD by the animals. An interesting topic for future experimental studies would be to figure out (1) whether the FaunaGuard scares away more harbour porpoises than vessel traffic and piling, or (2) whether a higher number of animals reduces echolocation activities during FaunaGuard operation than during vessel traffic and piling, but still stays in the area.

No long-term deterrence was shown and the wide range of different sound signals makes a habituation effect very unlikely.

Effective decrease in detection rates during the operation of the FaunaGuard

In order to avoid a TTS or PTS during pile driving, the FaunaGuard aimed at deterring all harbour porpoises to an area where the noise levels fall below 160 dB SEL, which means deterrence to a distance of at least 750 m (better 1 km) if the German noise threshold criteria are met. When looking at the data of the mobile C-PODs, the detection rates of harbour porpoises indeed decreased by 48 % during FaunaGuard operation up to distances of 1.5 km, compared to the preceding 6.20 hours (average length of detection period before FaunaGuard operation). Thus, during the operation of a FaunaGuard as AHD the detection rates seemed to have halved.

In the Gescha 2 study, a methodologically equivalent analysis was conducted, but using a seal scarer as AHD: In this case, detection rates only decreased by 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, even though the FaunaGuard is technically much more difficult to detect at a distance of 750 m from the acoustic measuring device when compared to the seal scarer (ROSEMEYER et al. 2021).

Decrease in detection rates due to increased vessel traffic for preparing the NMS and the upcoming pile driving

The real relative decrease of detection rates during operation of a FaunaGuard/seal scarer as AHD compared to a true reference baseline would probably have been higher, in this as well as the Gescha 2 study: In both studies, Phase 1 of the mobile C-POD data (Before FaunaGuard/seal scarer) and thus the hours immediately prior to AHD operation were considered as reference value, meaning that the decrease during the operation of the AHD was compared to this period. However, during the two to three hours preceding the operation of the AHD, vessel traffic for preparing the NMS and the upcoming pile driving already increases, so that this period could not be considered a true undisturbed reference. The presence of marine mammals and especially harbour porpoises might be reduced by construction-related vessel traffic (CULLOCH et al. 2016; NEHLS et al. 2016). The animals either respond directly to this type of noise or associate it with subsequent piling noise, in this case being conditioned (DIEDERICHS et al. 2010; HERMANNSEN et al. 2014; DYNDO et al. 2015; OAKLEY et al. 2017; WISNIEWSKA et al. 2018). Harbour porpoises respond by altered diving and echolocation behaviour as well as by displacement (WISNIEWSKA et al. 2018).

That the detection rates of the mobile C-PODs during the six hours before FaunaGuard operation (referred to as Phase 1 in the analyses) did not represent a true baseline was supported by several findings in this study: (1) The stationary C-PODs in up to 2.5 km distance from the pile-driving sites (using DPM per minute) showed that in the six hours before using the FaunaGuard, 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 the six hours before using the FaunaGuard). (2) When using DPH per hour for the stationary C-PODs, detection rates in 0 to 5 km distance to the piling location were significantly lower in the three hours prior to FaunaGuard operation than in the reference phase before construction activities took place. (3) The analyses of the mobile C-PODs showed generally higher detection rates at 1.5 km distance from the pile-driving location than at 0.75 km distance. (4) The Generalised Additive Model (GAM) showed that the detection rates in the vicinity of the pile-driving sites were already reduced before FaunaGuard operation started.

Assuming that the detection rates correlate to a certain amount with the relative abundance, harbour porpoises probably avoided the vicinity of piling locations around the construction hours due to multiple possible reasons like associated vessel traffic, AHD operation and piling. However, although detection rates had already decreased in the hours before FaunaGuard operation, the rates in the vicinity of the pile-driving site further decreased during the operation of this type of AHD. Therefore, the FaunaGuard appeared to generally deter the animals. Even though individual responses obviously depended on factors such as food availability, demography or previous exposure (JOHNSTON 2002; OLESIUK et al. 2002; BRANDT et al. 2013b; VAN BEEST et al. 2018), detection rates in the vicinity of the piling location have been reduced to zero over the course of the AHD operation time and thus all animals seemed to have been driven away from the danger zone after 20 to 25 minutes of FaunaGuard operation (see section 4.5).

More studies are needed to further evaluate the effect of increased vessel traffic a few hours before pile driving on porpoise detection rates. Since even individual responses to same noise levels seem to differ (WISNIEWSKA et al. 2018), future studies should aim at recording vessel activity before construction works begin and to directly link it to harbour porpoise detection rates in order to analyse to what extent and in which radius harbour porpoises react to the presumably increased vessel traffic a few hours before piling. However, effects of vessel traffic were not the main focus of this study.

Increased detection rates during pile driving compared to FaunaGuard operation

After the detection rates had dropped to almost zero during the FaunaGuard operation, they significantly increased again at close range during pile driving. Therefore, sound emissions of noise-reduced pile driving were obviously perceived as less disturbing as the AHD by the animals. The detection rates of the mobile C-POD data at a distance up to 1.5 km from the piling location were even similar during the actual piling (referred to as Phase 3 in the analyses) and in the six hours before FaunaGuard operation (referred to as Phase 1 in the analyses): At a distance of 0.75 km, detection rates during pile driving were 30 % lower than in the six hours immediately prior to AHD operation, whereas at a distance of 1.5 km, detection rates during pile driving were 18 % higher. Instead of being at a similar level, both distance classes would have been expected to have significantly lower detection rates during pile driving than during the six hours before FaunaGuard operation. The analyses of the individual wind farms showed that similar detection rates in the six hours before FaunaGuard operation and during pile driving were not caused by outliers in one particular OWF, but were observed at all wind farms. The following two reasons are among possible explanations for this unexpected finding:

(1) Construction-related vessel traffic during the hours before FaunaGuard operation and mitigated pile driving might have affected the detection rates on a similar level in a close range. On the one hand, improved noise mitigation systems were used, leading to pile-driving noise levels being lower than in other studies (BIOCONSULT SH et al. 2016). On the other hand, improved noise mitigation systems lead to increased vessel traffic a few hours before pile driving as bubble curtains must be laid out, etc. Nevertheless, lowest detection rates were always measured during FaunaGuard operation at distances up to 1.5 km. This could be due to the fact that thresholds for the acoustic avoidance behaviour of harbour porpoises are correlated with audibility (TOUGAARD et al. 2015): Vessel traffic as well as pile driving are quite loud at a close range and thus lead to deterrence by high noise levels, whereas the FaunaGuard is not that loud but specifically targeting at the echolocation perception of harbour porpoises. Therefore, the AHD may have had a

stronger effect on the decrease in detection rates and thus led to a stronger displacement than the vessel traffic and also the pile driving itself.

(2) A certain number of animals might have only reduced echolocation activities during FaunaGuard operation, but not left the area. In this case, which is less likely due to results of studies with other AHD devices, the decrease in the detection rate would not properly reflect the physical absence of the animals.

It would be an interesting topic for future experimental studies to figure out why in the vicinity the detection rates during pile driving have already increased again compared to times of FaunaGuard operation.

No long-term deterrence observed and no habituation expected

The FaunaGuard was not expected to cause a long-term deterrence as the detection rates of the mobile C-POD data decreased only by 7 % from 6.20 hours before FaunaGuard operation until 3.04 hours after piling (average phase durations). Obviously, as described above, the hours immediately prior to AHD operation cannot be considered a true reference level and hence the stationary C-PODs up to a distance of 2.5 km (using DPM per minute) showed significantly lower detection rates in the three hours after pile driving than during an actual reference phase. However, the Gescha 2 study showed that harbour porpoises often take at least 4 hours up to about 48 hours to return to the area after exposure (BIOCONSULT SH ET AL. 2019). Nevertheless, detection rates of the mobile C-PODs six hours before FaunaGuard operation and three hours after pile driving were already at a similar level, indicating that the decrease in detection rates and thus displacement during FaunaGuard operation and pile driving was only for a short period of time. This was supported by the stationary C-POD data up to a distance of 5 km using DPH per hour: Detection rates in the reference periods before and after pile driving did not differ significantly. Therefore, no long-term deterrence was expected after FaunaGuard operation.

A habituation effect also seems unlikely, as the FaunaGuard uses eight separate and complex signal sequences and thus a wide range of different sound signals. Whether this assumption is correct and harbour porpoises will not show any signs of habituation to FaunaGuard sounds in the long term has to be observed over the next years.

4.3 How did the detection rates of harbour porpoises change during FaunaGuard operation at larger distances up to 20 km?

Outline

Supposedly, the FaunaGuard did not cause far-reaching disturbance. The detection rates were only reduced up to a distance of 2 to 2.5 km from piling locations during operation of a FaunaGuard. Above this distance range, detection rates were consistently higher as, on the one hand, harbour porpoises may have generally avoided areas with regularly increased vessel traffic and pile-driving noise and, on the other hand, higher detection rates in areas further away from pile-driving may indicate a displacement of the animals to these areas.

This only small-scale effect of the FaunaGuard on harbour porpoises was to expect in accordance with the technical properties of this device, as the FaunaGuard generates sound in a high-frequency range, in which sound propagation in the water is significantly less expressed than at lower frequencies (such as produced by pile-driving or seal scarer noise). Therefore, in the water column the sound signals of a FaunaGuard are more strongly absorbed than those of a seal scarer with increasing distance (ROSEMEYER et al. 2021).

Moreover, construction-related vessel traffic probably did not have any influence on the detection rates of harbour porpoises in distances a few km away from piling locations.

Generally, no far-reaching effects of the FaunaGuard detected

The FaunaGuard development aimed at minimising such large-scale disturbances as produced by the seal scarer (BRANDT et al. 2013b). In fact, the Generalised Additive Model on the overall data set from mobile and stationary C-PODs indicated that the detection rates were only reduced up to a maximum distance of about 2.5 km during FaunaGuard operation. Also, the three-dimensional Boosted Regression Tree model just showed a decrease up to about 2 km distance.

In apparent contrast, the analysis of the DPM per minute at the stationary C-PODs showed that the detection rates during FaunaGuard operation at a distance of 5 to 7.5 km from the pile-driving sites were lower than in the other phases. However, this result was doubtful for three reasons: (1) It contradicted with the results for the distance classes 2.5 to 5 km and 7.5 to 10 km in which increased detection rates were recorded during FaunaGuard operation, relative to the reference phase. (2) It can be assumed that the FaunaGuard can no longer be heard by the animals at this distance (ROSEMEYER et al. 2021). High-frequency noise, such as the sound of a FaunaGuard, is absorbed more rapidly and is therefore less audible at greater distances. In contrast, lower-frequency noise like vessel traffic, pile driving or seal scarer is absorbed to a lesser extent and therefore transmitted over larger distances. (3) It became visible from the raw data of the stationary C-PODs 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 with only few data), but not during the majority of minutes in between (Figure 14). Furthermore, increasing detection rates were observed in this distance class during FaunaGuard operation. With far-reaching effects, decreasing detection rates would instead have been expected. As detection rates already started at rather low levels in this distance class, it was probably not the FaunaGuard but other unknown processes that caused those low rates during its operation.

We explain the low detection rates at distances between 5 and 7.5 km by a higher heterogeneity since this analysis was based on only a few C-POD stations at various regions, compared to the many mobile C-PODs analysed for distances below 2.5 km.

Higher detection rates in areas further away from piling

Generally higher detection rates were observed in areas further away from piling. For example, high detection rates were found in the raw data (stationary C-POD data using DPM per minute and DPH per hour) as well as in the partial dependency plots at distances of more than 2 to 2.5 km. Three reasons are possible:

(1) Environmental factors could have been more favourable in these areas providing a better food supply (GILLES et al. 2011a; NABE-NIELSEN et al. 2014; OAKLEY et al. 2017; VAN BEEST et al. 2018; STALDER et al. 2020). However, it seems rather unlikely that the environmental conditions in all wind farms considerably change from a distance of 2 to

2.5 km to the piling location and improve as habitat for harbour porpoises. Therefore, this factor rather appears to be relevant at larger distances (for example 15 to 20 km), but cannot explain the increase in detection rates at a few km distance to the piling location.

(2) Harbour porpoises may have generally avoided areas with regularly increased vessel traffic and piling noise, since construction-related activity cannot only cause short-term (THOMPSON et al. 2013; CULLOCH et al. 2016) but also long-term displacement (TEILMANN & CARSTENSEN 2012). As described in section 4.3, construction-related vessel traffic in this study probably affected detection rates of harbour porpoises at distances up to a few km away from piling locations for short periods of time. At the same time, some animals may have avoided the vicinity of the piling location for a longer period of time, so that generally higher detection rates were observed in areas further away from piling. To investigate the influence of this factor more precisely, it would have been useful to compare the detection rates during the construction phase with those one year before, to avoid creating a seasonal difference. However, no data were available for this, and furthermore, effects of vessel traffic were not the main focus of this study.

(3) Higher detection rates in areas further away from piling might indicate a displacement of the animals to these areas. This was particularly suggested by the Boosted Regression Tree model: Detection rates decreased at a distance of 0 to 1.25 km from the piling location after the FaunaGuard was switched on, and increased at a distance of 1.25 to 2.5 km after about ten minutes FaunaGuard operation. As various studies have shown that detection rates indicate presence and absence even during construction-related activities (see section 4.1), harbour porpoises in this study appeared to have already been displaced by construction-related vessel traffic and then further enhanced by FaunaGuard operation and subsequent piling. To confirm this hypothesis, additional visual observations would have been helpful.

No effect of increased vessel traffic for preparing the NMS and the upcoming pile driving at larger distances

Although the actual pile driving lowered the detection rates at larger distances, construction-related vessel traffic did not appear to affect the detection rates of harbour porpoises in these distances. DPH per hour of the stationary C-PODs at a distance of 0 to 5 km was significantly lower during the three hours prior to pile driving (phase Pre-piling) than during a day before pile driving (phase Baseline), but this was no longer the case at a distance of 5 to 10 km. Thus, construction-related vessel traffic just seemed to lead to a small-scale disturbance. Indeed, harbour porpoises are known to react to vessel traffic within distances of a few hundred metres, and to low-frequency noise of ships even at distances of over 1 km (HERMANNSEN et al. 2014; DYNDO et al. 2015; WISNIEWSKA et al. 2018). Individual animals also seem to react at a much more distant radius, but these reactions seem to depend on various factors such as age, previous exposure or food availability (JOHNSTON 2002; OLESIUK et al. 2002; BRANDT et al. 2013b; VAN BEEST et al. 2018). For example, a harbour porpoise in the Baltic Sea was already reacting to an approaching ferry boat when still 7 km away, while the same individual had not reacted to a similarly loud ship recently before (WISNIEWSKA et al. 2018). In general, however, harbour porpoises seem to respond rather on a smaller spatial scale, as this study as well as the Gescha studies showed (BIOCONSULT SH et al. 2016; BIOCONSULT SH ET AL. 2019).

4.4 How did the detection rates of harbour porpoises during FaunaGuard operation differ between wind farms at smaller and larger distances?

Outline

Although factors such as previous exposure, age and food availability can be decisive for the behavioural response of the individual harbour porpoise to noise (JOHNSTON 2002; OLESIUK et al. 2002; BRANDT et al. 2013b; VAN BEEST et al. 2018), the FaunaGuard aimed at deterring all animals from a radius of 1 km around the piling location before the start of the noise-intensive pile driving, and at the same time not causing large-scale disturbance or long-term deterrence – irrespective of habitat characteristics.

Even though we observed project-specific differences among the OWFs indicating the heterogeneous distribution of harbour porpoises within the German Bight, the detection rates in all wind farms significantly decreased by between 37 % and 75 % during FaunaGuard operation up to a distance of 1.5 km, compared to the six hours before using the FaunaGuard. Thus, as expected, the FaunaGuard as AHD always seemed to lead to an effective short-term decrease in detection rates at smaller distances. Assuming that a decrease in detection rates indicates physical absence, the FaunaGuard successfully prevented harbour porpoises from TTS and PTS.

The FaunaGuard as AHD apparently did not cause far-reaching disturbance at any of the OWFs, although harbour porpoise detections during FaunaGuard operation, as well as during pile driving, returned to the reference level at different distances to the sound source depending on the OWF.

As areas of varying importance for harbour porpoises were included in this study, the FaunaGuard generally seemed to lead to a short-term decrease in detection rates without causing large-scale disturbance, and thus be applicable in various areas of the North Sea.

In addition, project-specific differences in detection rates a few hours before pile driving were observed, suggesting that the response of harbour porpoises to increased vessel traffic for preparing the NMS and the upcoming pile driving differed between OWFs.

Regional differences in detection rates

The number of detections within a phase varied among the OWFs positioned in different regions of the German Bight, reflecting the heterogeneous distribution of harbour porpoises in this area shown by the MINOS projects (GILLES et al. 2007) and the BfN monitoring (GILLES & SIEBERT 2010; GILLES et al. 2011b, 2013, 2014; VIQUERAT et al. 2015). Different environmental factors lead to this unequal distribution of harbour porpoises, as the animals generally prefer areas with e. g. high chlorophyll concentrations, low salinity and steep bottom slopes due to food availability (SANTOS et al. 2004; GILLES et al. 2011a; STALDER et al. 2020).

In this study, for example, generally higher detection rates were recorded in “Borkum Riffgrund 2” compared to the other wind farms (stationary C-POD data using DPM per minute and DPH per hour). The FFH area “Borkum Riffgrund” in the western part of the southern North Sea is classified as a nursery area for harbour porpoise juveniles and the abundance of harbour porpoises in this area has increased continuously in recent years (THOMSEN et al. 2006; GILLES et al. 2009; CAMPHUYSEN 2011; DEGRAER et al. 2011).

In contrast, in the wind farm “Deutsche Bucht”, we observed considerably lower detection rates (stationary C-POD data using DPM per minute and DPH per hour). This area is known to have generally few harbour porpoises at the times of data collection using it only as a migration area: Namely, in autumn and winter the density of harbour porpoises in this region is at its lowest (GILLES et al. 2011a), coinciding with the timing of the pile driving and thus data collection between September and January.

Short-term decrease at smaller distances up to 2.5 km irrespective of offshore wind farm

Even though the studied OWFs were probably positioned in more as well as less attractive areas for harbour porpoises, the mobile C-POD data showed that the detection rates in all wind farms significantly decreased by between 37 % and 75 % during FaunaGuard operation up to a distance of 1.5 km, compared to the six hours before using the FaunaGuard. Furthermore, during the three hours after piling the detection rates reached again 84 % to 93 % of the level during the six hours before FaunaGuard operation. Summarising this, the FaunaGuard as AHD seemed to lead to a significant short-term decrease in detection rates at smaller distances, despite varying environmental factors between the OWFs, and thus is most probably applicable in the different regions of the

North Sea for scaring harbour porpoises away from the danger zone around pile-driving sites.

No far-reaching disturbance irrespective of offshore wind farm

In the individual wind farms, harbour porpoise detections during FaunaGuard operation as well as during piling returned to the reference value at different distances to the sound source (stationary C-POD data using DPM per minute): For example, at the wind farms "EnBW Hohe See" and "Albatros", as well as "Trianel Windpark Borkum Phase 2", detection rates were already at a similar level at distances between 0 and 5 km in all phases, and no clear trends were observed. In contrast, at the wind farms "Borkum Riffgrund 2" and "Deutsche Bucht" in the same distance category highest detection rates were observed in the reference period, and the detection rates already decreased in the hours before the FaunaGuard (referred to as Phase 1 in the analyses), with a further decline during the operation of the FaunaGuard (referred to as Phase 2 in the analyses). However, at larger distances (5 to 10 km), the data from the stationary C-PODs showed that the detection rates no longer decreased during FaunaGuard operation (OWF "Deutsche Bucht" excluded due to low average distance), so that the FaunaGuard as AHD did not appear to have caused a far-reaching disturbance at any of the OWFs, despite more as well as less attractive habitat conditions for harbour porpoises.

The fact that the detection rates during FaunaGuard operation reached back the reference level at different distances may – besides factors like the source level during pile driving, seasonal differences in data collection and the age of the harbour porpoise specimen – also be due to the following aspects in this study:

(1) Average distance: How sensitive harbour porpoises react to noise is strongly dependent on the distance to the sound source (KASTELEIN et al. 2011). For the distance classes of this study, the average distance of stationary C-PODs to piling sites varied especially at distances between 5 and 10 km among the OWFs, affecting cross-project comparisons.

(2) Sample size: In particular, relatively few data were evaluated in the wind farm "Trianel Windpark Borkum Phase 2" compared to other wind farms. Accordingly,

short-term fluctuations in porpoise movements may have masked the actual trend at this OWF more severely than at other OWFs.

(3) Function of the area for harbour porpoises: In the wind farm "Deutsche Bucht", there are generally few harbour porpoises present during the times of data collection (autumn and winter) and the animals tend to use this area more in terms of transit to their preferred grounds (GILLES et al. 2011a). This renders them more sensitive to noise in that region, as there is no reason to stay. In contrast, the FFH area "Borkum Riffgrund" is a concentration area for harbour porpoises in the southern North Sea; here the animals occur continuously (THOMSEN et al. 2006; GILLES et al. 2009; HAELTERS et al. 2010; CAMPHUYSEN 2011). Adjacent to this region is the wind farm "Trianel Windpark Borkum Phase 2". There, pile driving took place between June and November and detection rates were already at a similar level at distances between 0 and 5 km in all phases (stationary C-POD data using DPM per minute). Since the response of harbour porpoises to noise depends not only on the noise level and quality, but also strongly on food supply (HAELTERS et al. 2015; OAKLEY et al. 2017; VAN BEEST et al. 2018) and conditions in this area are favourable, the animals in this wind farm seemed to rather stay despite the noise and be less easily displaced. However, in the wind farm "Borkum Riffgrund 2", which also borders the FFH area "Borkum Riffgrund", detection rates considerably decreased during FaunaGuard operation and pile driving in the same distance category. The FFH area "Borkum Riffgrund" is also known as a breeding ground for harbour porpoise juveniles during the summer months, with calves accounting for between 6.2 to 13.4 % of the population (SCHUBERT et al. 2016). As pile driving in the wind farm "Borkum Riffgrund 2" took place between March and May and harbour porpoises in that area usually give birth around mid-May, harbour porpoises may have been more sensitive to noise in order to protect the unborn foetus.

(4) Number of pile-driving operations: In the wind farms "EnBW Hohe See" and "Albatros", by far the highest number of pile-driving operations took place. Harbour porpoise response may weaken over time. In the UK, a 50 % probability of a response within 7.4 km was found for the first location of pile driving, being reduced during the 10-month foundation installation sequence to a range of 1.3 km at the last location of pile driving (GRAHAM et al. 2019). Thus, especially in the OWFs "EnBW Hohe See" and "Albatros", harbour porpoises might have reacted less sensitively after some time due to the high number of piles.

(5) Noise transmission depending on habitat conditions: Noise is transmitted better or worse over long distances, depending on the ocean environment and driven by factors such as sediment, bathymetry, temperature, salinity and pressure (FARCAS et al. 2016). While deep mud is more noise-absorbing, sand is more reflective. With respect to this study, salinity is fully marine and the substrate rather similar (sand and muddy sand) among all OWFs; however, water depth is shallower (between 24 and 34 m) at “Borkum Riffgrund 2” and “Trianel Windpark Borkum Phase 2” than in “EnBW Hohe See” and “Albatros” as well as “Deutsche Bucht” (between 39 and 41 m), which might have caused differences in noise transmission among the wind farms.

This study included, on the one hand, sandy areas where the seafloor reflects rather than absorbs noise emissions. Nevertheless, far-reaching disturbances during FaunaGuard operation were not observed. On the other hand, this study partly included important areas for harbour porpoises, which are presumably less likely to be left. Despite these favourable environmental conditions, the detection rates in the vicinity of the FaunaGuard consistently decreased in the short term. Therefore, it is assumed that the FaunaGuard generally leads to short-term decreases in detection rates, but does not cause far-reaching disturbances and that this result is also applicable to a number of other areas of the North Sea.

OWF-dependent effect of increased vessel traffic before pile driving

Among different OWFs, not only differences in detection rates during FaunaGuard operation and subsequent piling were observed in this study, but also differences in the rates a few hours before pile driving. Two patterns were observed for DPH per hour at distances between 0 and 10 km (data from the stationary C-PODs):

First, in the wind farms “Borkum Riffgrund 2”, as well as “EnBW Hohe See” and “Albatros”, the lowest detection rates were recorded during the phase with AHD and pile driving (referred to as phase Piling in the analyses). Indeed, piling can affect the detection rates of harbour porpoises up to distances of around 15 to 20 km (CARSTENSEN et al. 2006; TOUGAARD et al. 2009a; BRANDT et al. 2011; DÄHNE et al. 2013; BIOCONSULT SH ET AL. 2019).

Second, in the wind farms "Deutsche Bucht" and "Trianel Windpark Borkum Phase 2" lowest DPH per hour rates were not recorded over pile driving, but during the three hours before AHD/pile driving (referred to as phase Pre-piling in the analyses). In the wind farm "Deutsche Bucht", this is probably due to the fact that the average distance in the distance class up to 10 km was only 2.73 km and thus considerably lower than for the other OWFs. Particularly in the vicinity of vessel traffic, harbour porpoises may react strongly (HERMANNSEN et al. 2014; DYNDO et al. 2015; WISNIEWSKA et al. 2018). With the OWF "Trianel Windpark Borkum Phase 2", the particularly low DPH rate during the hours before piling could on the one hand be related to the installation ship. Compared to the other wind farms, the installation ship of this wind farm was kept in position by 8 anchors. These were placed by anchor tugs about two hours before the operation of the AHD. However, until the anchor grips the seabed, it drags across the ground. Since the anchors have a dead weight of several tons and the chains and steel cables on the anchors are correspondingly large, this work can lead to high noise levels before the operation of the AHD. Various studies have shown how harbour porpoises respond to vessel noise on a small scale of a few hundred metres (HERMANNSEN et al. 2014; DYNDO et al. 2015; WISNIEWSKA et al. 2018), but activities such as dragging anchors across the seabed could even have further-reaching effects. On the other hand, at the wind farm "Trianel Windpark Borkum Phase 2" a pontoon with the pile to be erected was towed next to the erection ship. The pile was craned from the pontoon onto the ship, and for this purpose two additional tugs were used in this construction field. For these two reasons, the detection rates in the wind farm "Trianel Windpark Borkum Phase 2" may have been particularly low during the three hours before FaunaGuard operation, indicating a comparatively strong harbour porpoise reaction.

4.5 What effect did the duration of operation of the FaunaGuard have on the detection rates during this phase?

Outline

After the first 20 to 25 minutes of FaunaGuard operation, the detection rates had nearly declined to zero in the close range of up to 1.25 km distance; thus, the original demand of reducing detection rates to zero at close range was achieved. A decrease in detection rates was recorded up to a distance of about 2 km and a longer duration seemed to lead only to a slight increase in the maximum distance and the intensity of the effect and thus, on the one hand, to no further benefit and, on the other hand, to no risk of far-reaching disturbance. It is recommended for future OWF projects that the device should operate not much longer than 20 to 25 minutes.

After 20 to 25 minutes nearly no more detections: Target of reducing detection rates to zero at close range achieved

Depending on the project, a minimum duration of 20 or 30 minutes was prescribed for the FaunaGuard operation. This study investigated which duration is actually necessary to scare porpoises safely out of a danger zone of at least 750 m around the piling location.

All analyses showed that after 20 to 25 minutes of FaunaGuard operation, hardly any detections were recorded in the vicinity of the piling location anymore: In terms of raw data of the mobile and stationary C-PODs, from minute 23 onwards of FaunaGuard operation, almost no detection rates were observed up to distances of at least 1.25 km. The Generalised Additive Model, which is only capable of smooth but not of stepwise model outcomes as those possible by the BRT model, indicated that after about 20 minutes a decrease in detection rates was observed up to a distance of about 2 km. However, also resulting from the three-dimensional Boosted Regression Tree (BRT) model, it seemed to be sufficient that the FaunaGuard would be switched on for 20 minutes, after which time nearly no more detections were produced by the model within a radius of 2 km as well.

So even though the mobile C-POD data at close range of 750 m showed that detections occurred during FaunaGuard operation (referred to as Phase 2 in the analyses), this does not mean that the detection rates in the vicinity of the piling location have not been reduced to zero over the course of the AHD operation time. It has to be taken into account that the FaunaGuard produces increasing noise levels during the first five minutes of operation ("ramp-up" function), in order to gradually deter porpoises from the piling location (VAN DER MEIJ et al. 2015). Correspondingly, the raw data, the Generalised Additive Model and the Boosted Regression Tree model showed that the detections were more likely to occur at the beginning of the scaring process, hence at the time when the full volume was not yet reached. The FaunaGuard appeared to generally disturb the animals, although individual responses obviously depended on factors such as food availability, demography or previous exposure (JOHNSTON 2002; OLESIUK et al. 2002; BRANDT et al. 2013b; VAN BEEST et al. 2018). Nevertheless, the disturbance seemed to be so strong that after 20 to 25 minutes of FaunaGuard operation, almost no more detections occurred and thus all animals seemed to have been driven away from the vicinity after this time. Hence, the FaunaGuard met the original demand to scare all porpoises safely out of a danger zone of at least 750 m around the piling location.

Longer application gave no more benefit and is therefore not recommended for OWF construction projects

A longer duration seemed to lead to a slight increase in the maximum distance and intensity of deterrence, as the Generalised Additive Model showed. As a sufficient effect distance was already reached after the first 20 to 25 minutes, no more benefit was produced by longer application of the FaunaGuard. At the same time, a longer application showed no risk of far-reaching disturbance. Pointing into the same direction, in the BRT models not the variable "A_min_FaunaGuard" had the highest explanatory power, but the total number of clicks ("allClx_min"), the pile ID ("pile"), and DPM per minute in the previous minute ("DPMt"; to correct for autocorrelation). The duration of the FaunaGuard operation ("A_min_FaunaGuard") was always ranked fourth regarding its relative importance (Figure 17). The duration of the FaunaGuard operation thus appeared to still have a minor influence on detection rates; after the 20th minute of operation, however, the desired effect was already achieved.

In this study, the increased vessel traffic led to a decrease in detection rates already before the operation of the AHD and thus to a previous partial deterrence in the vicinity (see section 4.2). Without this pre-AHD effect, a longer duration of FaunaGuard operation might be necessary to successfully decrease detection rates and thus to presumably scare all animals away from an area. Therefore, for projects without increased vessel traffic prior to FaunaGuard operation, a separate field study must test whether 20 to 25 minutes of FaunaGuard operation is sufficient or whether the AHD must be deployed over a longer period of time. For that purpose, a FaunaGuard should be placed far away from vessel traffic and other noise sources and the reaction of the harbour porpoises should be observed.

However, projects without increased vessel traffic prior to AHD operation are rather unusual; in fact, almost all projects (construction of offshore wind farms and all types of platforms, mine explosion, etc.) have this pre-AHD effect for example to build up a bubble curtain. Therefore, a FaunaGuard operation time of 20 to 25 minutes seems to be generally sufficient. In this study, the FaunaGuard at that time span safely scared away harbour porpoises from a danger zone of at least 750 m around the pile site, so longer deployment is not recommended.

4.6 How did the detection rates of harbour porpoises during FaunaGuard operation differ from those during seal scarer operation?

Outline

At the OWF "Trianel Windpark Borkum Phase 2", the FaunaGuard was not working during pilings for three 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 effect of the FaunaGuard to that of the seal scarer under similar conditions. As expected, in the vicinity of piling locations, both AHDs led to a similar decrease in detection rates. However, at larger distances of on average 8 km, the detection rates during FaunaGuard operation decreased by only 12 % compared to the detection rates in the six hours before, but by 94 % when using a seal scarer. Therefore, the seal scarer appeared to cause a far-reaching effect on porpoise response, while the FaunaGuard only led to very local disturbance.

Due to the AHD in use as well as due to improved noise mitigation systems there was a less severe large-scale disturbance. The response to the combined effects of FaunaGuard/pile driving was weaker at larger distances than those shown by studies where the combined effects of seal scarer/pile driving were investigated. Other causes such as habitat and individual-response differences were considered less likely to have caused this weaker response of harbour porpoises to the construction of different OWFs.

Comparison at OWF "Trianel Windpark Borkum Phase 2": Seal scarer with far-reaching disturbance and FaunaGuard not

Up to a distance of 1.5 km, the mobile C-POD data showed only a minor difference between seal scarer and FaunaGuard effects. Both AHDs led to strongly decreased detection rates in the vicinity of pile-driving locations. This corresponds to the results from section 4.2: In this study, detection rates decreased by 48 % during FaunaGuard operation up to distances of 1.5 km when all OWFs were considered (data from mobile C-PODs); in an equivalent analysis in the Gescha 2 study when using a seal scarer as AHD, detection rates decreased by 36 % (BioConsult SH et al. 2019). Assuming that a decrease in detection rates indicates physical absence, at close range both AHDs appeared to be highly effective in scaring harbour porpoises away from the danger zone around pile-driving sites.

However, at distances of on average 8 km (mean for the distance class 5 to 10 km) some evidence was given that the seal scarer had a much more far-reaching effect. 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 (data from stationary C-PODs). This observation is consistent with the technical properties of the devices, because the FaunaGuard generates sound in a high-frequency range, in which sound propagation in the water column is significantly stronger attenuated than at lower frequencies (such as produced by the seal scarer). Therefore, with increasing distance the sound signals of a FaunaGuard are more strongly absorbed than those of a seal scarer (ROSEMEYER et al. 2021). Accordingly, in other studies the seal scarer showed significant deterrence effect on harbour porpoises in a much larger range than intended (BRANDT et al. 2013b) and appeared to have the potential to induce a TTS (SCHAFFELD et al. 2019), whereas the response of harbour porpoises to the FaunaGuard in this study only ranged up to 2 to 2.5 km distance (see section 4.3).

Although especially the seal scarer sample was very 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 between June and November, harbour porpoise densities in summer and autumn are generally rather similar in this area (GILLES et al. 2011a). This gives further evidence to our former findings that the FaunaGuard leads to a significant decrease in detection rates up to a distance of about 2 to 2.5 km, whereas far-reaching deterrence as observed during operation of a seal scarer here and in other studies (BRANDT et al. 2013b) is highly unlikely.

Comparison to Gescha studies: Weaker response of harbour porpoises to AHD and subsequent piling when using the FaunaGuard

Piling can affect the detection rates of harbour porpoises up to distances of around 15 to 20 km (CARSTENSEN et al. 2006; TOUGAARD et al. 2009a; BRANDT et al. 2011; DÄHNE et al. 2013; BIOCONSULT SH ET AL. 2019). In this study, harbour porpoises seemed to respond slightly less to pile driving with a FaunaGuard as AHD than to piling in other configurations (no AHD, seal scarer as AHD, no NMS, etc.). Although significantly lower detection rates were still observed up to a distance of 15 km than in the reference periods before and after pile driving (stationary C-POD data using DPH per hour), the detection rates decreased less strongly.

When comparing the results to the Gescha 1 and Gescha 2 studies, DPH rates were similar during the reference phases before and after pile driving as well as during the three hours before pile driving (BIOCONSULT SH et al. 2016; BIOCONSULT SH ET AL. 2019). However, for distances of 0 to 5 km, DPH per hour decreased from the reference before pile driving to the combined effects of the AHD and subsequent pile driving by only 31% in this study, whereas it decreased by 54 to 56 % in the Gescha 1 and Gescha 2 studies. For distances of 5 to 10 km, DPH per hour decreased from the reference before pile driving to the operation of the AHD with subsequent pile driving by 22 % in this study, whereas it decreased by 28 to 38 % in the Gescha 1 and Gescha 2 study. Hence, the negative effect of piling was weaker in this study using a FaunaGuard as AHD.

Possible reasons for this result were: (1) Habitat and individual-response differences, (2) improved noise mitigation systems and/or (3) the AHD used.

Regarding (1) habitat and individual-response differences: 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 the specific habitat characteristics between the project areas of the present study compared with the project areas of the Gescha studies. But since different habitat variables were included into the analyses 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, the differences between the studies cannot be explained by habitat and individual-response differences.

Regarding (2) improved noise mitigation systems: The main difference between the Gescha 1 and the Gescha 2 study was the improvement of the noise mitigation systems. But even though noise mitigation systems could reduce the emitted sound level by about 9 dB (SEL_{05}) on average (at 750 m), DPH per hour rates in up to 10 km distance were not different during the operation of a seal scarer and subsequent pile driving. Hence, in the Gescha 2 report it was discussed, that harbour porpoises may have reacted more strongly to seal scarer noise than to the actual (reduced) pile driving noise (BIOCONSULT SH ET AL. 2019). Since the noise mitigation systems used in the projects for the present study have not changed to those in the Gescha 2 study and sound levels reached similar values, it can be assumed that there was no major difference in the sound emission by pile driving between this study and the Gescha 2 study. Therefore, a weaker negative effect of AHD operation and pile driving in this study compared to the Gescha 1 study will also be due to improved noise mitigation systems, but compared to the Gescha 2 study noise reduction systems were similar and thus cannot explain the weaker negative effect.

Regarding (3) the AHD used: The main difference between this study and the two Gescha studies is the different type of mitigation measure before the pile driving started (this study: FaunaGuard/ Gescha studies: seal scarer). Since piling and mitigation procedures otherwise remained similar, the seal scarer seems to have substantially contributed to the far-reaching effects of AHD/piling which were found in the Gescha 2 study (BIOCONSULT SH ET AL. 2019).

5. Conclusion

The FaunaGuard aims at deterring all harbour porpoises from a radius of 1 km around piling locations before the start of noise-intensive piling, but was also intended not to lead to large-scale disturbances as those caused by a seal scarer. This cross-project study examined whether these targets were met and the FaunaGuard was suitable as an effective, but not over-effective, acoustic harassment device.

Assuming that the detection rates indicate the physical presence and absence of harbour porpoises, this study showed the following:

(1) Detection rates of harbour porpoises decreased by 48 % during FaunaGuard operation at smaller distances up to around 1.5 km, compared to a period of on average six hours before the operation of the device. The FaunaGuard as AHD reduced detection rates even more effectively than piling itself and also than the seal scarer, without leading to long-term deterrence. Accordingly, the FaunaGuard seemed to have successfully scared the animals safely out of a danger zone of at least 750 m around the piling location and thus successfully prevented animals from TTS and PTS.

(2) During FaunaGuard operation, reduced detection rates were observed only up to a distance of 2 to 2.5 km, so that in contrast to the seal scarer, obviously no large-scale disturbance occurred.

(3) Although we observed certain project-specific differences between the OWFs, the detection rates at all wind farms decreased significantly by between 37 % and 75 % during FaunaGuard operation up to a distance of 1.5 km, compared to the six hours before using the FaunaGuard, and the FaunaGuard did not appear to have caused far-reaching disturbance at any of the OWFs. Therefore, the FaunaGuard generally seems to lead to short-term displacement of harbour porpoises without large-scale disturbance. As areas of varying importance for harbour porpoises were included in this study, the FaunaGuard generally appeared to be applicable in different regions of the North Sea.

(4) After the first 20 to 25 minutes of FaunaGuard operation, the detection rates had nearly declined to zero in the close range of up to 1.25 km distance. A longer duration seemed to lead to a slight increase in the maximum distance and intensity of the deterrence effect. Therefore, it is recommended for future offshore wind farm projects that the device should operate not much longer than this time span.

(5) Up to a distance of 1.5 km, the mobile C-PODs showed no pronounced effect difference whether a seal scarer or a FaunaGuard was used. However, in 5 to 10 km distance (mean around 8 km), some evidence was given that the seal scarer had a much more far-reaching effect. The detection rates during FaunaGuard operation decreased by only 12 % compared to the detection rates in the six hours before, but by 94 % when using a seal scarer. Therefore, the seal scarer appeared to cause a far-reaching effect on porpoise response, while the FaunaGuard seemed to lead to a much more local disturbance. Due to the shorter effect range of the FaunaGuard when used in combination with improved noise mitigation systems, the response to the FaunaGuard and subsequent pile driving seemed to be lower at larger distances than in other studies where mitigated pilings with a seal scarer as AHD were investigated.

As noise mitigation 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 side of the coin, improved noise mitigation 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. Thus, the FaunaGuard will considerably improve the situation for harbour porpoises because, as shown in this study, the FaunaGuard is a highly effective AHD to displace harbour porpoises from a small-scale area in the North Sea in the short term and thus prevent TTS and PTS. Therefore, der FaunaGuard and subsequent pile driving with NMS should have no effect on the population level given the current state of research.

Promising topics for future studies would be: (1) Did harbour porpoises in this study actually respond similarly to FaunaGuard signals and piling as in previous studies, implying that the observed decrease in detection rates during FaunaGuard operation is mainly due to the physical absence of harbour porpoises rather than to a reduction in echolocation? (2) Will harbour porpoises show signs of habituation to the sounds of a FaunaGuard in the long term, although the FaunaGuard uses eight different complex signal sequences to minimise possible habituation effects? (3) What is the role of other sources of pre-piling noise (e. g. vessels) in order to identify and mitigate those noise sources causing the most stress for harbour porpoises? How strong is the deterrent effect of construction-related vessel traffic? Would it be possible to dispense with additional deterrent measures before pile driving, since all animals have already been driven away anyway?

All results from the present study indicate that the FaunaGuard should be used instead of the seal scarer in the future construction process for offshore wind farms, assuming there is no habituation effect. 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 but in no way alarming range of audibility.

Acoustic harassment devices 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 AHD device has been developed to approach this goal. However, the FaunaGuard is only able to protect harbour porpoises from hearing damage. Noise during pile driving continues to cause considerable disturbance despite improved noise mitigation systems: In this study, we observed avoidance distances of porpoises into the double-digit km range. Future work should therefore focus on the effects of construction-related noise sources other than AHD noise.

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Appendix

A. Glossary

Abbre-viation	Explanation	Meaning
AHD	Acoustic Harassment Device	An Acoustic Harassment Device (AHD) is a technology used to keep animals, and in some cases people, away from an area.
AIC	Akaike Information Criterion	To find the best explanatory Generalised Additive Model, the Akaike Information Criterion (AIC) was used: The model with the lowest AIC value was considered to be the best explanatory model (WOOD 2017). Besides, the inclusion of additional parameters had to result in an AIC difference of more than 2, otherwise the inclusion was considered poorly justified and the model with fewer variables was considered the best (BURNHAM & ANDERSON 2002).
BBC	Big Bubble Curtain	The Big Bubble Curtain (BBC) is a Noise Mitigation System: A perforated pipe ring is located on the seabed and surrounds the foundation structure. Compressors inject air into the nozzle hoses, which rises as bubbles and forms a curtain around the foundation structure.
BRT	Boosted Regression Tree	Boosted Regression Tree (BRT) models combine decision tree algorithms and boosting methods.
BSH	German Federal Maritime and Hydrographic Agency	The Federal Maritime and Hydrographic Agency (BSH) is a German higher federal authority.
C-POD	Cetacean Porpoise Detector	A Cetacean Porpoise Detector (C-POD) is a hydrophone with a self-contained data logger that recognises the trains of odontocete echolocation clicks between 20 and 160 kHz by means of an algorithm.

DBBC	Double Big Bubble Curtain	The Double Big Bubble Curtain (DBBC) is a Noise Mitigation System: Two Big Bubble Curtains are positioned one behind the other.
DPH	Detection Positive Hour	Detection Positive Hour (0 = no detection, 1 = detection) was scaled to an hourly basis (DPH per hour) and thus was calculated by dividing the sum of DPH per phase by the duration of the phase in hours: As an example, 1 hour with porpoise clicks (in other words 1 DPH) in 3 hours equals 0.33 DPH per hour.
DPM	Detection Positive Minute	Detection Positive Minute (0 = no detection, 1 = detection) was scaled to a minutely basis (DPM per minute) and thus calculated by dividing the sum of DPM per phase by the duration of the phase in minutes: As an example, 20 minutes with porpoise clicks (in other words 20 DPM) in 3 hours (thus 180 minutes) equals 0.11 DPM per minute.
EEG	German Renewable Energy Sources Act	The German Renewable Energy Sources Act (EEG) legislatively regulates the expansion of electricity from renewable energies in Germany.
EEZ	Exclusive Economic Zone	The Exclusive Economic Zone (EEZ) describes the maritime area beyond the territorial sea.
GAM	Generalised Additive Model	In a Generalised Additive Model (GAM), a linear relationship between the response and the predictors is modelled by unknown smooth functions of the predictor variables.
HSD	Hydro Sound Damper	The Hydro Sound Damper (HSD) is a Noise Mitigation System: Instead of free gas bubbles as with the Big Bubble Curtain, elastic air-filled balloons or rigid PE foam elements are used.
IHC	Pile sleeve (company: “IHC”)	A pile sleeve is a Noise Mitigation System: Here, a steel pipe is placed over the foundation pile. In one particular type of this NMS category – the IHC – the space between the inner and outer cladding tube is filled with air and a bubble curtain is created between the IHC and the pile.

L_{Peak}	Peak Level	The Sound Pressure Level (SPL) is a tool for describing the amplitude of a sound. The Peak Level (L_{Peak}) describes the zero-to-peak SPL for a single strike.
NMS	Noise Mitigation System	A Noise Mitigation System (NMS) describes a technology that minimises underwater noise.
OWF	Offshore Wind Farm	An offshore wind farm (OWF) describes a wind farm in a body of water, usually the ocean.
PAM	Passive Acoustic Monitoring	Passive Acoustic Monitoring (PAM) describes the process of listening to the sounds of, for example, marine mammals.
PTS	Permanent Hearing Threshold Shift	With a Permanent Hearing Threshold Shift (PTS), only sounds louder than a certain level are permanently heard.
SEL_{05}	Upper 5 % percentile of Sound Exposure Level	The Sound Exposure Level (SEL) is a measure of energy that considers the received level as well as the duration of exposure. The SEL_{05} describes the SEL that was exceeded by 5 % of all analysed single strikes over a certain time interval (mostly over the piling strikes for one foundation).
TTS	Temporary Hearing Threshold Shift	With a Temporary Hearing Threshold Shift (TTS), only sounds louder than a certain level are temporarily heard.
VIF	Variance Inflation Factor	Multicollinearity can be estimated by computing the so-called variance inflation factor (VIF), which measures how much the variance of a regression coefficient is expanded due to multicollinearity in the model (MANSFIELD & HELMS 1982).

A. Figures

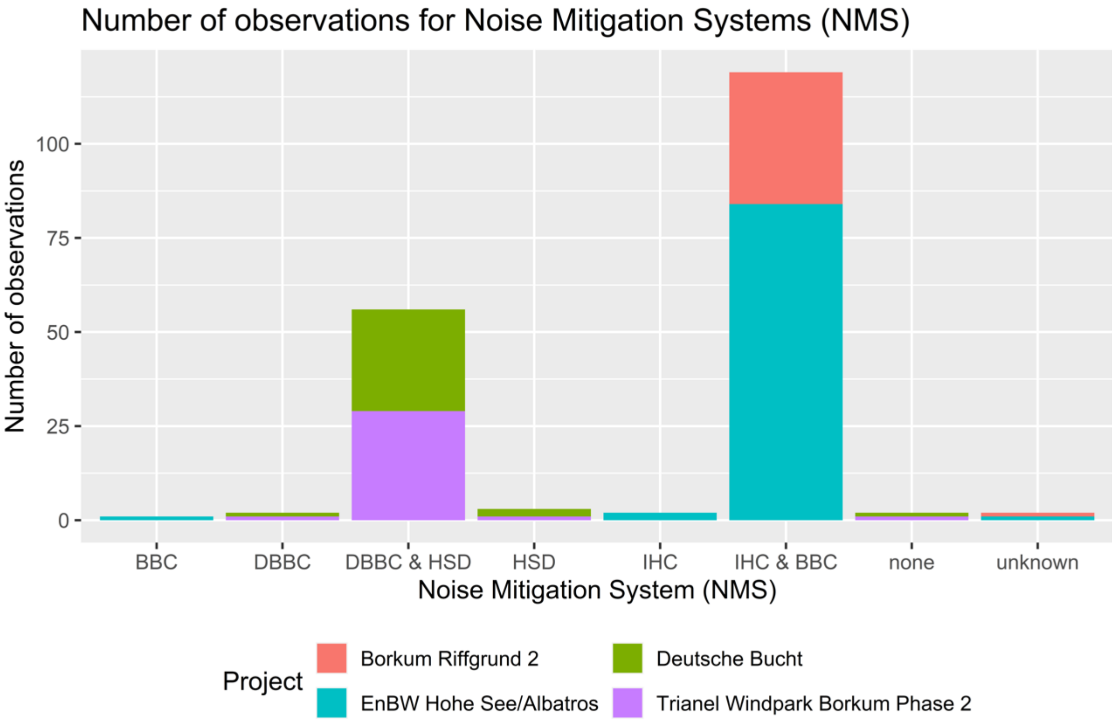

Figure A.1: Number of observations (in this case pilings) for Noise Mitigation Systems (NMS). In the wind farms “Deutsche Bucht” and “Trianel Windpark Borkum Phase 2”, a combination of the Double Big Bubble Curtain (DBBC) and Hydro Sound Dampers (HSD) was mostly used, while in the wind farms “Borkum Riffgrund 2” as well as “EnBW Hohe See” and “Albatros” a combination of pile sleevers (IHC) and the Big Bubble Curtain (BBC) was mostly used.

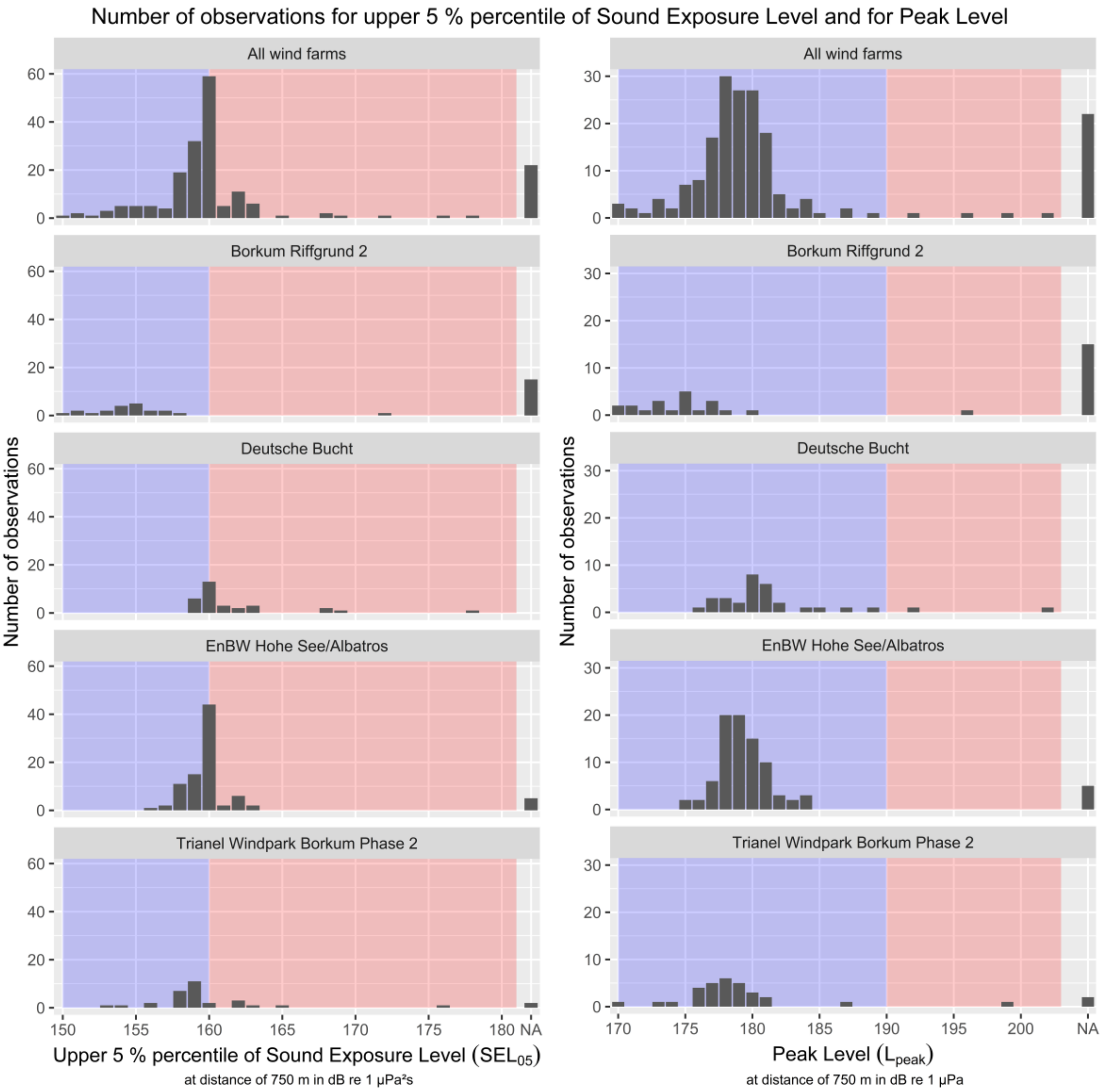

Figure A.2: Number of observations (in this case pilings) for upper 5 % percentile of Sound Exposure Level and for Peak Level at a distance of 750 m to piling location. In order to minimise the effects of noise emissions during piling, the German Federal Maritime and Hydrographic Agency (BSH) set a dual noise protection criterion: The upper 5 % percentile of the Sound Exposure Level (SEL_{05}) must remain below 160 dB re 1 µPa² s at a distance of 750 m, and the Peak Level (L_{Peak}) must remain below 190 dB re 1 µPa. Due to the continuous development of noise mitigation systems (NMS), L_{Peak} was complied with in most of the construction projects (blue background) and just a few construction projects exceeded the limit (red background), while SEL_{05} was exceeded more often.

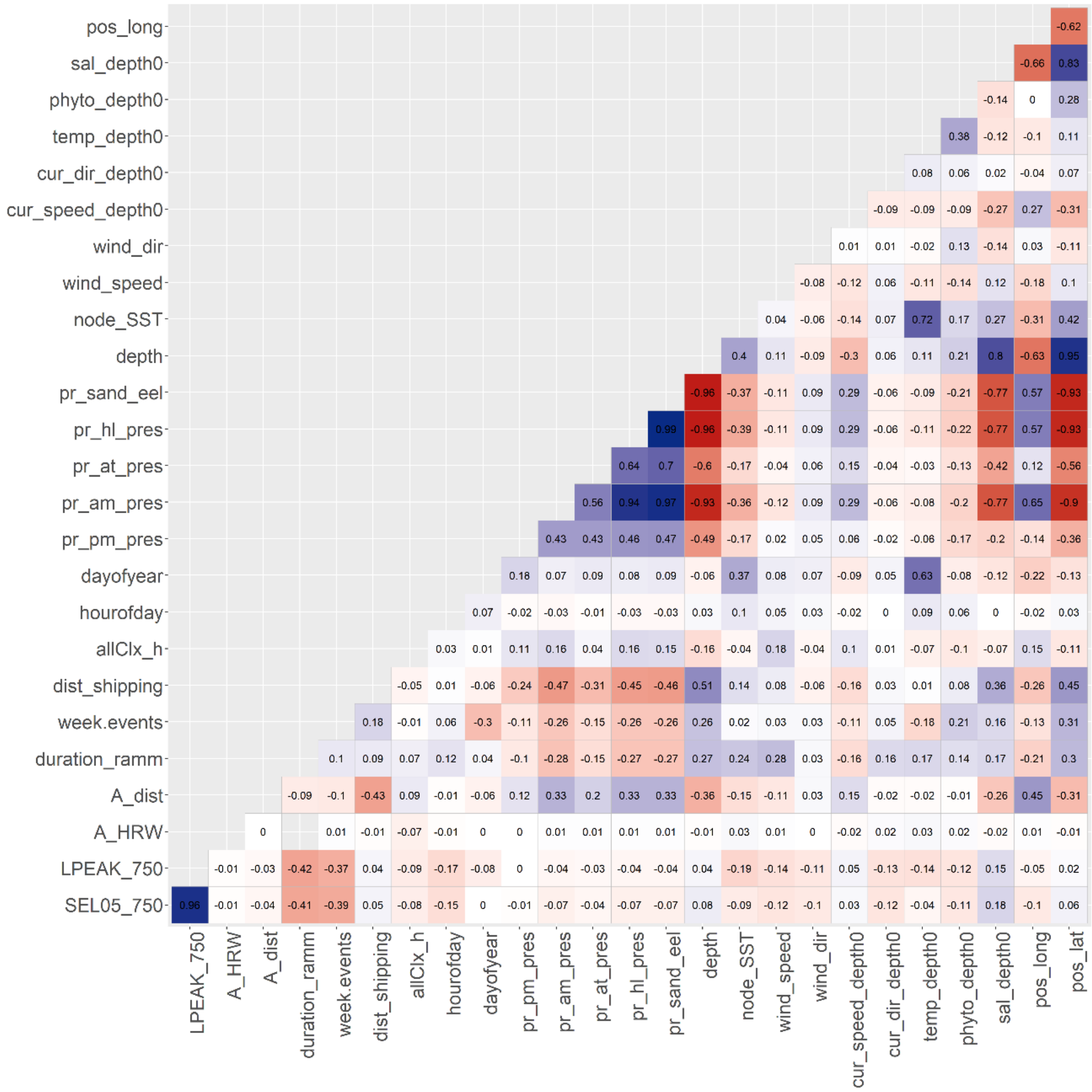

Figure A.3: Pearson correlation coefficients of all possible combinations of two variables except factors. Red boxes show a negative, blue boxes a positive r-value. However, since collinearity between variables can greatly distort model estimates and predictions at correlation coefficients above 0.7 (DORMANN et al. 2013), not all variables could be included in the analyses. For variables with high collinearity, the biologically more reasonable variable was retained and the other eliminated.

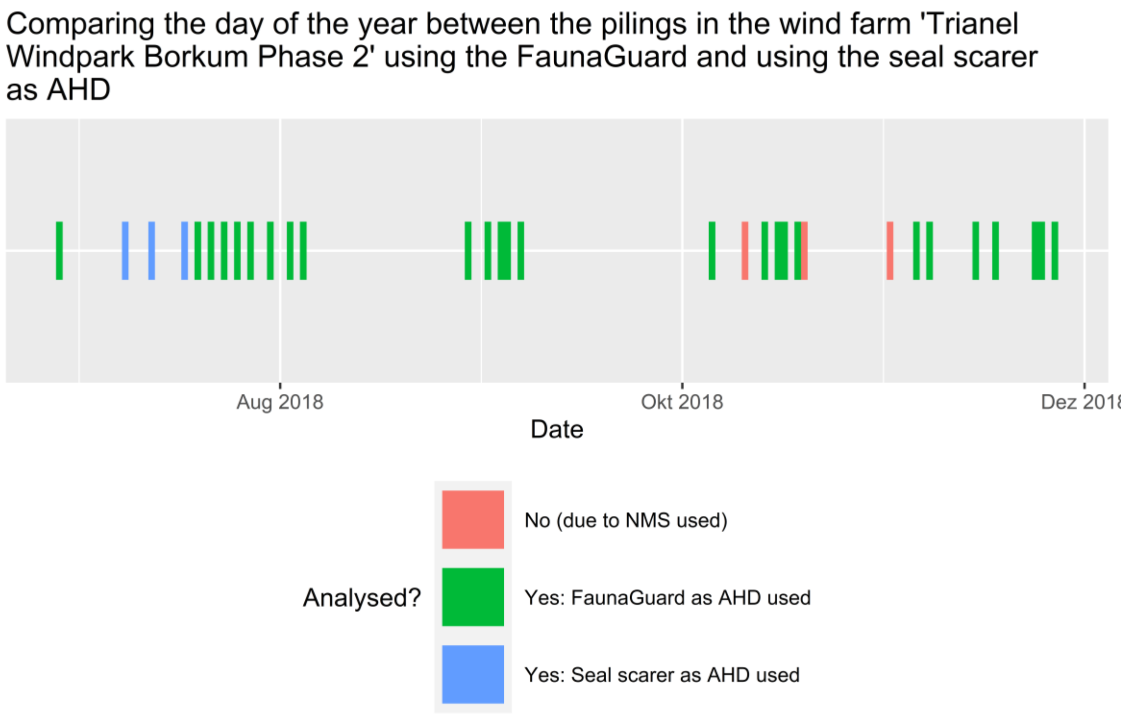

Figure A.4: Comparing the day of the year between pilings (start of each pile driving) in the wind farm “Trianel Windpark Borkum Phase 2” using the FaunaGuard and using the seal scarer as AHD. Pile driving with FaunaGuard use took place between June and November 2018, pile driving with seal scarer use took place in July 2018.

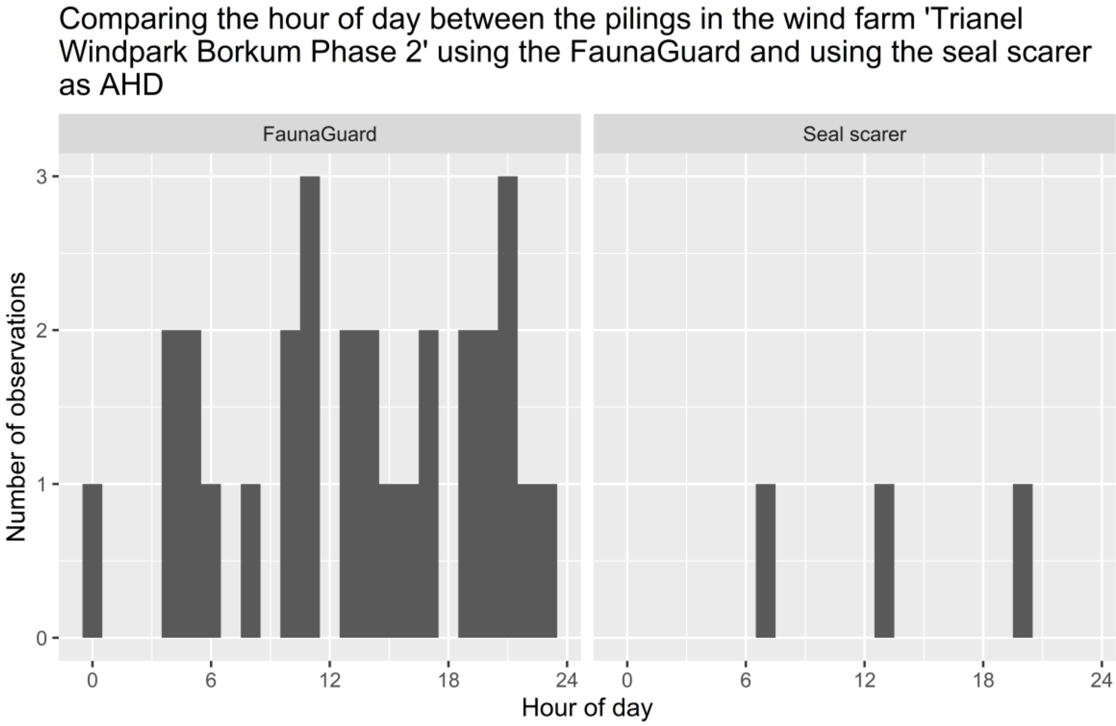

Figure A.5: Comparing the hour of day between pilings (start of each pile driving) in the wind farm “Trianel Windpark Borkum Phase 2” using the FaunaGuard and using the seal scarer as AHD. In both cases, pile driving took place during all times of day and night.

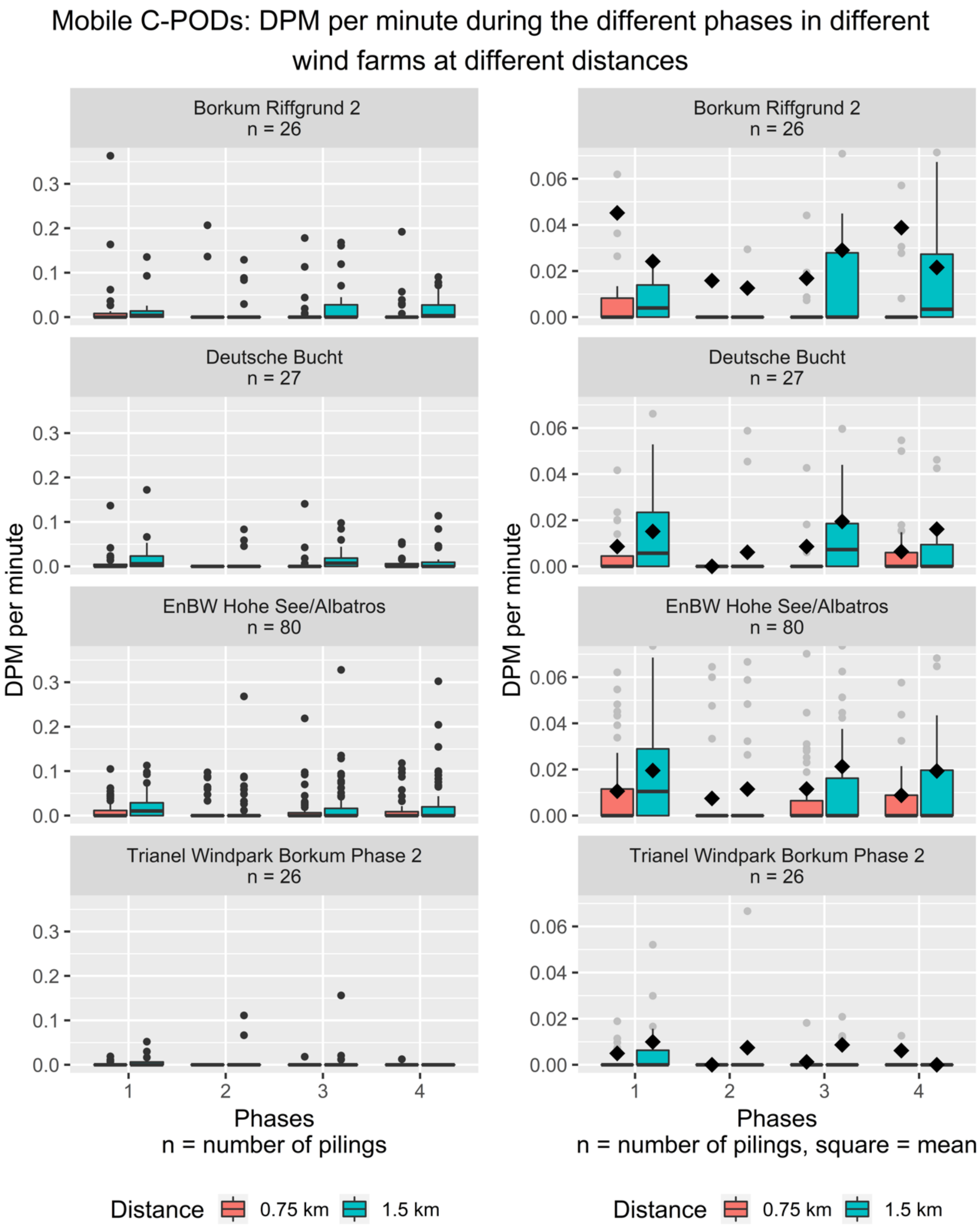

Figure A.6: Mobile C-PODs: DPM per minute during the different phases in different wind farms at a distance of 0.75 respectively 1.5 km to the FaunaGuard and subsequent piling (left column with all outliers, right column as zoom in quantile range). At all wind farms and both distances, DPM per minute were highest in Phase 1 (on average 6.20 hours before the FaunaGuard), lowest in Phase 2 (during the FaunaGuard, on average 0.55 hours), increased again in Phase 3 (during piling, on average 1.72 hours), and in Phase 4 (on average 3.04 hours after piling), DPM per minute remained close to the level of Phase 1.

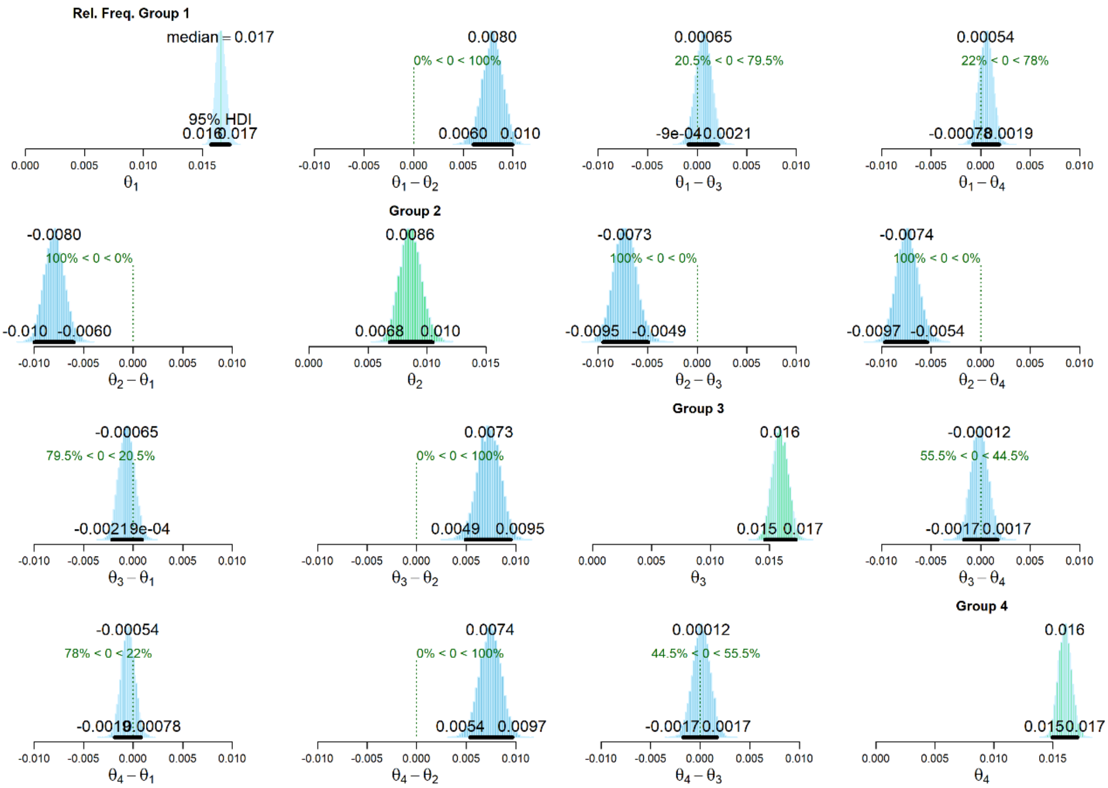

Figure A. 7: Bayesian proportion test for the mobile C-PODs up to a distance of 1.5 km to the piling location using DPM per minute. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Phase 1 (Before FaunaGuard), Group 2 means Phase 2 (During FaunaGuard), Group 3 means Phase 3 (During piling), and Group 4 means Phase 4 (After piling).

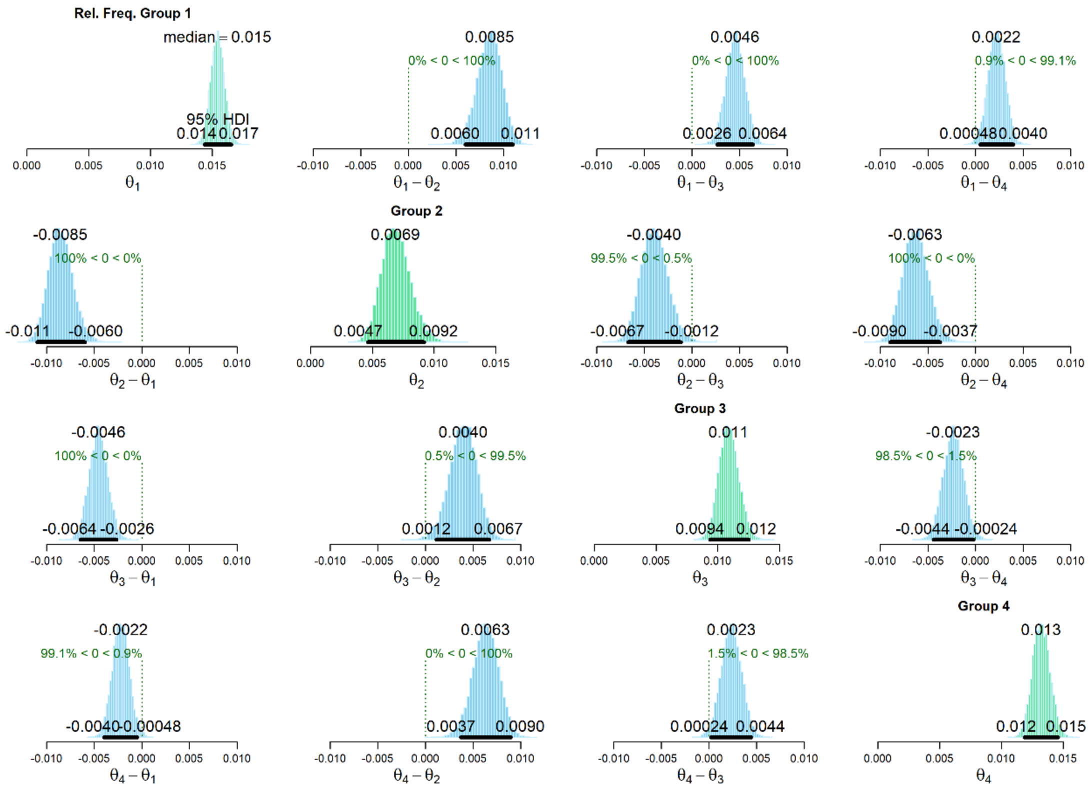

Figure A. 8: Bayesian proportion test for the mobile C-PODs of 0.75 km distance to the piling location using DPM per minute. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Phase 1 (Before FaunaGuard), Group 2 means Phase 2 (During FaunaGuard), Group 3 means Phase 3 (During piling), and Group 4 means Phase 4 (After piling).

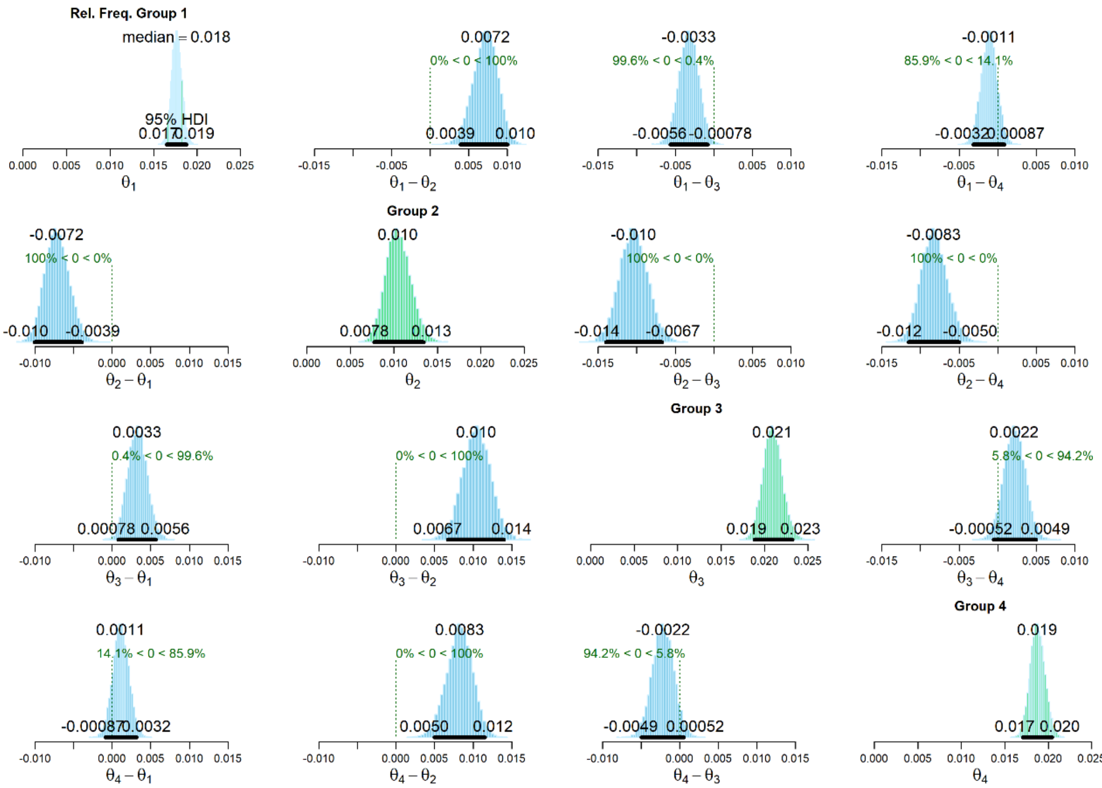

Figure A. 9: Bayesian proportion test for the mobile C-PODs of 1.5 km distance to the piling location using DPM per minute. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Phase 1 (Before FaunaGuard), Group 2 means Phase 2 (During FaunaGuard), Group 3 means Phase 3 (During piling), and Group 4 means Phase 4 (After piling).

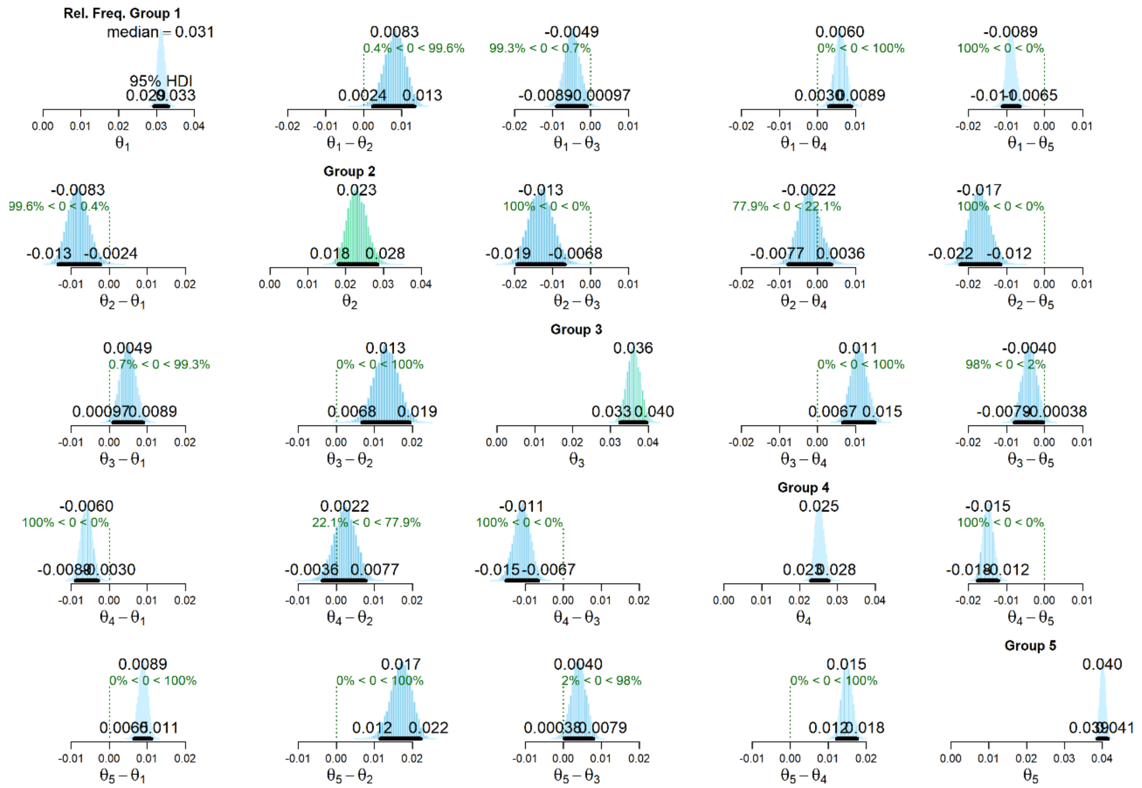

Figure A. 10: Bayesian proportion test for the stationary C-PODs at a distance of 0 to 2.5 km to the piling location using DPM per minute. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Phase 1 (Before FaunaGuard), Group 2 means Phase 2 (During FaunaGuard), Group 3 means Phase 3 (During piling), Group 4 means Phase 4 (After piling), and Group 5 means phase Reference (hours -48 until -25 before the FaunaGuard, as well as +49 until +72 after piling).

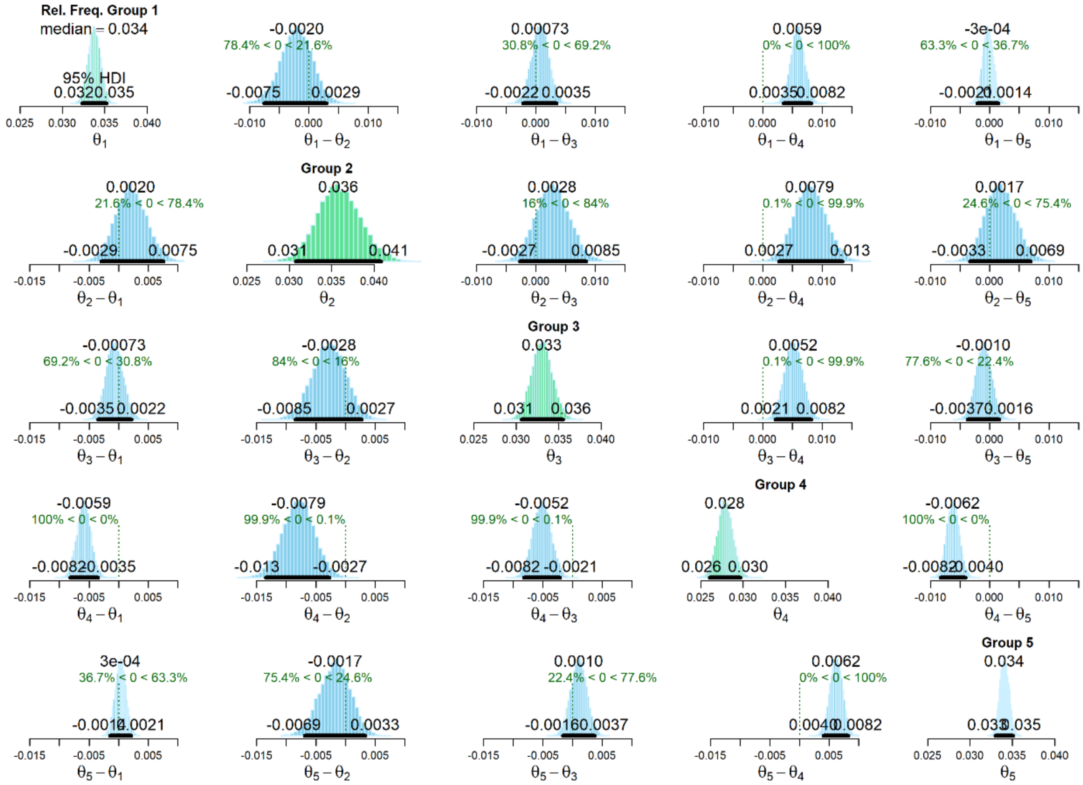

Figure A. 11: Bayesian proportion test for the stationary C-PODs at a distance of 2.5 to 5 km to the piling location using DPM per minute. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Phase 1 (Before FaunaGuard), Group 2 means Phase 2 (During FaunaGuard), Group 3 means Phase 3 (During piling), Group 4 means Phase 4 (After piling), and Group 5 means phase Reference (hours -48 until -25 before the FaunaGuard, as well as +49 until +72 after piling).

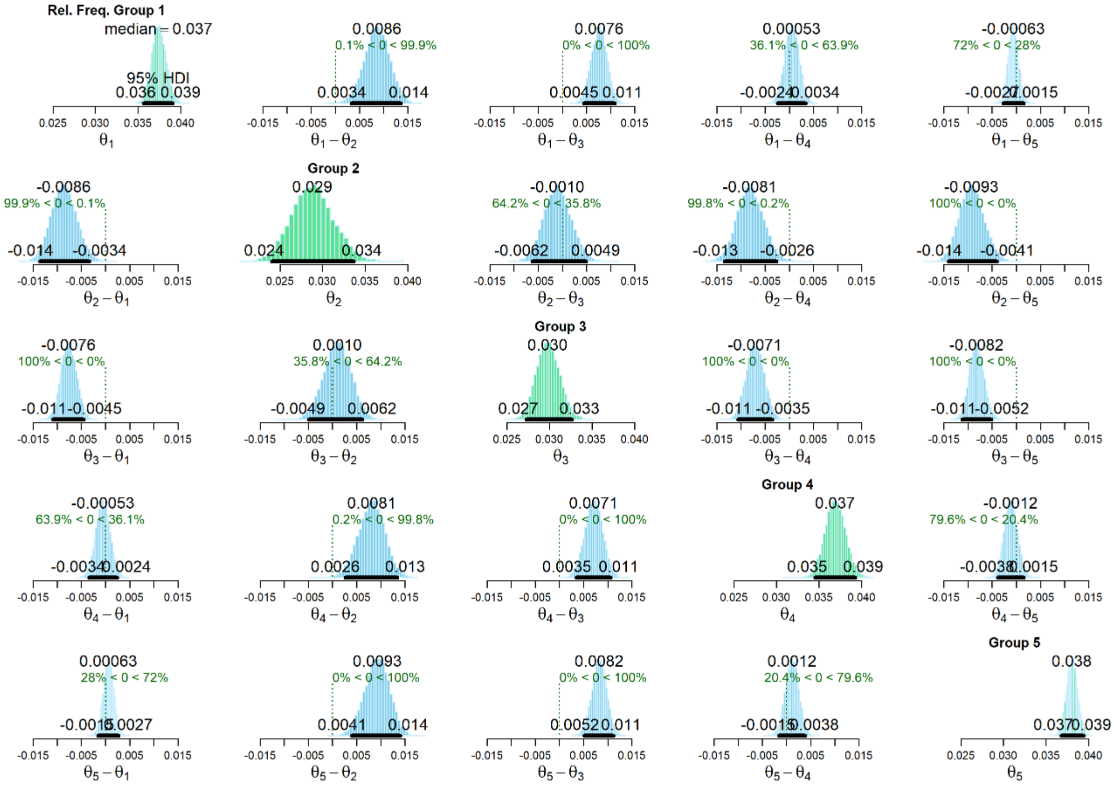

Figure A. 12: Bayesian proportion test for the stationary C-PODs at a distance of 5 to 7.5 km to the piling location using DPM per minute. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Phase 1 (Before FaunaGuard), Group 2 means Phase 2 (During FaunaGuard), Group 3 means Phase 3 (During piling), Group 4 means Phase 4 (After piling), and Group 5 means phase Reference (hours -48 until -25 before the FaunaGuard, as well as +49 until +72 after piling).

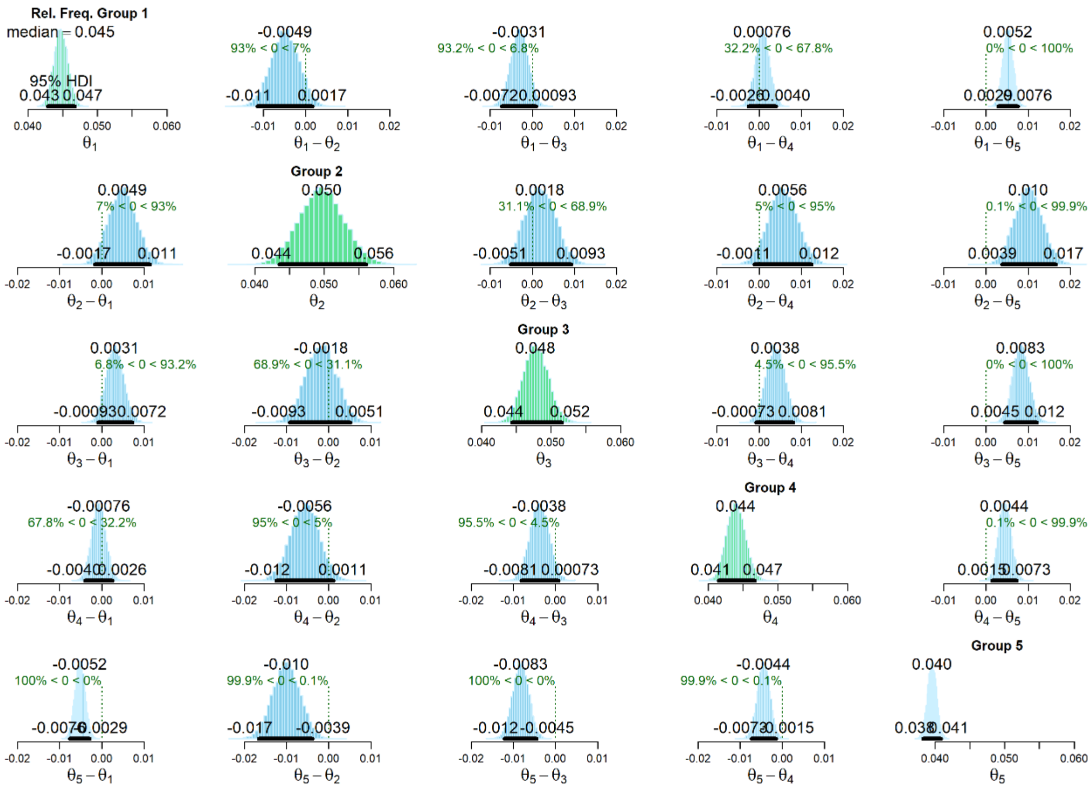

Figure A. 13: Bayesian proportion test for the stationary C-PODs at a distance of 7.5 to 10 km to the piling location using DPM per minute. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Phase 1 (Before FaunaGuard), Group 2 means Phase 2 (During FaunaGuard), Group 3 means Phase 3 (During piling), Group 4 means Phase 4 (After piling), and Group 5 means phase Reference (hours -48 until -25 before the FaunaGuard, as well as +49 until +72 after piling).

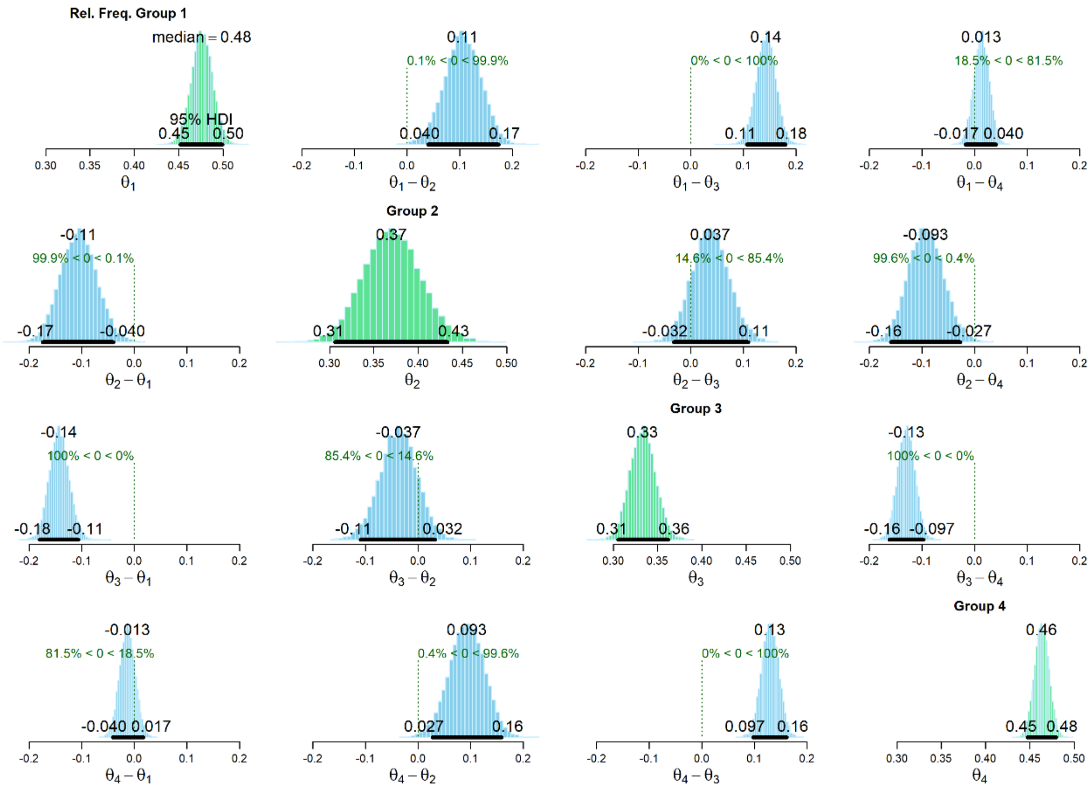

Figure A. 14: Bayesian proportion test for the stationary C-PODs at a distance of 0 to 5 km to the piling location using DPH per hour. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Baseline (hours -48 to -25 before FaunaGuard operation), Group 2 means Pre-piling (down to 3 hours before FaunaGuard operation), Group 3 means Piling (at least 1 minute of FaunaGuard operation or piling), and Group 4 means Reference after piling (hours +49 to +120 after piling).

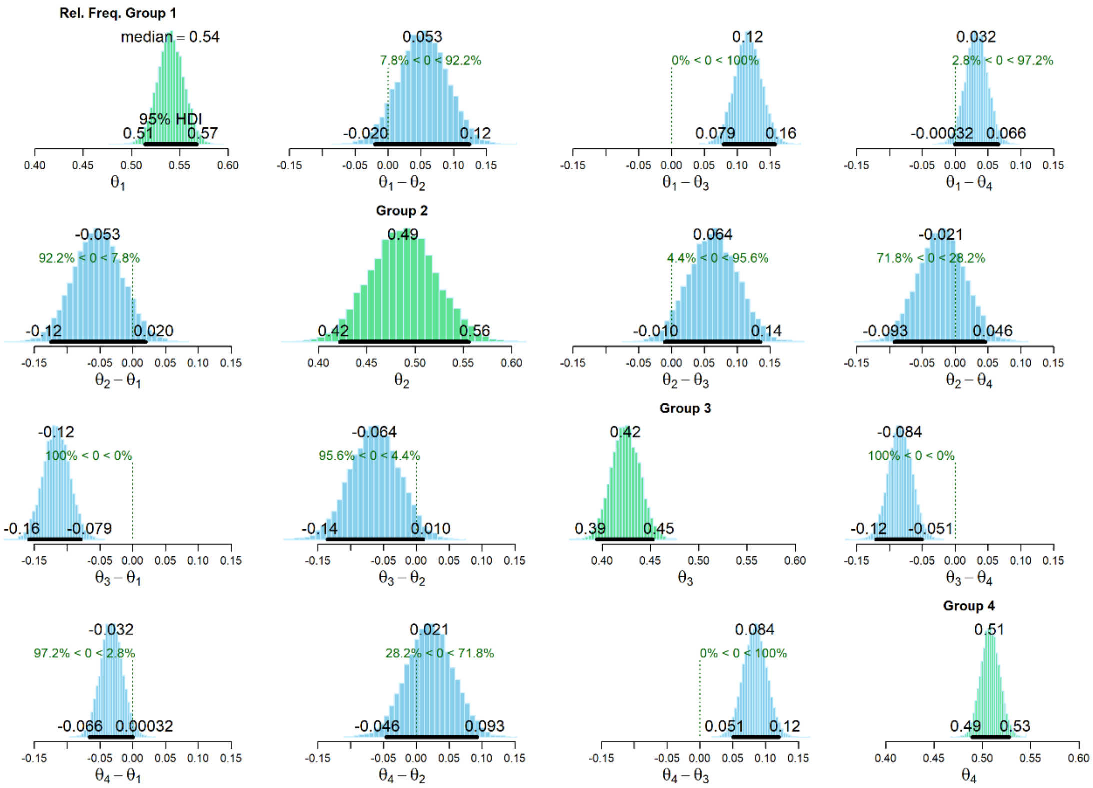

Figure A.15: Bayesian proportion test for the stationary C-PODs at a distance of 5 to 10 km to the piling location using DPH per hour. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Baseline (hours -48 to -25 before FaunaGuard operation), Group 2 means Pre-piling (down to 3 hours before FaunaGuard operation), Group 3 means Piling (at least 1 minute of FaunaGuard operation or piling), and Group 4 means Reference after piling (hours +49 to +120 after piling).

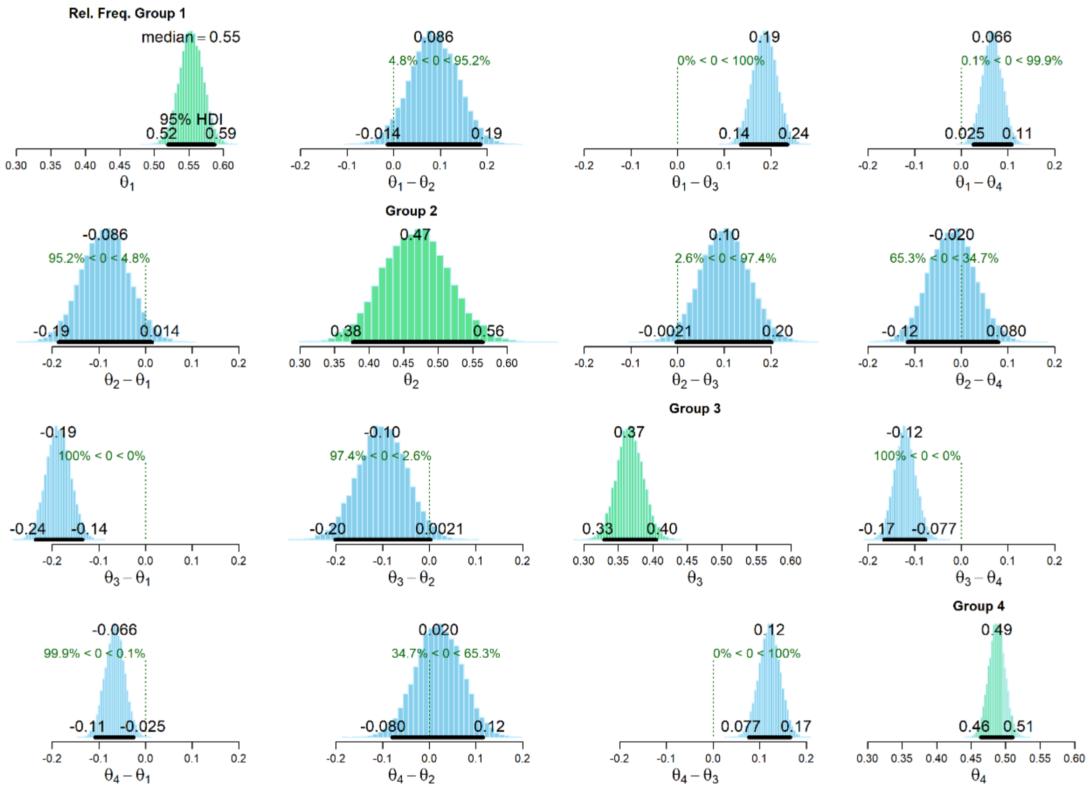

Figure A.16: Bayesian proportion test for the stationary C-PODs at a distance of 10 to 15 km to the piling location using DPH per hour. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Baseline (hours -48 to -25 before FaunaGuard operation), Group 2 means Pre-piling (down to 3 hours before FaunaGuard operation), Group 3 means Piling (at least 1 minute of FaunaGuard operation or piling), and Group 4 means Reference after piling (hours +49 to +120 after piling).

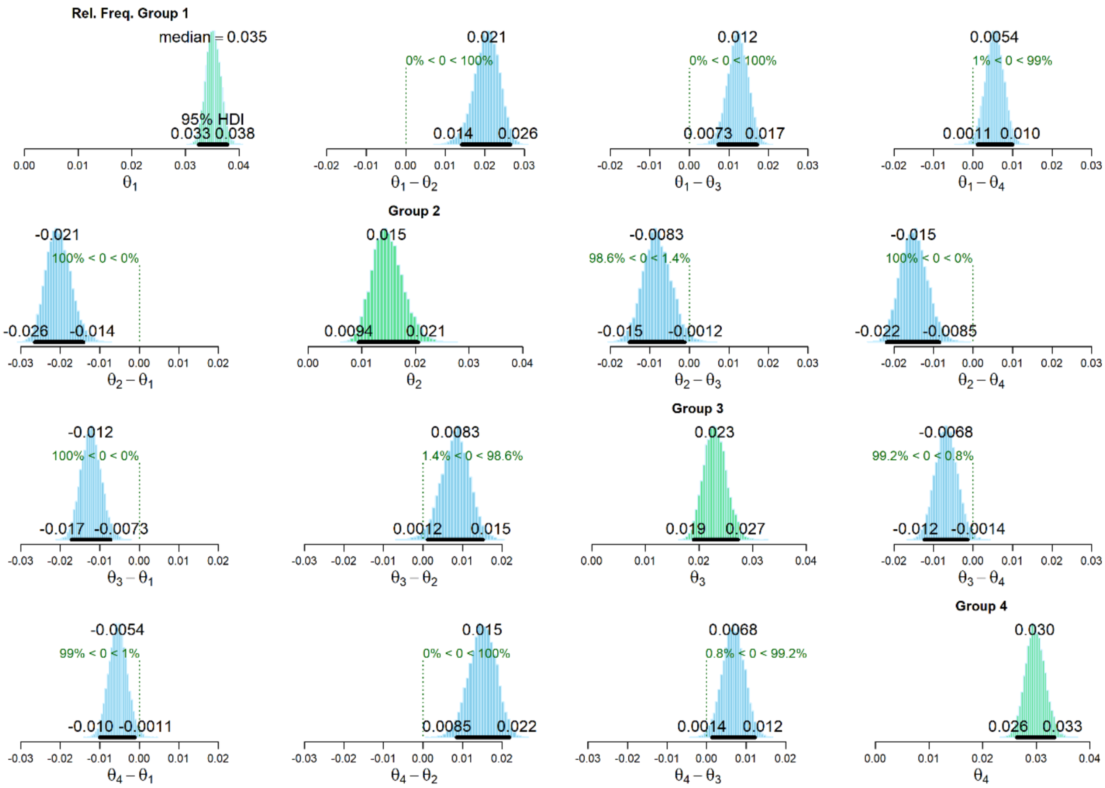

Figure A.17: Bayesian proportion test for the mobile C-PODs at the wind farm “Borkum Riffgrund 2” at a distance of up to 1.5 km to the piling location using DPM per minute. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Phase 1 (Before FaunaGuard), Group 2 means Phase 2 (During FaunaGuard), Group 3 means Phase 3 (During piling), and Group 4 means Phase 4 (After piling).

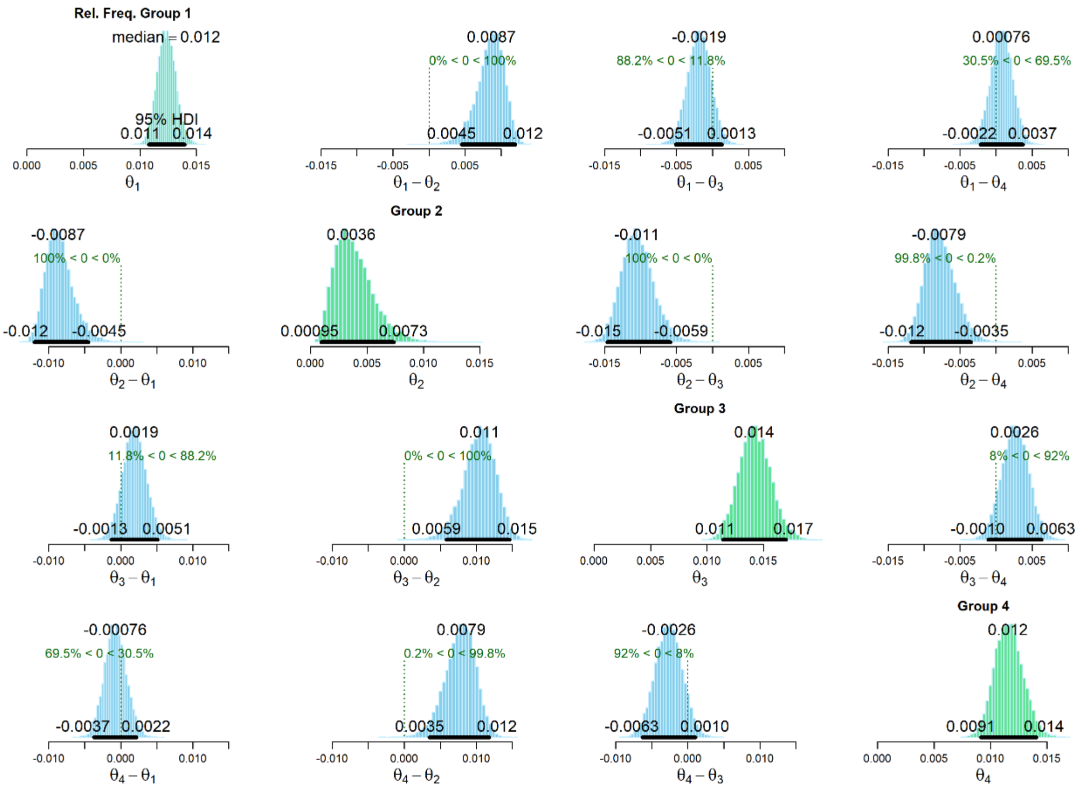

Figure A.18: Bayesian proportion test for the mobile C-PODs at the wind farm “Deutsche Bucht” at a distance of up to 1.5 km to the piling location using DPM per minute. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Phase 1 (Before FaunaGuard), Group 2 means Phase 2 (During FaunaGuard), Group 3 means Phase 3 (During piling), and Group 4 means Phase 4 (After piling).

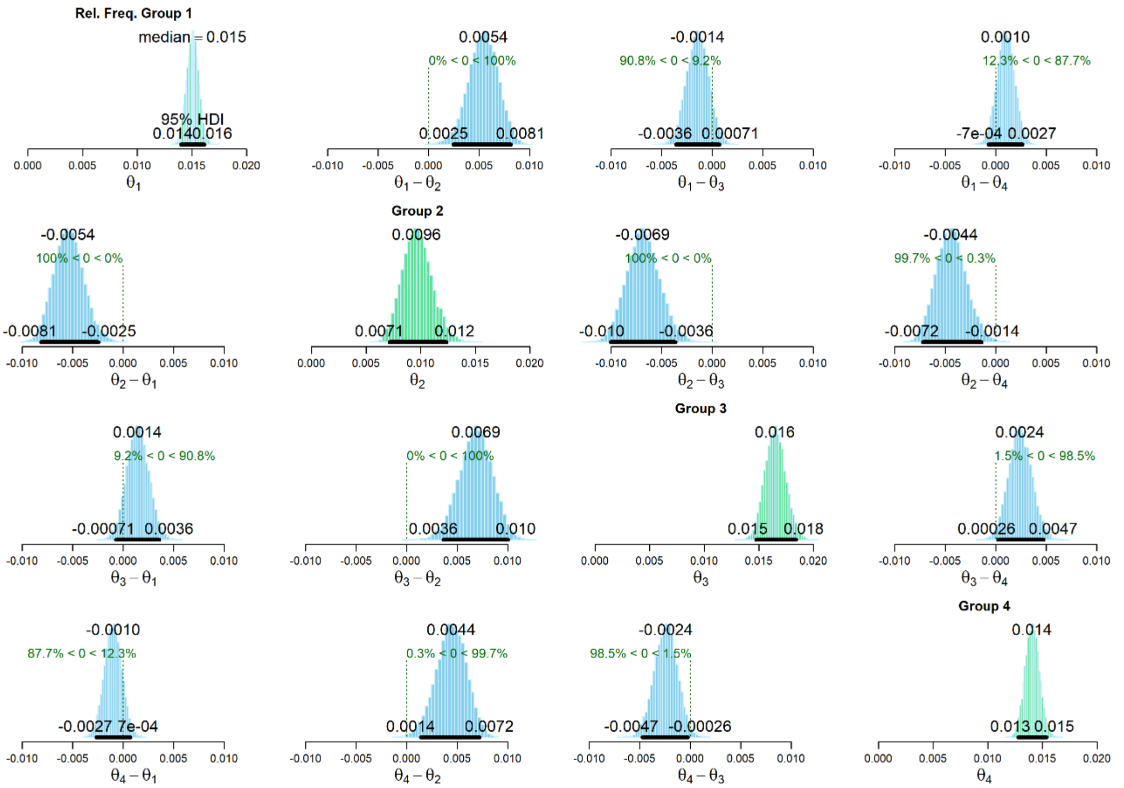

Figure A.19: Bayesian proportion test for the mobile C-PODs at the wind farms “EnBW Hohe See” and “Albatros” at a distance of up to 1.5 km to the piling location using DPM per minute. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Phase 1 (Before FaunaGuard), Group 2 means Phase 2 (During FaunaGuard), Group 3 means Phase 3 (During piling), and Group 4 means Phase 4 (After piling).

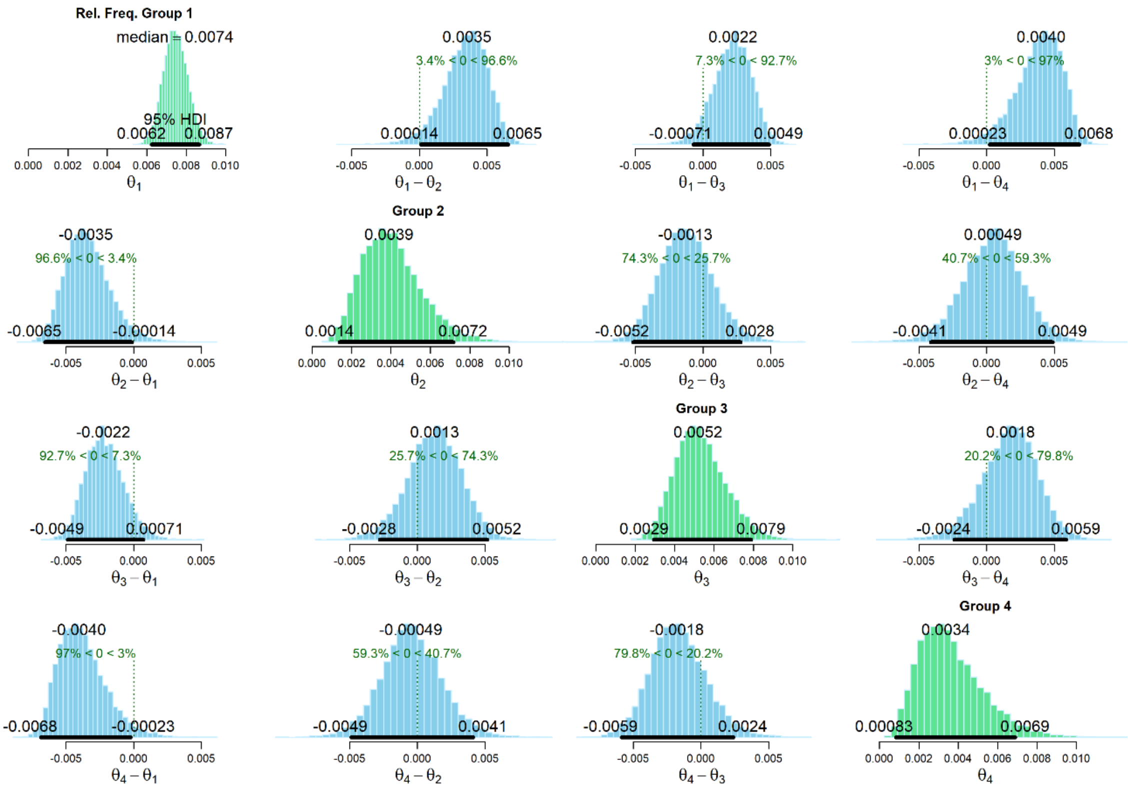

Figure A.20: Bayesian proportion test for the mobile C-PODs at the wind farm "Trianel Windpark Borkum Phase 2" at a distance of up to 1.5 km to the piling location using DPM per minute. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Phase 1 (Before FaunaGuard), Group 2 means Phase 2 (During FaunaGuard), Group 3 means Phase 3 (During piling), and Group 4 means Phase 4 (After piling).

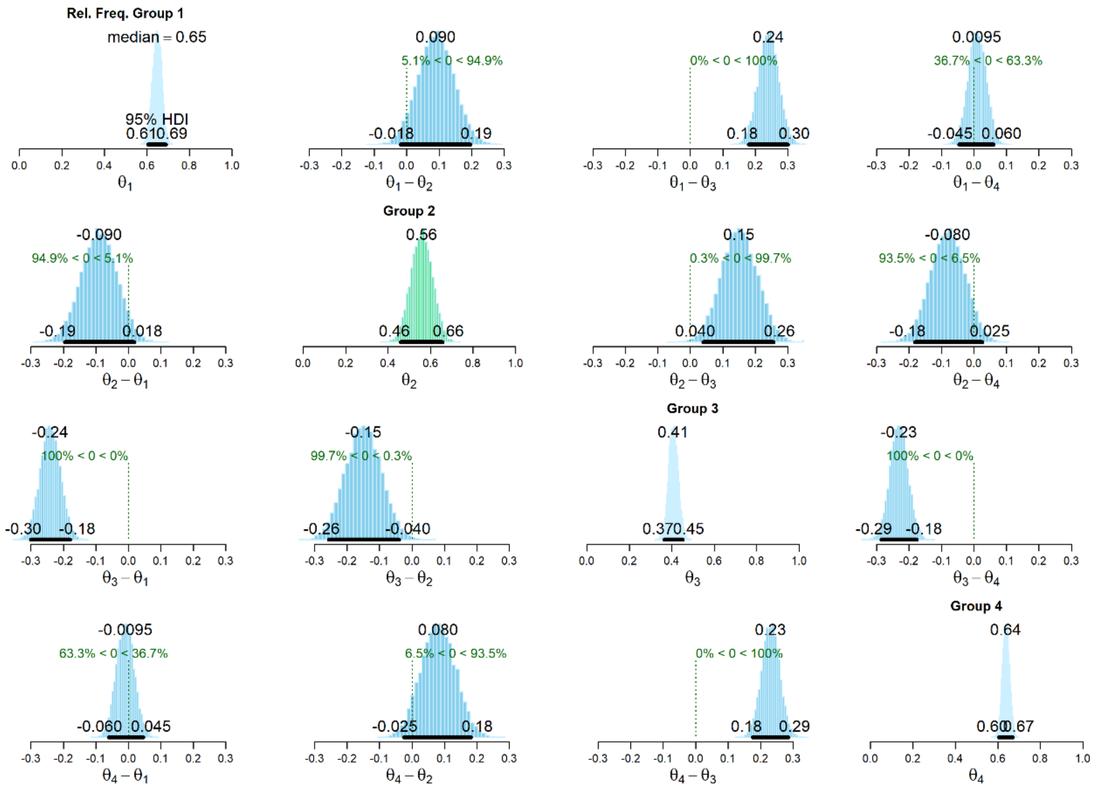

Figure A.21: Bayesian proportion test for the stationary C-PODs at the wind farm “Borkum Riffgrund 2” at a distance of up to 10 km to the piling location using DPH per hour. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Baseline (hours -48 to -25 before FaunaGuard operation), Group 2 means Pre-piling (down to 3 hours before FaunaGuard operation), Group 3 means Piling (at least 1 minute of FaunaGuard operation or piling), and Group 4 means Reference after piling (hours +49 to +120 after piling).

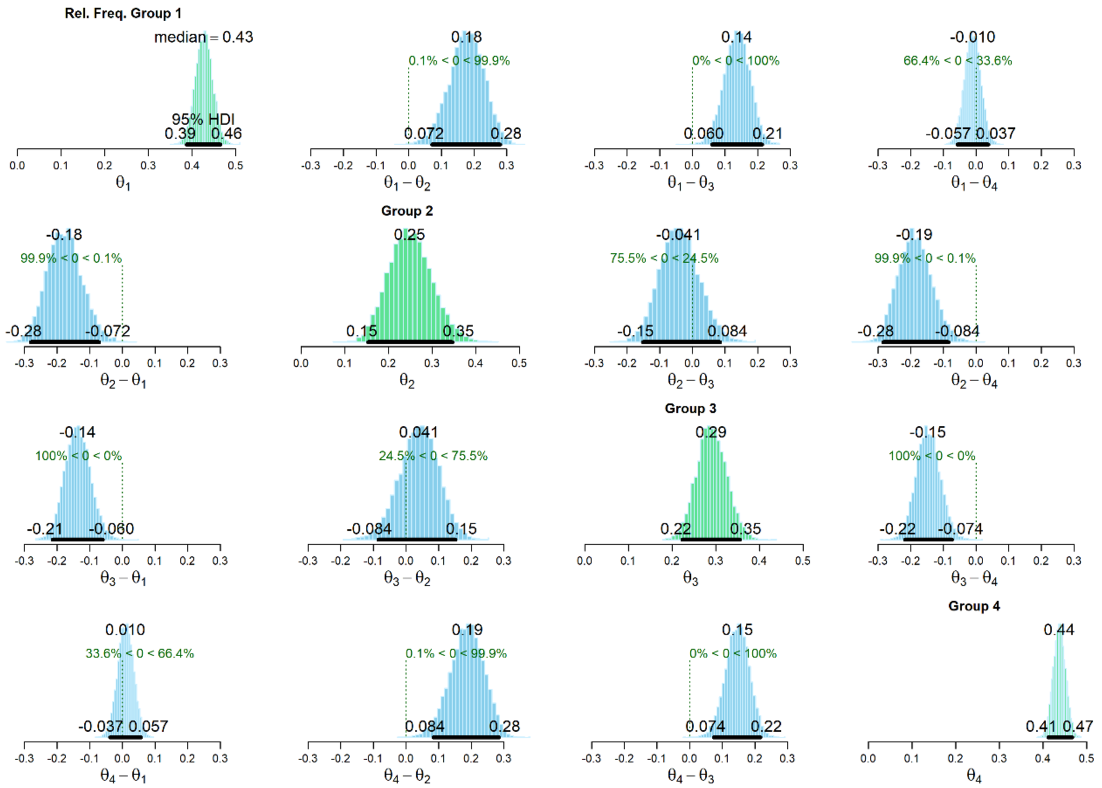

Figure A.22: Bayesian proportion test for the stationary C-PODs at the wind farm "Deutsche Bucht" at a distance of up to 10 km to the piling location using DPH per hour. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Baseline (hours -48 to -25 before FaunaGuard operation), Group 2 means Pre-piling (down to 3 hours before FaunaGuard operation), Group 3 means Piling (at least 1 minute of FaunaGuard operation or piling), and Group 4 means Reference after piling (hours +49 to +120 after piling).

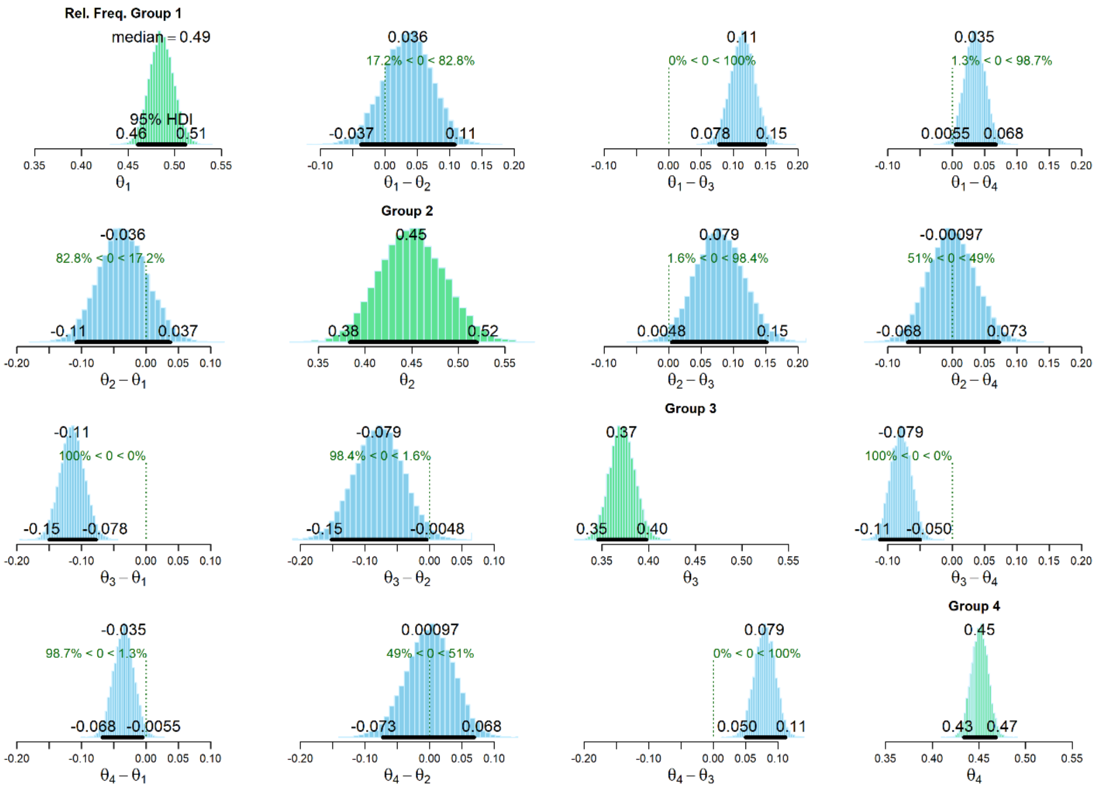

Figure A.23: Bayesian proportion test for the stationary C-PODs at the wind farms "EnBW Hohe See" and "Albatros" at a distance of up to 10 km to the piling location using DPH per hour. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Baseline (hours -48 to -25 before FaunaGuard operation), Group 2 means Pre-piling (down to 3 hours before FaunaGuard operation), Group 3 means Piling (at least 1 minute of FaunaGuard operation or piling), and Group 4 means Reference after piling (hours +49 to +120 after piling).

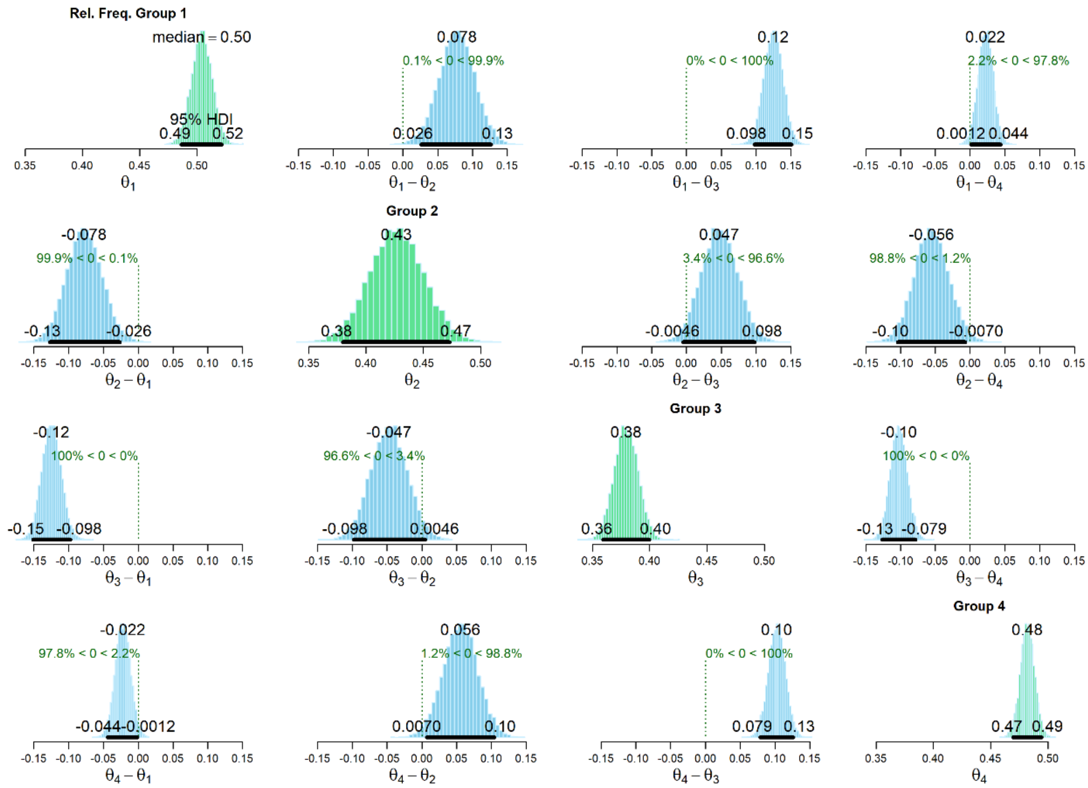

Figure A.24: Bayesian proportion test for the stationary C-PODs at a distance of up to 10 km to the piling location using DPH per hour. For each group, or in this case for each phase, it was examined how high the probability was that the median of one phase was within the 95 % confidence interval of another phase. Group 1 means Baseline (hours -48 to -25 before FaunaGuard operation), Group 2 means Pre-piling (down to 3 hours before FaunaGuard operation), Group 3 means Piling (at least 1 minute of FaunaGuard operation or piling), and Group 4 means Reference after piling (hours +49 to +120 after piling).

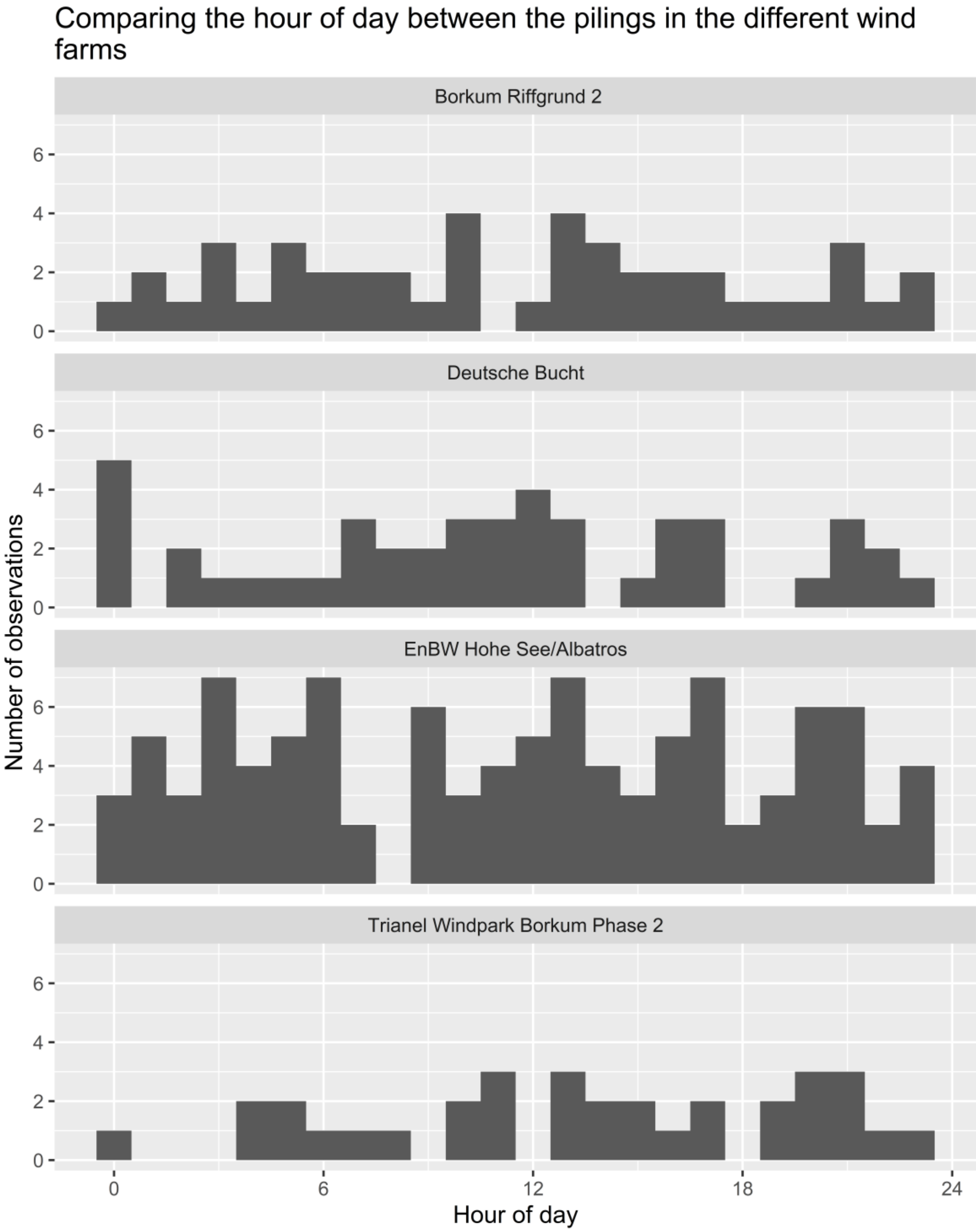

Figure A.25: Comparing the hour of day between pilings (start of each pile driving) in the different wind farms. In all wind farms, pile driving took place during all times of day and night.

A. Tables

Table A.1: Upper 5 % percentile of Sound Exposure Level (SEL_{05}) as well as Peak Level (L_{Peak}) at a distance of 750 m to piling location in relation to the dual noise protection criterion of the German Federal Maritime and Hydrographic Agency, BSH. Pilings with the NMS classes "DBBC", "HSD", "IHC", "none", and "unknown" did not comply with the thresholds for SEL_{05} and L_{Peak} and were thus excluded from subsequent analyses.

Level at distance of 750 m	**Noise Mitigation System (NMS)**	**N (number of pilings)**	**Mean**	**Standard deviation**	**Standard error**
Upper 5 % percentile of Sound Exposure Level	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	2	162.50	0.71	0.50
	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	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	2	183.50	0.71	0.50
	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 (in this case pilings) for Noise Mitigation Systems (NMS). In the wind farms "Deutsche Bucht" and "Trianel Windpark Borkum Phase 2", a combination of the Double Big Bubble Curtain (DBBC) and Hydro Sound Dampers (HSD) was mostly used, while in the wind farms "Borkum Riffgrund 2" as well as "EnBW Hohe See" and "Albatros" a combination of pile sleevers (IHC) and the Big Bubble Curtain (BBC) was mostly used.

NMS (Noise Mitigation System)	**All wind farms**	**Borkum Riffgrund 2**	**Deutsche Bucht**	**EnBW Hohe See/Albatros**	**Trianel Windpark 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

Table A.3: Number of observations (in this case pilings) for upper 5 % percentile of Sound Exposure Level (SEL_{05}) at a distance of 750 m to piling location. In order to minimise the effects of noise emissions during piling, the German Federal Maritime and Hydrographic Agency (BSH) set a dual noise protection criterion: The upper 5 % percentile of the Sound Exposure Level (SEL_{05}) must remain below 160 dB re 1 µPa² s at a distance of 750 m, and the Peak Level (L_{Peak}) must remain below 190 dB re 1 µPa. Due to the continuous development of noise mitigation systems (NMS), many construction projects complied with these limits or even fell below them.

SEL_{05}	All wind farms	Borkum Riffgrund 2	Deutsche Bucht	EnBW Hohe See/Albatros	Trianel Windpark Borkum Phase 2
150	1	1	0	0	0
151	2	2	0	0	0
152	1	1	0	0	0
153	3	2	0	0	1
154	5	4	0	0	1
155	5	5	0	0	0
156	5	2	0	1	2
157	4	2	0	2	0
158	19	1	0	11	7
159	32	0	11	15	6
160	59	0	13	44	2
161	5	0	3	2	0
162	11	0	2	6	3
163	6	0	3	2	1
165	1	0	0	0	1
168	2	0	2	0	0
169	1	0	1	0	0
172	1	1	0	0	0
176	1	0	0	0	1
178	1	0	1	0	0
NA	22	15	0	5	2

Table A.4: Number of observations (in this case pilings) for Peak Level (L_{Peak}) at a distance of 750 m to piling location. In order to minimise the effects of noise emissions during piling, the German Federal Maritime and Hydrographic Agency (BSH) set a dual noise protection criterion: The upper 5 % percentile of the Sound Exposure Level (SEL_{05}) must remain below 160 dB re 1 µPa² s at a distance of 750 m, and the Peak Level (L_{Peak}) must remain below 190 dB re 1 µPa. Due to the continuous development of noise mitigation systems (NMS), many construction projects complied with these limits or even fell below them.

L_{Peak}	All wind farms	Borkum Riffgrund 2	Deutsche Bucht	EnBW Hohe See/Albatros	Trianel Windpark Borkum Phase 2
170	3	2	0	0	1
171	2	2	0	0	0
172	1	1	0	0	0
173	4	3	0	0	1
174	2	1	0	0	1
175	7	5	0	2	0
176	8	1	1	2	4
177	17	3	3	6	5
178	30	1	3	20	6
179	27	0	2	20	5
180	27	1	8	15	3
181	18	0	6	10	2
182	5	0	2	3	0
183	2	0	0	2	0
184	4	0	1	3	0
185	1	0	1	0	0
187	2	0	1	0	1
189	1	0	1	0	0
192	1	0	1	0	0
196	1	1	0	0	0
199	1	0	0	0	1
202	1	0	1	0	0
NA	22	15	0	5	2

Table A.5: Mobile C-PODs: DPM per minute during the different phases in different wind farms at a distance of 0.75 respectively 1.5 km to the FaunaGuard and subsequent piling. At all wind farms and both distances, DPM per minute were highest in Phase 1 (on average 6.20 hours before the FaunaGuard), lowest in Phase 2 (during the FaunaGuard, on average 0.55 hours), increased again in Phase 3 (during piling, on average 1.72 hours), and in Phase 4 (on average 3.04 hours after piling), DPM per minute remained close to the level of Phase 1.

Wind farm	Distance in km	Phase	DPM per minute			
			N (number of minutes)	Mean	Standard deviation	Standard error
Borkum Riffgrund 2	0.75	1: Before FaunaGuard	9,265	0.045	0.21	0.0022
		2: During FaunaGuard	947	0.016	0.12	0.0041
		3: During piling	2,670	0.017	0.13	0.0025
		4: After piling	4,098	0.039	0.19	0.0030
	1.5	1: Before FaunaGuard	8,440	0.024	0.15	0.0017
		2: During FaunaGuard	873	0.013	0.11	0.0038
		3: During piling	2,580	0.029	0.17	0.0033
		4: After piling	4,589	0.022	0.15	0.0021
Deutsche Bucht	0.75	1: Before FaunaGuard	7,795	0.0086	0.09	0.0010
		2: During FaunaGuard	636	0.00	0.00	0.00
		3: During piling	3,485	0.0086	0.092	0.0016
		4: After piling	3,583	0.0064	0.080	0.0013
	1.5	1: Before FaunaGuard	10,098	0.015	0.12	0.0012
		2: During FaunaGuard	656	0.0061	0.078	0.0030
		3: During piling	3,598	0.019	0.19	0.0023
		4: After piling	3,900	0.016	0.13	0.0020
EnBW Hohe See/ Albatros	0.75	1: Before FaunaGuard	24,339	0.011	0.10	0.00066
		2: During FaunaGuard	2,679	0.0075	0.086	0.0017
		3: During piling	9,433	0.012	0.11	0.0011
		4: After piling	17,260	0.0088	0.093	0.00071
	1.5	1: Before FaunaGuard	24,015	0.020	0.14	0.00089
		2: During FaunaGuard	2,698	0.011	0.11	0.0021
		3: During piling	9,496	0.021	0.14	0.0015
		4: After piling	16,957	0.019	0.14	0.0011

Trianel Wind-park Bor-kum Phase 2	0.75	1: Before FaunaGuard	10,098	0.0050	0.070	0.00070
		2: During FaunaGuard	916	0.00	0.00	0.00
		3: During piling	1,583	0.0013	0.036	0.00089
		4: After piling	647	0.0062	0.078	0.0031
	1.5	1: Before FaunaGuard	9,745	0.010	0.099	0.0010
		2: During FaunaGuard	809	0.0074	0.086	0.0030
		3: During piling	1,622	0.0086	0.093	0.0023
		4: After piling	718	0.00	0.00	0.00

Table A.6: Bayesian proportion tests for analysing the mobile C-POD data. Phase 1 described the hours before FaunaGuard operation, Phase 2 covered the FaunaGuard operation, Phase 3 was defined as the time of piling and Phase 4 described the hours after piling.

Category	**Comparison**		**Probability**	**Significance**
Did DPM per minute differ significantly among phases up to a distance of 1.5 km?				
	4-sample test for equality of proportions without continuity correction		X-squared = 38.39 df = 3 p-value = 2.33e-08	
	Phase 1	Phase 2	0 %	*
	Phase 1	Phase 3	20.5 %	
	Phase 1	Phase 4	22 %	
	Phase 2	Phase 3	0 %	*
	Phase 2	Phase 4	0 %	*
	Phase 3	Phase 4	44.5 %	
Did DPM per minute differ significantly among phases of both distance categories?				
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 %	
	Phase 2	Phase 3	0 %	*
	Phase 2	Phase 4	0 %	*
	Phase 3	Phase 4	5.8 %	

Did the DPM per minute of the phases differ significantly up to a distance of 1.5 km at each wind farm?				
Borkum Riffgrund 2	4-sample test for equality of proportions without continuity correction		X-squared = 39.62 df = 3 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 p-value = 9.69e-03	
	Phase 1	Phase 2	0 %	*
	Phase 1	Phase 3	11.8 %	
	Phase 1	Phase 4	30.5 %	
	Phase 2	Phase 3	0 %	*
	Phase 2	Phase 4	0.2 %	*
	Phase 3	Phase 4	8 %	
EnBW Hohe See/Albatros	4-sample test for equality of proportions without continuity correction		X-squared = 15.47 df = 3 p-value = 1.46e-03	
	Phase 1	Phase 2	0 %	*
	Phase 1	Phase 3	9.2 %	
	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 p-value = 3.54e-02	
	Phase 1	Phase 2	3.4 %	*

	Phase 1	Phase 3	7.3 %	
	Phase 1	Phase 4	3 %	*
	Phase 2	Phase 3	25.7 %	
	Phase 2	Phase 4	40.7 %	
	Phase 3	Phase 4	20.2 %	

Table A.7: Bayesian proportion tests for analysing the stationary C-POD data. On the one hand, stationary C-POD data were divided into the same phases as mobile C-POD data in order to keep comparability; Phase 0 was based on 48 to 24 hours' records before piling, Phase 1 described the six hours before FaunaGuard operation, Phase 2 covered the FaunaGuard operation, Phase 3 was defined as the time of piling, Phase 4 described the three hours after piling, and Phase 5 was calculated from 49 to 120 hours' records after piling. On the other hand, stationary C-POD data were divided into the same phases as in the Gescha 2 study (BioConsult SH et al. 2019): Baseline (hours -48 to -25 before the FaunaGuard), Pre-piling (down to 3 hours before the FaunaGuard), Piling (at least 1 minute of FaunaGuard operation or piling) and Reference after piling (hours +49 to +120 after piling).

Category	**Comparison**		**Probability**	**Significance**
Did DPM per minute differ significantly among phases of a distance category?				
0 – 2.5 km	5-sample test for equality of proportions without continuity correction		X-squared = 138.01 df = 4 p-value < 2.2e-16	
	Phase 1	Phase 2	0.4 %	*
	Phase 1	Phase 3	0.7 %	*
	Phase 1	Phase 4	0 %	*
	Phase 1	Reference	0 %	*
	Phase 2	Phase 3	0 %	*
	Phase 2	Phase 4	22.1 %	
	Phase 2	Reference	0 %	*
	Phase 3	Phase 4	0 %	*
	Phase 3	Reference	2 %	*
	Phase 4	Reference	0 %	*
2.5 – 5 km	5-sample test for equality of proportions without continuity correction		X-squared = 32.58 df = 4 p-value = 1.46e-06	
	Phase 1	Phase 2	21.6 %	
	Phase 1	Phase 3	30.8 %	
	Phase 1	Phase 4	0 %	*
	Phase 1	Reference	36.7 %	
	Phase 2	Phase 3	16 %	
	Phase 2	Phase 4	0.1 %	*
	Phase 2	Reference	24.6 %	
	Phase 3	Phase 4	0.1 %	*

	Phase 3	Reference	22.4 %	
	Phase 4	Reference	0 %	*
5 – 7.5 km	5-sample test for equality of proportions without continuity correction		X-squared = 34.27 df = 4 p-value = 6.56e-07	
	Phase 1	Phase 2	0.1 %	*
	Phase 1	Phase 3	0 %	*
	Phase 1	Phase 4	36.1 %	
	Phase 1	Reference	28 %	
	Phase 2	Phase 3	35.8 %	
	Phase 2	Phase 4	0.2 %	*
	Phase 2	Reference	0 %	*
	Phase 3	Phase 4	0 %	*
	Phase 3	Reference	0 %	*
	Phase 4	Reference	20.4 %	
7.5 – 10 km	5-sample test for equality of proportions without continuity correction		X-squared = 40.23 df = 4 p-value = 3.89e-08	
	Phase 1	Phase 2	7 %	
	Phase 1	Phase 3	6.8 %	
	Phase 1	Phase 4	32.2 %	
	Phase 1	Reference	0 %	*
	Phase 2	Phase 3	31.1 %	
	Phase 2	Phase 4	5 %	
	Phase 2	Reference	0.1 %	*
	Phase 3	Phase 4	4.5 %	*
	Phase 3	Reference	0 %	*
	Phase 4	Reference	0.1 %	*
Did DPH per hour differ significantly among phases of a distance category?				
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 %	
	Pre-piling	Piling	14.6 %	
	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 %	
	Baseline	Piling	0 %	*
	Baseline	Reference after piling	2.8 %	*
	Pre-piling	Piling	4.4 %	*
	Pre-piling	Reference after piling	28.2 %	
	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 %	
	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	
Did DPH per hour of the phases differ significantly up to a distance of 10 km at each wind farm?				
Borkum Riffgrund 2	4-sample test for equality of proportions without continuity correction		X-squared = 81.91 df = 3 p-value < 2.2e-16	
	Baseline	Pre-piling	5.1 %	
	Baseline	Piling	0 %	*

	Baseline	Reference after piling	36.7 %	
	Pre-piling	Piling	0.3 %	*
	Pre-piling	Reference after piling	6.5 %	
	Piling	Reference after piling	0 %	*
Deutsche Bucht	4-sample test for equality of proportions without continuity correction		X-squared = 23.56 df = 3 p-value = 3.09e-05	
	Baseline	Pre-piling	0.1 %	*
	Baseline	Piling	0 %	*
	Baseline	Reference after piling	33.6 %	
	Pre-piling	Piling	24.5 %	
	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 p-value = 1.82e-08	
	Baseline	Pre-piling	17.2 %	
	Baseline	Piling	0 %	*
	Baseline	Reference after piling	1.3 %	*
	Pre-piling	Piling	1.6 %	*
	Pre-piling	Reference after piling	49 %	
	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 p-value = 6.58e-02	
Did DPH per hour differ significantly among phases up to a distance of 10 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 %	*

Table A.8: Stationary C-PODs: DPH per hour during the different phases at different distances. DPH per hour for the distance categories up to 20 km from the piling location were highest during the phases Baseline (hours -48 to -25 before FaunaGuard operation) and Reference after piling (hours +49 to +120 after piling), in the intermediate range during the phase Pre-piling (down to 3 hours before FaunaGuard operation) and lowest during the phase Piling (at least 1 minute of FaunaGuard operation or piling).

Distance category (mean) in km	**Phase**	**DPH per hour**			
		N (number of hours)	**Mean**	**Standard deviation**	**Standard error**
0 – 5 (2.89)	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)	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)	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)	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: Stationary C-PODs: DPM per minute during the different phases in different wind farms at different distances. 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 mainly 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.

Wind farm	**Distance (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	0.26	0.0023
		2: During FaunaGuard	1,354	0.057	0.23	0.0063
		3: During piling	4,089	0.048	0.21	0.0033
		4: After piling	6,900	0.041	0.20	0.0024
		Reference	16,833	0.074	0.26	0.0020
	5 – 10 (7.73)	1: Before FaunaGuard	16,749	0.057	0.23	0.0018
		2: During FaunaGuard	1,669	0.040	0.19	0.0048
		3: During piling	4,835	0.047	0.21	0.0031
		4: After piling	8,530	0.051	0.22	0.0024
		Reference	20,151	0.048	0.21	0.0015
Deutsche Bucht	0 – 5 (2.71)	1: Before FaunaGuard	14,686	0.031	0.17	0.0014
		2: During FaunaGuard	1,014	0.0089	0.093	0.0029
		3: During piling	5,707	0.037	0.19	0.0025
		4: After piling	8,126	0.026	0.16	0.0018
		Reference	43,624	0.050	0.22	0.0010
	5 – 10 (5.17)	1: Before FaunaGuard	720	0.072	0.26	0.0097
		2: During FaunaGuard	43	0.023	0.15	0.023
		3: During piling	285	0.018	0.13	0.0078
		4: After piling	360	0.12	0.32	0.017
		Reference	2,882	0.11	0.31	0.0058
EnBW Hohe See/ Albatros	0 – 5 (3.06)	1: Before FaunaGuard	61,008	0.024	0.15	0.00062
		2: During FaunaGuard	5,416	0.027	0.16	0.0022
		3: During piling	19,571	0.031	0.17	0.0012
		4: After piling	31,308	0.023	0.15	0.00084

		Reference	118,786	0.026	0.16	0.00046
	5 – 10 (7.37)	1: Before FaunaGuard	68,527	0.032	0.17	0.00067
		2: During FaunaGuard	6,570	0.034	0.18	0.0022
		3: During piling	22,432	0.032	0.18	0.0012
		4: After piling	35,806	0.034	0.18	0.00096
		Reference	131,705	0.031	0.17	0.00048
Trianel Wind-park Bor-kum Phase 2	0 – 5 (2.80)	1: Before FaunaGuard	7,065	0.045	0.21	0.0025
		2: During FaunaGuard	721	0.044	0.21	0.0077
		3: During piling	1,760	0.032	0.18	0.0042
		4: After piling	3,631	0.039	0.19	0.0032
		Reference	16,134	0.040	0.20	0.0015
	5 – 10 (8.34)	1: Before FaunaGuard	7,210	0.090	0.29	0.0034
		2: During FaunaGuard	862	0.079	0.27	0.0092
		3: During piling	1,741	0.10	0.30	0.0073
		4: After piling	3,892	0.068	0.25	0.0040
		Reference	17,372	0.075	0.26	0.0020

Table A.10: Stationary C-PODs: DPH per hour during the different phases in the different wind farms up to 10 km distance from the piling location. At all wind farms, DPH per hour were highest during the phases Baseline (hours -48 to -25 before FaunaGuard operation) and Reference after piling (hours +49 to +120 after the piling); at the wind farms "Borkum Riffgrund 2" as well as "EnBW Hohe See" and "Albatros", DPH per hour were lowest during the phase Piling (at least 1 minute of FaunaGuard operation or piling) and at the wind farms "Deutsche Bucht" and "Trianel Windpark Borkum Phase 2", DPH per hour were lowest during the phase Pre-piling (down to 3 hours before FaunaGuard operation).

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: Mobile and stationary C-PODs: DPM per minute (mean and standard error) during FaunaGuard operation at different distances. Higher detection rates were generally observed further away from the pile-driving site. In addition, detection rates in the distance class 0 to 1.25 km to the pile-driving site continued to decrease as the duration of use of the FaunaGuard increased; no clear trends could be identified for larger distances.

Distance category in km	**A_min_FaunaGuard**	**DPH per hour**			
		N (number of minutes)	**Mean**	**Standard deviation**	**Standard error**
0 – 1.25	1	402	0.010	0.099	0.0050
	3	398	0.013	0.11	0.0056
	5	393	0.0051	0.071	0.0036
	7	393	0.0077	0.087	0.0044
	9	395	0.0025	0.050	0.0025
	11	388	0.013	0.11	0.0057
	13	376	0.0053	0.073	0.0038
	15	373	0.0080	0.089	0.0046
	17	359	0.0084	0.091	0.0048
	19	342	0.0088	0.093	0.0050
	21	311	0.0064	0.080	0.0045
	23	296	0.00	0.00	0.00
	25	286	0.00	0.00	0.00
	27	281	0.0036	0.060	0.0036
	29	253	0.00	0.00	0.00
	31	186	0. 00	0.00	0.00
	33	137	0. 00	0.00	0.00
	35	76	0. 00	0.00	0.00
1.25 – 2.5	1	479	0.019	0.14	0.0062
	3	478	0.025	0.16	0.0072
	5	478	0.015	0.12	0.0055
	7	476	0.013	0.11	0.0051
	9	478	0.00	0.00	0.00
	11	478	0.019	0.14	0.0062
	13	476	0.025	0.16	0.0072
	15	467	0.017	0.13	0.0060

	17	444	0.018	0.13	0.0063
	19	420	0.014	0.12	0.0057
	21	387	0.0078	0.088	0.0044
	23	375	0.013	0.11	0.0059
	25	360	0.017	0.13	0.0068
	27	357	0.014	0.12	0.0062
	29	316	0.013	0.11	0.0063
	31	233	0.026	0.16	0.010
	33	178	0.028	0.17	0.012
	35	100	0.010	0.10	0.010
2.5 – 5	1	365	0.047	0.21	0.011
	3	365	0.036	0.19	0.0097
	5	372	0.032	0.18	0.0092
	7	370	0.022	0.15	0.0076
	9	370	0.038	0.19	0.0099
	11	366	0.044	0.20	0.011
	13	359	0.025	0.16	0.0083
	15	356	0.028	0.17	0.0088
	17	338	0.036	0.19	0.010
	19	321	0.031	0.17	0.0097
	21	286	0.049	0.22	0.013
	23	268	0.034	0.18	0.011
	25	252	0.044	0.20	0.013
	27	247	0.036	0.19	0.012
	29	218	0.023	0.15	0.010
	31	150	0.027	0.16	0.013
	33	93	0.065	0.25	0.026
	35	51	0.059	0.24	0.033
5 – 7.5	1	280	0.018	0.13	0.0079
	3	278	0.022	0.15	0.0087
	5	281	0.036	0.19	0.011
	7	280	0.032	0.18	0.011
	9	284	0.042	0.20	0.012

	11	281	0.036	0.19	0.011
	13	281	0.036	0.19	0.011
	15	274	0.026	0.16	0.0096
	17	276	0.025	0.16	0.0095
	19	268	0.030	0.17	0.010
	21	251	0.028	0.16	0.010
	23	239	0.046	0.21	0.014
	25	232	0.022	0.15	0.0096
	27	230	0.039	0.19	0.013
	29	210	0.024	0.15	0.011
	31	162	0.012	0.11	0.0087
	33	90	0.011	0.10	0.011
	35	56	0.00	0.00	0.00
7.5 – 10	1	272	0.070	0.26	0.015
	3	274	0.044	0.21	0.012
	5	272	0.037	0.19	0.011
	7	274	0.066	0.25	0.015
	9	274	0.047	0.21	0.013
	11	273	0.062	0.24	0.015
	13	271	0.044	0.21	0.013
	15	270	0.063	0.24	0.015
	17	271	0.063	0.24	0.015
	19	266	0.064	0.25	0.015
	21	257	0.058	0.23	0.015
	23	259	0.031	0.17	0.011
	25	260	0.012	0.11	0.0066
	27	258	0.047	0.21	0.013
	29	231	0.052	0.22	0.015
	31	181	0.028	0.16	0.012
	33	125	0.056	0.23	0.021
	35	66	0.030	0.17	0.021

Table A. 12: Mobile C-PODs: Comparison of FaunaGuard and seal scarer in the wind farm "Trianel Windpark Borkum Phase 2". DPM per minute were highest in Phase 1 (on average 6.20 hours before AHD operation), lowest in Phase 2 (during AHD operation, on average 0.55 hours), increased again in Phase 3 (during piling, on average 1.72 hours), and in Phase 4 (on average 3.04 hours after piling), DPM per minute remained close to the level of the previous phase. Due to the generally low detection rates, no difference could be detected between the FaunaGuard and the seal scarer as AHD at distances up to 1.5 km.

AHD	Distance in km	Phase	DPM per minute			
			N (number of minutes)	Mean	Standard deviation	Standard error
FaunaGuard	0.75	1: Before AHD	10,098	0.0050	0.070	0.00070
		2: During AHD	916	0.00	0.00	0.00
		3: During piling	1,583	0.0013	0.036	0.00089
		4: After piling	647	0.0062	0.078	0.0031
	1.5	1: Before AHD	9,745	0.010	0.099	0.0010
		2: During AHD	809	0.0074	0.086	0.0030
		3: During piling	1,622	0.0086	0.093	0.0023
		4: After piling	718	0.00	0.00	0.00
Seal scarer	0.75	1: Before AHD	1,655	0.0079	0.088	0.0022
		2: During AHD	118	0.00	0.00	0.00
		3: During piling	129	0.023	0.15	0.013
		4: After piling	37	0.00	0.00	0.00
	1.5	1: Before AHD	1,737	0.020	0.14	0.0034
		2: During AHD	117	0.00	0.00	0.00
		3: During piling	125	0.00	0.00	0.00
		4: After piling	35	0.00	0.00	0.00

Table A. 13: Stationary C-PODs: Comparison of FaunaGuard and seal scarer in the wind farm "Trianel Windpark Borkum Phase 2" (5 to 10 km away from piling). When using the FaunaGuard as AHD, DPM per minute were similar during all phases (Phase 1: Before AHD/ Phase 2: During AHD/ Phase 3: During Piling/ Phase 4: After piling/ Reference); however, when using the seal scarer as AHD, DPM per minute were considerably lower in Phase 2, meaning during the use of the seal scarer, compared to the other phases.

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	0.090	0.29	0.0034
	2: During AHD	862	0.079	0.27	0.0092
	3: During piling	1,741	0.10	0.30	0.0073
	4: After piling	3,892	0.068	0.25	0.0040
	Reference	21,066	0.071	0.26	0.0018
Seal scarer (7.77 km)	1: Before AHD	1,077	0.13	0.34	0.010
	2: During AHD	117	0.0085	0.092	0.0085
	3: During piling	290	0.12	0.33	0.019
	4: After piling	578	0.15	0.36	0.015
	Reference	6,207	0.22	0.42	0.0053

A. Declaration of originality

I hereby affirm in lieu of oath that I wrote this work independently and did not use any other sources and aids than those indicated. I also affirm that I have followed the general principles of scientific work and publication as laid down in the guidelines of good scientific practice of the Carl von Ossietzky University of Oldenburg.

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Hiermit versichere ich an Eides statt, dass ich diese Arbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe. Außerdem versichere ich, dass ich die allgemeinen Prinzipien wissenschaftlicher Arbeit und Veröffentlichung, wie sie in den Leitlinien guter wissenschaftlicher Praxis der Carl von Ossietzky Universität Oldenburg festgelegt sind, befolgt habe.

Hattstedt, 2021-01-28

Place, date, signature