HARBOUR PORPOISE RESPONSES TO PILE DRIVING ARE BETTER PREDICTED BY DISTANCE TO SOURCE THAN BY ENERGY-BASED RECEIVED SOUND LEVELS

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Author contributions: Paul Thompson and Isla Graham conceived the ideas and designed the general methodology. Isla Graham, Aude Benhemma-Le Gall, Barbara Cheney, Virginia Iorio-Merlo and Oihane Fernandez-Betelu all collected and processed data; Aude Benhemma-Le Gall analysed the data; Paul Thompson and Aude Benhemma-Le Gall led the writing of the manuscript. All authors contributed critically to drafts of the manuscript.

Abstract

1. Regulatory assessments for offshore construction are required to avoid impacts on protected marine mammals through noise-related injury or disturbance. Criteria for injury risk are widely accepted, but the extent to which behavioural responses are related to noise levels or co-varying contextual factors such as proximity remains uncertain.

2. This study used arrays of echolocation detectors to compare behavioural responses of harbour porpoises along gradients of exposure to pile installation noise at three offshore wind farms. Differences in the size of piles and installation hammers at these sites meant that received levels at given distances differed by up to 15 dB, providing an opportunity to assess whether behavioural responses to pile installation noise were best predicted by received doses of impulsive noise or distance to source.

3. Using balanced data from within 35 km of the first two piling bouts at each site, the probability of detecting a response was better explained by the distance to the piling vessel than either weighted or unweighted sound exposure levels of impulsive piling noise. Response functions for individual wind farms were also more similar for distance functions (50 % probability of response at 6.5, 4 & 5.5 km) compared to those unweighted single strike Sound Exposure Levels (50 % probability of response at 148.5, 152 & 166.5 dB re 1 µPa^{2}s). This suggests that energy-based metrics do not capture all the acoustic cues that best explain behavioural responses to pile driving noise.

4. *Synthesis & applications.* Regulatory assessments for increasingly large offshore wind farms have been constrained by uncertainty over the most appropriate behavioural response functions for estimating disturbance. Earlier single site studies found similar support for response functions based on both received noise levels and distance. Some UK Statutory Nature Conservation Bodies have therefore recommended using a dose-response as a precautionary measure, but extrapolation has subsequently led to unrealistic predictions of far-field disturbance. There is growing evidence that marine mammal responses to other noise sources are highly dependent upon proximity to source. Our findings suggest that distance-based response functions provide a more consistent and practicable variable for assessing disturbance for a range of different foundation types and source levels.

Keywords:

Underwater Noise Management; Marine mammal disturbance; Environmental Impact Assessment; Offshore Wind Farms

1 INTRODUCTION

The rapid development of offshore wind farms is underpinning global efforts to transition from fossil fuels, but there are concerns that this may impact marine biodiversity (Watson *et al.* 2025). Construction typically involves the installation of foundations into the seabed using percussive pile driving techniques. This introduces high levels of impulsive noise into the marine environment, which may impact protected marine mammals and their prey (Tyack 2008; Brandt *et al.* 2018). Robust prediction and appropriate mitigation of the potential impacts of injury or disturbance to marine mammals during pile installation is therefore a critical issue during the assessment and regulation of offshore wind developments that are being proposed to address climate targets (Bailey, Brookes & Thompson 2014; Faulkner, Farcas & Merchant 2018).

A key step within current environmental assessments for offshore wind farm construction is the prediction of how many individual marine mammals may be injured or disturbed during the installation of each foundation pile (Thompson *et al.* 2013; Faulkner, Farcas & Merchant 2018). These predictions are generally underpinned by acoustic propagation models that use available information on noise source levels to predict spatial variation in received levels (Farcas, Thompson & Merchant 2016). Using agreed noise exposure criteria (e.g. Southall *et al.* 2019b, NMFS 2024), predictions of received noise levels can be integrated with available data on marine mammal densities to estimate how many individuals might be impacted by the noise levels experienced during wind farm construction. In combination with available information on potential fitness consequences for these individuals, these numbers are then used within population modelling frameworks to determine the long-term consequences of these impacts for protected marine mammal populations (e.g. King *et al.* 2015).

Noise criteria for assessing the risk of injury from impulsive piling noise are widely accepted and used by many national regulators (Southall *et al.* 2019b; Southall 2021). However, it has proved more challenging to identify appropriate criteria for estimating how many individuals may be disturbed during pile installation. This is because a variety of contextual factors, such as proximity to source and behavioural state, will influence the likelihood that marine mammals will respond to impulsive noise (Southall *et al.* 2021; Booth *et al.* 2022). The quantification of behavioural responses in relation to a noise source is therefore best considered as a probabilistic function (Southall 2024), but there are currently limited data available to characterise these probabilistic responses to impulsive noise sources.

Ideally, controlled exposure experiments (CEE) would be used to determine how individual marine mammals respond to impulsive noise, but opportunities for these playback studies are rare (Tyack 2009). Instead, current understanding of responses to impulsive pile driving noise depends largely upon studies of population level changes in occurrence or density around wind farm construction sites (e.g. Tougaard *et al.* 2009; Brandt *et al.* 2018). For example, a broad-scale array of echolocation click detectors was previously used to record changes in the occurrence of harbour porpoise during pile driving at the Beatrice offshore wind farm in NE Scotland (Graham *et al.* 2019). These data were used to investigate the extent to which porpoises were disturbed at this development and produce proxy response functions that have since been used to support environmental assessments across UK waters (NRW 2023). However, two key assumptions constrain the extent to which response functions such as this can be used in regulatory assessments for proposed offshore wind projects, particularly where these involve new foundation technologies in increasingly deeper waters.

First, all previous studies of marine mammal disturbance during foundation installation have assumed that observed disturbance is a direct response to pile driving noise (Dähne *et al.* 2017; Brandt *et al.* 2018; Graham *et al.* 2019; Tougaard 2025). The installation of driven piles is recognised to be the loudest source during construction. But marine mammals also respond to continuous noise from vessel activity around construction sites (Benhemma-Le Gall *et al.* 2021; Benhemma-Le Gall *et al.* 2023) and acoustic deterrent devices (ADD) deployed to mitigate near-field risks of injury (Brandt *et al.* 2013; Thompson *et al.* 2020; Graham *et al.* 2023). Comparisons across studies have similarly assumed that differences in response levels are a result of differences in received levels of impulsive piling noise (Dähne *et al.* 2017; Brandt *et al.* 2018) and it has not been possible to control for these other confounding factors. Uncertainty over the relative importance of different noise sources in shaping overall disturbance response at wind farm construction sites therefore constrains current assessments of the costs and benefits of alternative engineering options and mitigation measures that aim to reduce cumulative levels of disturbance.

Second, previous studies have assumed that the primary driver of marine mammal responses to pile driving is either the level of impulsive noise received by an individual, or the perception of noise levels given the species' hearing range (Tougaard 2025). An alternative hypothesis is that responses may be driven, or at least moderated, by an animals' perception of distance to the noise source and the threat that this may pose (Frid & Dill 2002; Miller *et al.* 2022). It has not previously been possible to test these alternative hypotheses at wind farm construction sites because received levels of noise and distance to source are highly correlated (Graham *et al.* 2019). However, increasing evidence from experimental playbacks of both continuous and impulsive noise suggest that responses depend upon both received levels and distance to source (Dunlop *et al.* 2018). For example, the probability of response of blue whales exposed to the same received levels of mid-frequency sonar decreased as the distance from source increased from 1 - 5km (Southall *et al.* 2019a). Similarly, models that accounted for both distance to source and received levels of mid-frequency sonar noise indicated that sperm whale response probability declined sharply with distance and approached zero beyond 14 km (Wensveen *et al.* 2025). Currently, however, there is only one published study of cetacean responses to impulsive noise that has successfully decoupled the correlation between distance to source and received levels (Dunlop *et al.* 2018). In that CEE study of responses of migrating humpback whales to seismic air guns, Dunlop et al. (2018) conducted a series of experiments using different sized air guns, such that received levels differed by up to 20 dB at any given distance.

Despite this uncertainty in the extent to which disturbance responses are directly dependent upon received levels of impulsive noise (Gomez *et al.* 2016), there remains a strong focus on reducing levels of piling noise within guidance for regulatory assessment (Faulkner, Farcas & Merchant 2018) and mitigation strategies (DEFRA 2025) for offshore wind farm construction. Here, we characterise harbour porpoise behavioural responses during the construction of three offshore wind farms, and present results that challenge the assumptions underlying current approaches to assessing and mitigating the impacts of pile driving noise. We built upon the approach used by Dunlop et al. (2018) by replicating Graham et al.'s (2019) population level study at two additional wind farms, including one where much higher hammer energies were required to install large diameter monopiles. Our primary aim was to assess whether behavioural responses of harbour porpoises to pile driving were best predicted by received levels of impulsive noise (dose-response function) or distance to the source of the noise (deterrence function).

2 MATERIALS AND METHODS

2.1 Study system

The study was conducted in the Moray Firth, NE Scotland, over a seven-year period within which three commercial offshore wind farms were constructed (Figure 1). In 2017, four 2.2 m diameter pin piles were installed at 86 locations in the Beatrice offshore wind farm to secure the quadruped jacket foundations used to support each 7 MW turbine. In 2019 and 2020, three ≤ 2.5 m diameter piles were installed at 103 locations in the Moray East offshore wind farm to secure tripod jacket foundations used for their 9.5 MW turbines. Finally, in 2023 and 2024, 9.5-10.0 m monopiles were installed at 62 locations in the Moray West offshore wind farm to support 14.7 MW turbines.

Differences in the foundation systems used at each of the wind farms required increasingly large piles and hammer energies, which resulted in concurrent increases in maximum levels of impulsive noise during pile installation (ORJIP 2023). At Beatrice, 35 to 45 m long pin piles were driven into the seabed using a pile installation frame and a 2,500 kJ hydraulic piling hammer (IHC Hydrohammer S-2500). At Moray East, piles of 30 to 55 m in length were driven into the seabed using a pile installation frame and a 1,900 kJ hammer (MENCK MHU 1900). At Moray West, 74 to 92 m long monopiles were installed through pre-installed scour pads using a 4,400 kJ hammer (MENCK MHU 4400).

The three developments also differed in the heavy lift vessels used for pile installation, which resulted in differences in the nature, duration and spatial footprint of continuous noise inputs around piling events. Beatrice installed piles using a heavy lift vessel (Stanislav Yudin, IMO: 8219463) which was positioned using eight anchors and supported by two anchor handlers and an additional vessel that supplied piles at each location. Moray East installed piles using a dynamically positioned (DP) heavy lift vessel (Apollo, IMO: 9769764) that jacked up at each location and was supplied with piles by an additional vessel at every second location. Finally, most monopiles at Moray West were deployed from a DP heavy lift vessel (Bokalift 2, IMO: 9190705) that returned to port to collect additional piles after every third location. A second vessel (Orion, IMO: 9825453) was also used to install some of the monopiles at Moray West in 2024 after the end of this study.

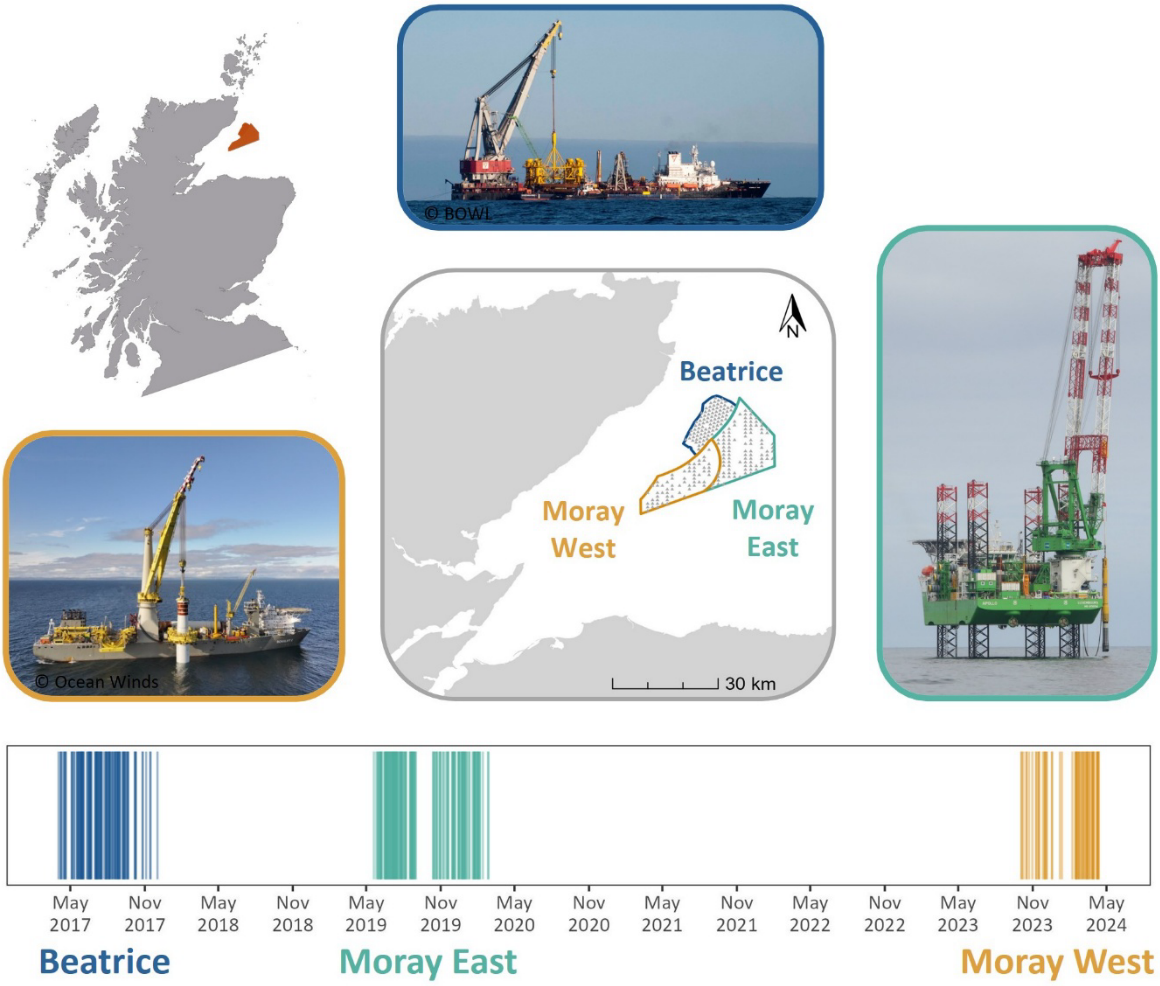

Figure 1 Map of the Moray Firth study area showing the turbine layout within each of the three wind farms (grey triangles) and the installation vessels used for each piling campaign. The lower panel shows the timeline for the study with vertical lines representing each day on which pile driving occurred at Beatrice (blue) Moray East (green) and Moray West (orange) offshore wind farms.

Typically, all piles were installed at each location before moving to the next location. For the pin piles installed at Beatrice and Moray East, only short breaks in piling were required to move the hammer between pin piles required at each turbine location. On occasion however, for example due to weather or technical downtime, there were longer breaks in piling of both pin piles and monopiles. Here, we define a bout of piling as a period of continuous piling at a single location where any intervals in piling were less than 12 hours (see Benhemma-Le Gall *et al.* 2021). The average duration of these bouts of active piling was 4.9 h at Beatrice, 3.5 h at Moray East and 2.5 h at Moray West (Table 1). Broad scale temporal patterns of pile driving events through the study are shown in Figure 1, and detail on the timing and maximum hammer energy during each bout of piling is provided in Table S1.

Table 1. Duration of piling bouts from the start to end of piling at a single location including breaks less than 12 h (Total time) and duration of active piling excluding any breaks (Active piling) at Beatrice, Moray East and Moray West offshore wind farms, NE Scotland. Mean duration in hours (range in parentheses) for all piling bouts (up to December 2023), the subset of piling bouts used in the 24-h dose response analyses and for the first two piling bouts for each campaign.

Duration (h)	**All bouts**		**24-h analyses**		**First two piling bouts**	
	Active piling	**Total time**	**Active piling**	**Total time**	**Active piling**	**Total time**
Beatrice	4.9 (2.3-8.8)	7.7 (2.3-19.9)	5.1 (3.3-7.1)	7.5 (4.1-11.5)	6.4 (5.8-7.1)	9.6 (7.7-11.5)
Moray East	3.5 (0.3-5.7)	6.6 (0.3-19.3)	2.8 (0.9-4.0)	6.3 (0.9-16.8)	2.1 (0.9-3.3)	3.4 (0.9-5.9)
Moray West *	2.5 (1.5-4.2)	3.1 (1.5-12.7)	2.9 (2-4.2)	4.2 (2-12.7)	3.6 (3-4.2)	7.8 (3-12.7)

** up to December 2023*

2.2 Characterisation of piling noise

Direct measurements of unweighted sound exposure level (SEL) for a single strike (SEL_{ss}) were obtained for a sub-set of locations and piling events within each of the three wind farms (Figure S1, Table S2) as part of the developers' consent monitoring programme (Thompson et al. 2020, 2026; Stephenson et al. 2026). See Supplementary Material for further details.

Here, we used data from this sub-set of pile installations to characterise how received levels of noise varied with distance from source at each wind farm development. We fitted equations to describe empirical attenuation patterns derived from measured SEL_{ss}, and then used these to predict how received levels of piling noise varied across sites used to monitor porpoise disturbance responses (see below). We focus on comparisons using unweighted sound exposure level for a single strike given the use of this metric in current regulatory assessments. As highlighted by Tougaard (2025), behavioural responses are expected to be most closely related to noise that is within the normal hearing range of exposed individuals. We therefore also converted unweighted SEL_{ss} levels to auditory weighted SEL_{ss} levels using the range dependant weighting factor provided as equation 4 in Tougaard (2025).

2.3 Assessing harbour porpoise responses to pile driving

Graham et al. (2019) used data from arrays of echolocation click detectors (CPODs) to detect changes in porpoise occurrence and estimate proxy response functions to pile driving events at the Beatrice offshore wind farm. This approach was replicated by deploying additional arrays of CPODs at Moray East in 2019 and 2020, and during the first three months of the piling campaign at Moray West in 2023. The size and spatial extent of arrays differed slightly between wind farms (Figure 2, Table 1), but all aimed to assess variation in porpoise occurrence along gradients of exposure to noise from pile installations at multiple locations within each development.

Following recovery of devices, porpoise echolocation clicks were identified using v. 2.044 of the manufacturer's custom software and click trains categorized as high or moderate quality were used in subsequent analyses. High levels of background noise can adversely affect CPOD performance by saturating the recording buffer and affecting the detection probability (Wilson, Benjamins & Elliott 2013; Clausen *et al.* 2019). We therefore excluded all data from CPODs within 1 km of piling locations from analyses. In addition, observations were excluded if the number of saturated minutes during the response period exceeded 1 % of the response duration (i.e. > 14 minutes for the 24-h response). Finally, we standardised the maximum spatial scale of the CPOD array across wind farms by selecting only those sites that were within 35 km of piling locations (see Hastie *et al.* 2026, In Review).

These data on variation in porpoise detections were then related to engineering records to quantify behavioural responses to piling bouts. For each CPOD, changes in the number of detection positive hours (DPH) were estimated for each selected piling bout in the 24-h period from the end of the piling bout relative to a baseline 24-h period immediately before the event. To provide a relatively undisturbed baseline period (see Graham et al (2019)), only piling bouts that started > 72 hours after the end of the previous piling bout were selected. This requirement for sufficient baseline and impact periods around potential disturbance events meant that only a sub-set of pile installations could be included in the analyses, for example following periods of weather downtime (Table S 4).

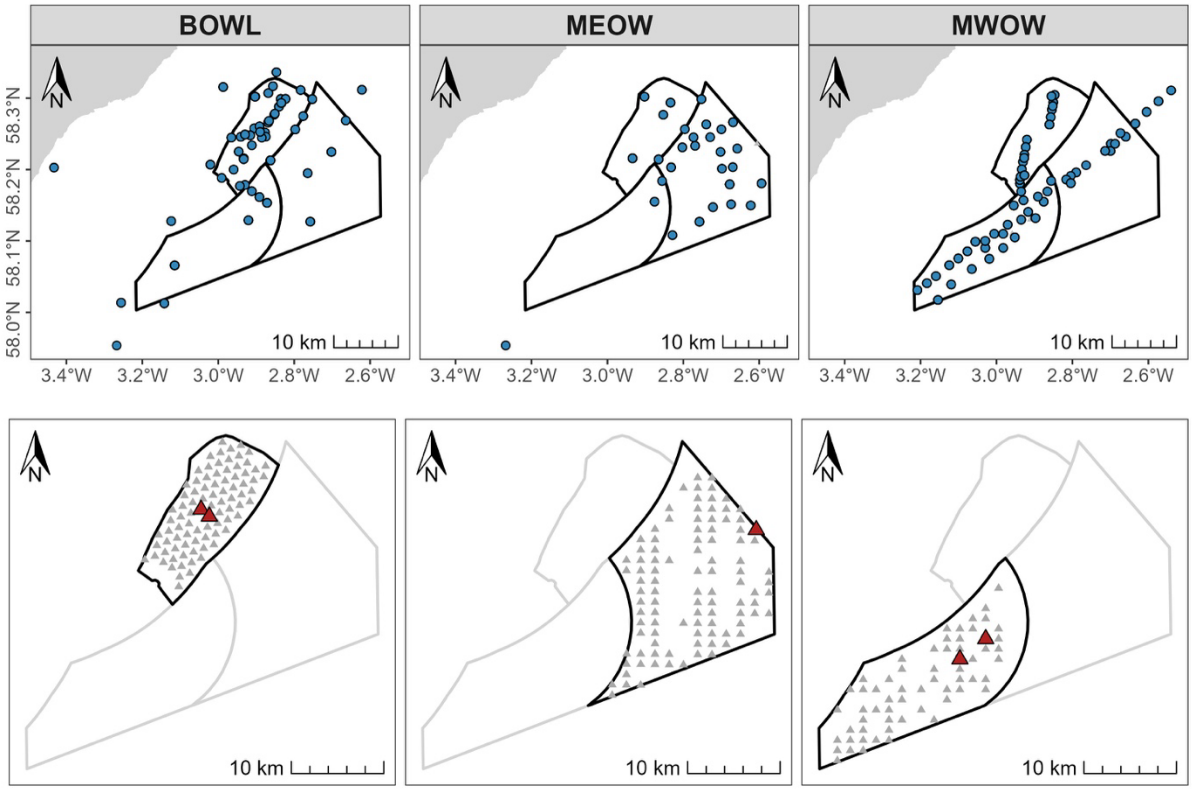

Figure 2 Maps of the three offshore wind farm developments with the Passive Acoustic Monitoring arrays deployed during pile driving campaigns at Beatrice (BOWL) in 2017, Moray East (MEOW) in 2019 and 2020 and Moray West (MWOW) in 2023. The top panels show the locations of each CPOD (blue circles). The bottom panels show the location the focal pilings events (red triangles) used for the characterisation of piling noise in relation to all other turbine locations (grey triangles).

Data from the first two piling bouts at each wind farm were selected to provide a balanced data set that reduced potential effects of variation in the number of piling events or confounding co-variates such as piling order (see Graham *et al.* 2019). Separate models were developed for distance to piling (on a logarithmic scale) and for both the predicted unweighted and Very High Frequency (VHF)-weighted received SEL_{ss} at each CPOD. The durations of both active piling within a bout and Acoustic Deterrent Device (ADD) use, as well as the maximum hammer energy and vessel intensity within 1 km buffer around CPOD site were included as co-variates if they provided significant contribution to the models. All models included a random effect that combined CPOD identity and deployment location to account for differences in click detections arising from differences in device sensitivity or site-specific environmental variation.

Following Graham et al. (2019), porpoises were initially considered to have exhibited a behavioural response to piling when the proportional decrease in occurrence compared to baseline was > 0.5. This threshold was based upon the 1st percentile of a null distribution of proportional change in occurrence (DPH) produced by randomly sampling 1,000 times from

C-POD data collected before (9 to 15 March 2017) and after (9 to 15 December 2017) the Beatrice piling campaign. This - 0.5 threshold was used to define a response for all three wind farms. The probability that porpoise occurrence at different locations responded to piling was modelled as a binomial response with a complementary log-log link function using generalized linear mixed models (GLMM) in R (Bates *et al.* 2015; R Core Team 2020).

To visualise the differences in level of porpoise response for each individual wind farm, we first ran models with either distance to source or received noise levels with an interaction with wind farm. We then ran additional models removing the *windfarm* covariate but using co-variates that best characterised differences between piling campaigns (e.g. active piling and ADD durations, maximum hammer energy), so that deterrence function or dose response relationships could be visualised irrespective of the wind farm in development. The relative performance of each model was compared using Akaike Information Criterion (AIC) (Burnham & Anderson 2002).

3 RESULTS

3.1 Characterising variation in received levels of impulsive piling noise

Measurements of received noise levels resulting from a sub-set of pile installations at each of the three wind farm sites confirmed that received levels of piling noise at any given distance were highest for the large monopiles at Moray West, and 10 to 15 dB lower for the smaller pin-piles installed at Moray East and Beatrice (Figure 3).

3.2 Changes in the occurrence of harbour porpoises in relation to piling activity

Porpoises were detected throughout all three pile installation campaigns, although the median number of detection positive hours per day varied considerably both seasonally and between each wind farm (Figure 4). Comparison of the subset of data collected within each wind farm site indicated that there was a slight reduction in the median number of hours that porpoises were detected on those days in which piling occurred compared to non-piling days at all three wind farms (Wald test: $\chi^2 = 29.5$, d.f. = 1, $p < 0.001$, Figure S2).

Data from the first two piling bouts at each site suggest that the probability of detecting a response could be explained by the distance to the piling vessel (Wald test: $\chi^2 = 15.6$, d.f. = 1, $p < 0.001$), with both the duration of active piling (Wald test: $\chi^2 = 9.97$, d.f. = 1, $p < 0.01$) and ADD use (Wald test: $\chi^2 = 12.6$, d.f. = 1, $p < 0.001$; Figure 5B). Alternatively, the probability of detecting a response could be explained by received levels of piling noise (Wald test: $\chi^2 = 13.5$ d.f. = 1, $p < 0.001$) with both the duration of active piling (Wald test: $\chi^2 = 7.76$, d.f. = 1, $p < 0.01$) and ADD use (Wald test: $\chi^2 = 8.36$, d.f. = 1, $p < 0.01$), and with the maximum hammer energy (Wald test: $\chi^2 = 7.76$, d.f. = 1, $p < 0.01$). The covariate characterising the levels of vessel intensity around monitoring sites was retained in both models but was not significant. Comparisons between models suggested the distance from piling vessel was a slightly better predictor of porpoise responses to piling than (audiogram-weighted) received levels of piling noise (Table 2).

Response functions for individual wind farms further illustrate that there is greater similarity in distance functions (Figure 5A, Table 2) compared to those for unweighted noise levels (Figure 5E, Table 2). This difference remains consistent when using VHF-weighted noise levels (Figure 5C, Table 2). At all three wind farms, responses to the first two piling bouts were stronger than those predicted when using all piling bouts that started > 72 hours after previous bouts (Figure S3, Table S4).

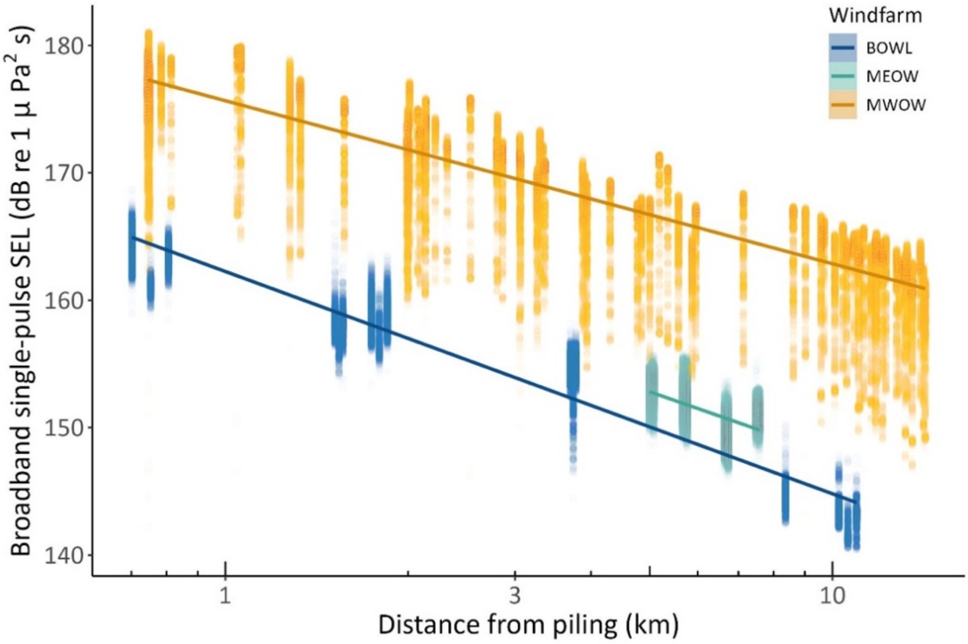

Figure 3 Variation in received single-strike sound exposure levels (SEL_{ss}) at different distances from piling during three wind farm piling campaigns, in the Moray Firth NE Scotland (Linear regression, $F_{5,466297} = 1.06 \times 10^6$, $p < 0.001$, $R^2 = 0.92$). Equations for the fitted logarithmic spreading loss for each wind farm are at Beatrice (BOWL), SELss = 162.253 - 7.578 log (Distance) (blue line); at Moray East (MEOW), SELss = 162.253 - 7.578 log (Distance) + 2.171 + 0.364 log (Distance) (green line); at Moray West (MWOW), SELss = 162.253 - 7.578 log (Distance) + 13.406 + 2.021 log (Distance) (orange line).

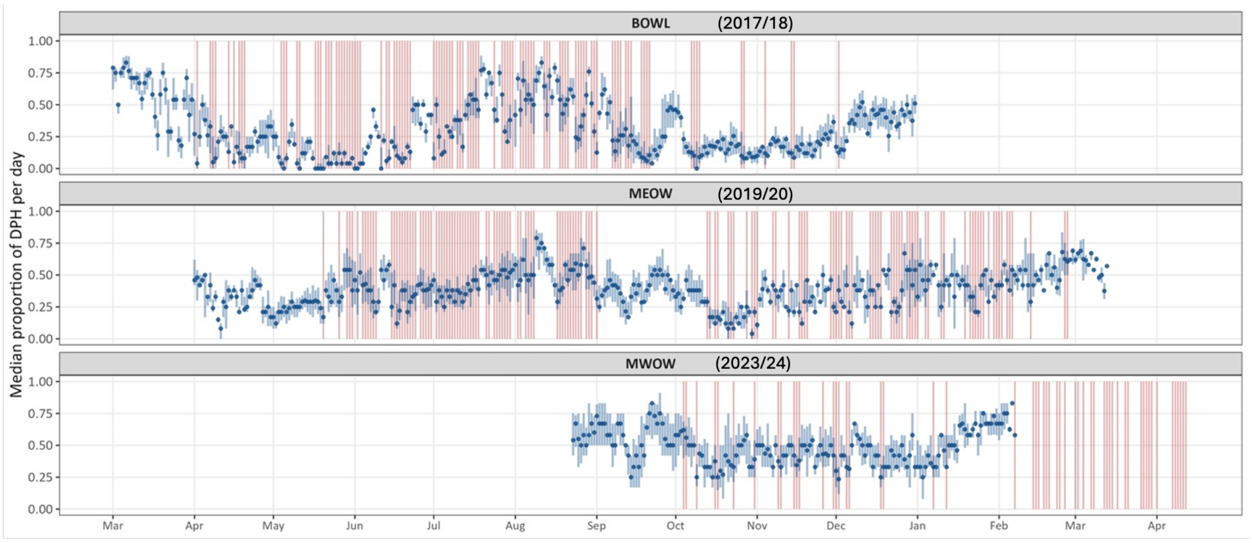

Figure 4 Variation in the median proportion of hours (DPH) per day that porpoises were detected (blue dots) throughout passive acoustic monitoring studies at Beatrice (BOWL, 2017), Moray East (MEOW, 2019 to 2020) and Moray West (MWOW, 2023 to 2024) offshore wind farms, NE Scotland. Days on which pile driving occurred are shown as vertical red bars. The interquartile range is represented with blue line.

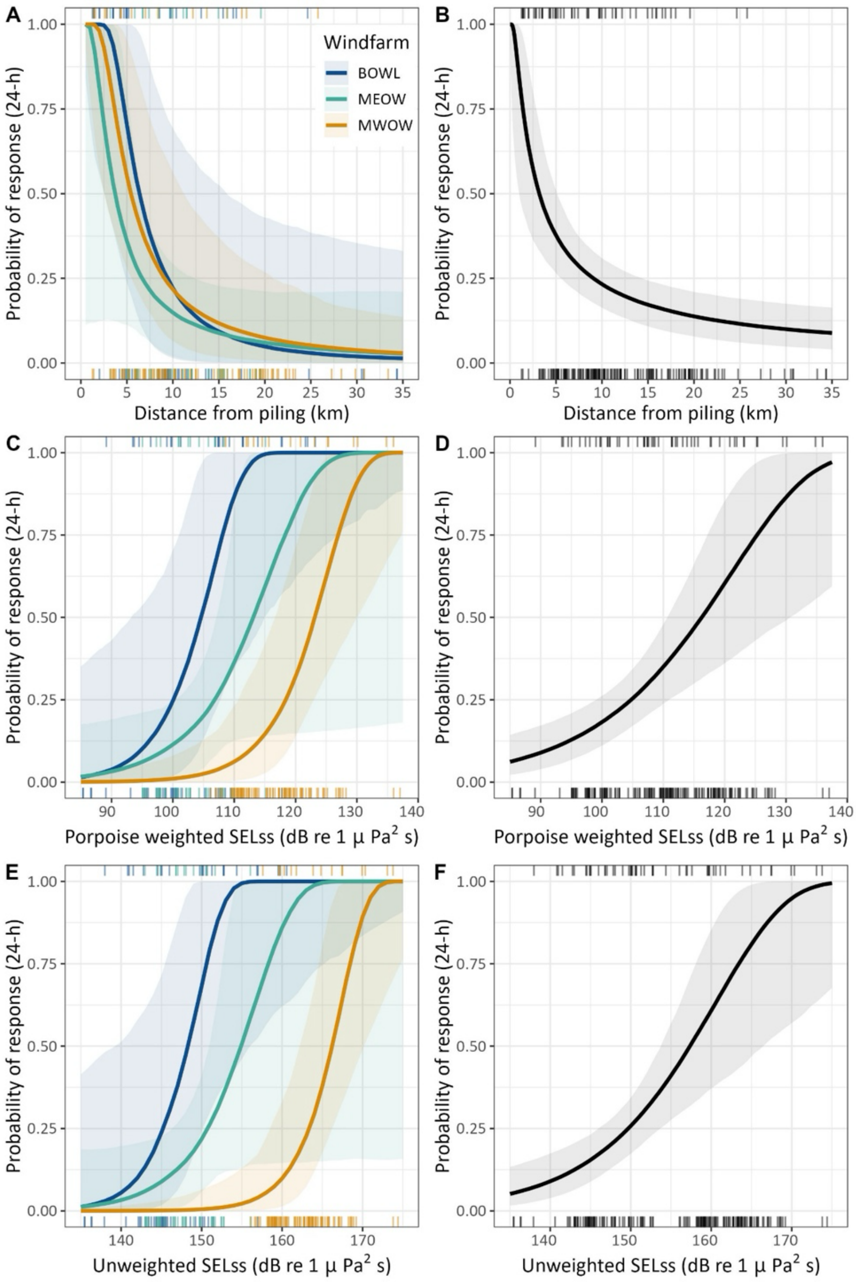

Figure 5 Variation in the probability of detecting a behavioural response following the first two bouts of pile driving at three offshore wind farms in the Moray Firth. The top panels show the general response across all three sites in relation to A-B) distance from source (deterrence function), C-D) very high frequency (VHF) audiogram-weighted received single-pulse SEL and E-F) estimated received levels of piling noise (dose-response functions). All these relationships were predicted assuming no vessels were within 1 km buffer of monitoring sites. Additionally, the panels on the left show the responses for individual wind farm sites (A, C, E) predicted assuming a median active piling duration of 4.7 h at Beatrice (BOWL), 2.8 h at Moray East (MEOW) and 2.9 h at Moray West (MWOW). The panels on the right show the general level of responses during the three piling campaigns, predicted assuming a median ADD duration of 10 mins, a median active piling duration of 3.4 h and a median maximum hammer energy of 1,356 kJ (only for D, F). Confidence intervals (shaded areas) estimated for uncertainty in fixed effects only. Rug plots show actual response data used in the analyses.

Table 2. Models of harbour porpoise behavioural response to piling at the Beatrice, Moray East and Moray West offshore wind farms, NE Scotland. Response was defined as a proportional decrease in porpoise acoustic occurrence > 0.5 in the 24-h period after piling. Generalised Linear Mixed Models with a binomial error distribution and a 'cloglog' link function were used to model these relationships. Distance from piling, both active piling and ADD use durations, maximum hammer energy, vessel activity and received noise levels were used as explanatory variables. All models included a random effect combining monitoring site identity and CPOD identity.

Models	**AIC**	**Marginal R^2**	**BIC**	**Deviance**	**df**	**Fig.**
First two piling bouts of each wind farm						
Log(distance) + active piling duration + ADD duration + no. vessels within 1 km	211.3	0.398	231.6	199.3	210	5B
Weighted SELss + active piling duration + ADD duration + max. hammer energy + no. vessels within 1 km	213.5	0.377	237.1	199.5	209	5D
SELss + active piling duration + ADD duration + max. hammer energy + no. vessels within 1 km	213.9	0.368	237.6	199.9	209	5F
All piling bouts of the three wind farms						
Log(distance) + active piling duration + max. hammer energy + no. vessels within 1 km	674.6	0.327	702.4	662.6	754	S5B
Weighted SELss + active piling duration + max. hammer energy + no. vessels within 1 km	683.9	0.314	711.7	671.9	754	S5F
SELss + active piling duration + max. hammer energy + no. vessels within 1 km	693.3	0.301	721.1	681.3	754	S5D

4 DISCUSSION

Offshore wind farms are deploying increasingly large turbines to improve the efficiency of renewable energy generation (Mehta, Zaaijer & von Terzi 2024). This requires larger foundation piles and installation hammers (ORJIP 2023), raising concerns over disturbance to marine mammals from underwater noise (Bailey, Brookes & Thompson 2014). The key aim of this study was to determine whether the extent of disturbance is best predicted by changes in received levels of underwater noise (as measured using energy-based metrics), or distance from the noise source. As expected from earlier meta-analyses of noise from foundation installation (ORJIP 2023), received levels of noise from 10 m diameter piles at Moray West were around 15 dB higher than those from < 2.5 m diameter piles at Beatrice and Moray East wind farms (Figure 3). However, contrary to expectations, disturbance responses of harbour porpoises during the initial construction of three offshore wind farms were more closely related to proximity to piling vessels than to predicted sound exposure levels (Figure 5).

This may partly be because predicted sound exposure levels were derived from empirical relationships and therefore have less certainty and predictive power than the precise measure of distance. However, there is growing evidence from other sources that suggests marine mammal responses to underwater noise levels are highly dependent upon an animals' proximity to source. This is best demonstrated through controlled exposure experiments, where focal individuals or groups have been exposed to both military sonar and air guns (Harris *et al.* 2018; Southall *et al.* 2021). Beyond 14 km, Cure *et al.* (2025) found that sperm whales were unlikely to respond to sonar irrespective of received noise levels, resulting in a 65-fold reduction in predicted impact areas. Similarly, blue whales exposed to the highest received level of mid-range sonar exhibited > 50% probability of a low-level behavioural response at 1 km, but this reduced to < 10% at 5 km (Southall *et al.* 2019a). Similar patterns were seen during controlled exposures of impulsive noise to humpback whales, where Dunlop et al. (2018) found limited responses beyond 5 km and no evidence that groups responded any more to a louder full commercial array than quieter single air guns.

Previously, experimental studies of the effects of impulsive pile driving noise on marine mammals have only been possible using playbacks in captivity (Hastie *et al.* 2021; Kastelein *et al.* 2022). Understanding how wild marine mammals respond to higher levels of impulsive noise at offshore wind farms has therefore required observational studies around commercial construction sites. Individual tracking has provided some insights into individual movements of pinnipeds around these events (Russell *et al.* 2016). However, sample sizes are typically small, and it is impossible to pre-determine the distances at which these highly mobile animals are exposed to piling noise. Consequently, most data on marine mammal responses to pile driving noise are based upon static passive acoustic monitoring at pre-determined distances from source (e.g. Brandt *et al.* 2011; Dähne *et al.* 2013; Brandt *et al.* 2018; Graham *et al.* 2019). These studies have focused on harbour porpoises, which are abundant around offshore wind farm sites in European waters (Hammond *et al.* 2013) and can be monitored cost effectively using echolocation detectors (CPODs) (Van Parijs *et al.* 2021; Todd *et al.* 2023). One disadvantage of using CPODs to characterize changes in occurrence or foraging activity is that finer-scale temporal changes in behaviour cannot usually be assessed, and individuals cannot be followed. However, responses based upon changes in acoustic detections across larger spatial and temporal scales may better represent population level change. Our study built upon earlier work that quantified changes in behaviour using data collected across a 24-h period after exposure (Graham *et al.* 2019), thereby integrating a wider range of the state-dependent responses which can complicate interpretation of finer-scale studies. In common with all PAM studies using this approach, observed changes in detection rates could result either from aversive movement or a change in vocalization rate (Van Parijs *et al.* 2009). However, this is of less concern in response studies such as ours given that changes in either movements or vocalisations represent a behavioural response to the focal disturbance event (Sarnocińska *et al.* 2020), e.g. by reducing foraging performance and consequently impacting individual energy budgets. Porpoises also have high echolocation rates, and finer-scale data from instrumented individuals demonstrates that changes in vocalization rates following a disturbance are typically < 10 mins (Wisniewska *et al.* 2018). Our main conclusions should be robust to this issue given that detection of responses was based upon data collected over a 24-hour period.

Another challenge in these observational studies has been the lack of adequate controls when assessing behavioural responses to pile driving noise. Typically, a gradient design has been used to explore variation in responses to pile installation, but impulsive noise is not the only potential stressor during these events (Dähne *et al.* 2013; Brandt *et al.* 2018; Graham *et al.* 2019). Instead, animals are responding to a cumulative exposure of several potential sources of disturbance. For example, porpoises move away from construction sites before piling starts in response to the arrival of heavy lift vessels (Benhemma-Le Gall *et al.* 2023). Furthermore, porpoise responses to acoustic deterrent devices (ADD) deployed before pile driving to reduce risk of near-field injury can extend to 5 to 10 km in the absence of piling noise (Brandt *et al.* 2013; Thompson *et al.* 2020). These confounding variables have constrained our understanding of the extent to which received levels of impulsive piling noise shape observed disturbance responses.

Here, we selected a sub-set of data from monitoring studies conducted at three adjacent wind farm sites to compare the relative effect of proximity and received noise levels on harbour porpoise responses. Simulations based upon earlier studies at the Beatrice wind farm indicated that the spatial extent and density of the array can impact the likelihood of detecting responses and the nature of response functions (Hastie *et al.* In Review, 2026). We therefore restricted the spatial extent of data to 35 km to provide a balanced comparison between sites. Deterrence functions were similar at all three wind farms, with slightly lower response levels at the most recent piling campaigns at Moray East and Moray West developments (Figure 5). These differences may simply represent sampling variation or result from slight differences in array design (Hastie *et al.* 2026). Dahne et al. (2017) also found lower response levels at the Dan Tysk offshore wind farm compared to earlier studies in other parts of the Southern North Sea. However, they attributed this to the use of bubble curtains to reduce piling noise levels at Dan Tysk because earlier studies had not used any noise abatement systems. In contrast, noise abatement was not used at any of the sites in our study, and received levels at the most recent Moray West development were highest. It is possible that response levels could decline over time due to habituation or tolerance. While there is some evidence of this within a construction season at Beatrice (Graham *et al.* 2019), it is difficult to assess the consequences of repeated sound exposure over longer periods without better information on porpoise movement patterns (Aarts *et al.* 2016). However, even with a high residency population, available data on population age-structure indicates that around half the animals present during piling at Moray West were born after Beatrice was constructed (Kesselring *et al.* 2017; Murphy *et al.* 2020). Nevertheless, it is important to recognise that porpoises in the Moray Firth and wider North Sea have been regularly exposed to a variety of impulsive noise sources over recent decades, and this may have shaped response levels during all phases of our study. Stronger responses might therefore be expected if pile driving occurs in, for example, polar areas which have not previously been exposed to similar anthropogenic noise sources (Heide-Jørgensen *et al.* 2013; Darias-O'Hara *et al.* 2025).

A slightly stronger response during the first phase of the study at Beatrice (Figure 5A) could also have resulted from other differences in pile installation processes. First, more vessels were required at Beatrice because the heavy lift vessel was anchored. Second, ADDs were generally deployed for 15 mins prior to pile driving at Beatrice, but this was reduced to 10 mins at Moray East and Moray West following studies that highlighted the extent to which ADD use might contribute to overall disturbance (Thompson *et al.* 2020). In addition, response levels may vary at different sites due to local variation in prey availability (Hastie *et al.* 2021). Understanding how these different disturbance sources shape response functions now requires a meta-analysis using data from a wider variety of wind farm sites.

4.1 Management implications

These findings have implications for both the assessment and mitigation of disturbance to marine mammals during the installation of foundation piles at offshore wind farms.

When assessing recent UK offshore wind projects, some Statutory Nature Conservation Bodies (SNCB) have recommended that developers assess behavioural disturbance using a dose-response curve based upon studies at the Beatrice offshore wind farm (NRW 2023). Those data suggested that distance to the piling vessel was a better predictor of porpoise behavioural responses than either unweighted (Graham et al. 2017) or audiogram weighted

(Graham et al. 2019) noise levels. As a result, Graham et al (2019) recommended that "*Distance proved as good a predictor of responses as audiogram-weighted received levels, presenting a more practicable variable for environmental assessments.*" Nevertheless, it was recognised that there was similar support for alternative models (see Table 1 in Graham et al. (2019), and that future developments would involve larger piles and higher noise levels. SNCBs have therefore advised developers to take a precautionary approach by estimating the number of animals disturbed by applying the Beatrice dose-response function to project-specific predictions of animal density and received noise levels.

Our findings show that responses at Moray West did not scale with received noise levels as currently assumed in regulatory assessments. Instead, data from all three developments showed a more consistent relationship with distance to piling (Figure 5). As a result, disturbance impacts based upon predicted noise levels within regulatory assessments are highly conservative. For example, assessments for Moray West predicted that > 4,500 porpoises could be disturbed by a single piling event, whereas subsequent monitoring indicated that < 100 individuals were disturbed (Thompson *et al.* 2026). More recent planning applications have involved even larger (> 15 m) foundations, requiring extrapolation further outside the range of observed data and biologically unrealistic predictions for disturbance impacts. At Muir Mhòr Offshore wind farm, for example, noise modelling predicted that unweighted SEL_{ss} levels of 135 dB could occur > 150 km from source. Recommended application of the Graham et al. (2017) dose-response function to these outputs resulted in a > 25% probability of disturbance at 150 km and estimates of > 14,000 porpoises being disturbed during a single piling event (see Figure 12-9 and Table 12-39 in Muir Mhòr Offshore Wind Farm 2024). Such extreme predictions are partly the result of Graham et al (2017) basing their dose-response function on unweighted noise levels. Most of the energy reaching these extreme distances will be in low frequencies that are outside the hearing range of porpoises (Tougaard 2025). In addition, as pile driving noise propagates away from the source, the received sound changes not only in level but also in spectral content, impulsiveness and temporal structure. These characteristics may influence how animals perceive and interpret the sound but are not captured by simple broadband energy metrics such as single-strike sound exposure level. If the fundamental driver of disturbance responses is the perceived loudness of a sound, then more realistic predictions may be expected if using audiogram weighted noise levels. However, distance remained a better predictor of disturbance responses at the three Moray Firth wind farms when using both unweighted and audiogram weighted energy-based measures of noise levels (Table 2).

While it is recognised that behavioural responses to anthropogenic noise are moderated by extrinsic and intrinsic contextual factors (Ellison *et al.* 2012; Booth *et al.* 2022), the perceived loudness of sounds has generally been considered the fundamental driver of disturbance responses (Tougaard 2025). However, experimental studies of both baleen and toothed whales found much lower (or no) responses to comparable levels of noise when animals are at a greater distance from the source (Dunlop *et al.* 2018; Southall *et al.* 2019a; Wensveen *et al.* 2025). Experimental work further indicates that behavioural responses are shaped by the animals' perception of predation risk (Miller *et al.* 2022). Thus, assessment and mitigation of impacts from pile installation may be better considered within the context of the risk-disturbance hypothesis (Frid & Dill 2002), consistent with observed cut off distances where responses ceased to be observed irrespective of received noise levels. This understanding has now been built into US guidance on the assessment of impacts from military sonar, with a cut off distances for any predicted impacts (Dunlop *et al.* 2018; Southall *et al.* 2019a; Wensveen *et al.* 2025). As seen by Dunlop et al (2019) for seismic air guns, relationships with distance to pile driving were also consistent across a range of received levels (Figure 5). We therefore suggest regulatory assessments of responses to impulsive pile driving noise are best characterised by a deterrence function that relates responses to distance from source. The extent to which remaining variation between the construction campaigns was due to differences in vessel type or mitigation procedures now deserves further investigation as this could inform best practice for reducing cumulative disturbance impacts during future construction programmes.

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SUPPLEMENTARY MATERIAL

Measurements of pile-driving noise

At Beatrice, underwater noise levels were measured using four calibrated broadband noise recorders (Soundtrap ST300HF, Ocean Instruments) moored 2 m above the seabed between 7 and 13 September 2017, during the installation of foundations at four focal locations (see Thompson et al. 2020). Three recorders were moored 50 m apart within 4 km of the piling sites and recorded for a minimum of 1 min in every 10 minutes at a 576 kHz sampling rate. The fourth recorder was moored 8 to 11 km from piling sites and recorded for 10 minutes every 30 minutes at a 96 kHz sampling rate (Figure S1B). At Moray East, underwater noise levels were measured using three calibrated broadband noise recorders (Soundtrap ST300HF, Ocean Instruments) moored 2 m above the seabed between 10 and 23 July 2019, during the installation of ten turbine foundations (Figure S1D). The three recorders were moored 50 m apart 1.4 to 7.6 km from the piling sites and recorded continuously at a 48 kHz sampling rate. At Moray West, underwater noise levels were measured using a series of deployments of calibrated broadband noise recorders (RT-SYS Sylence-LP 440 ARUs with an HT-96-MIN-210 dB hydrophone) between 5 October and 2 December 2023 (see Thompson et al. 2026; Stephenson et al 2026), during the installation of 13 monopiles (Figure S1C). Recorders were moored 8 m above the seabed, at nominal distances 0.75 and 2.0 km from each monopile and recorded continuously at a 128 kHz sample rate. In all cases, recorders were deployed for sufficiently long periods to record multiple piling events, providing data at a range of distances from source.

Recordings from Beatrice and Moray East were analysed by Cefas using a modified version of PAMGuide (Merchant *et al.* 2015; Thompson et al. 2020). Recordings from Moray West were analysed by Seiche Ltd using purpose written software to provide a standard set of measurements using metrics recommended in Robinson et al. (2014) (see Stephenson et al. 2026).

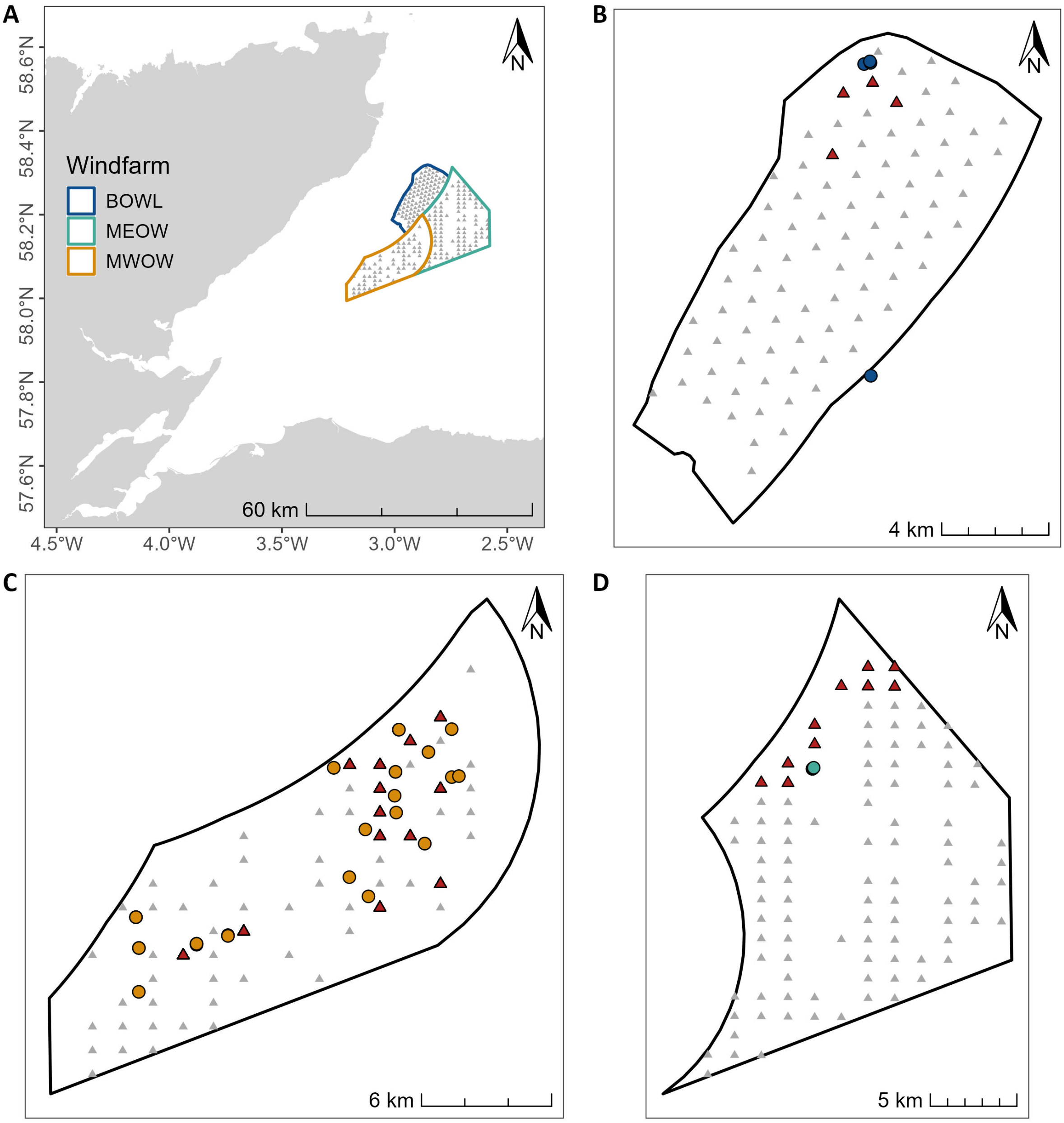


Figure S1 Locations of broadband noise recorders (circles) used to measure piling noise levels from focal piling sites (red triangles) within B) Beatrice (BOWL; blue circles), C) Moray West (MWOW; orange circles) and D) Moray East (MEOW; green circles) windfarm sites, in the outer Moray Firth, NE Scotland. Other turbine sites appear as grey triangles. Three recorders moored within Moray East and at the north of Beatrice all appear as one circle due to the scale.

Table S1 Summary of piling bout information for the Beatrice, Moray East and West offshore wind farms, NE Scotland. A piling bout was defined as a period of consecutive piling at a single location and with less than 12-h break between piling activities. The total duration of a piling bout was the difference between the end and start times of a piling bout, while the duration of active piling was the total number of minutes with piling activities. The maximum hammer energy (in kJ) recorded during each piling bout ranged between 655 and 2,299 kJ at Beatrice, between 628 and 2,071 kJ at Moray East and between 1,882 and 4,526 kJ at Moray West. Rows highlighted in grey are the piling bouts (with enough baseline period) used in the 24-h response analyses.

Wind farm	Piling bout ID	Tur-bine	Piling bout start time	Piling bout End time	Active piling duration (h)	Piling bout duration (h)	Max hammer energy (kJ)
BOWL	1	G7	02/04/2017 06:51	02/04/2017 18:20	7.1	11.48	662
BOWL	2	F8	07/04/2017 17:52	08/04/2017 01:35	5.78	7.71	951
BOWL	3	E1	09/04/2017 16:21	09/04/2017 22:47	4.78	6.43	1035
BOWL	4	E2	14/04/2017 02:38	14/04/2017 11:49	4.67	9.18	861
BOWL	5	F3	16/04/2017 14:26	16/04/2017 21:19	4.82	6.9	655
BOWL	6	E3	18/04/2017 20:49	19/04/2017 02:48	4.21	5.99	1048
BOWL	7	H6	20/04/2017 07:43	20/04/2017 14:47	4.97	7.07	766
BOWL	8	J5	04/05/2017 06:36	04/05/2017 15:45	7.05	9.15	737
BOWL	9	G6	05/05/2017 17:01	06/05/2017 01:04	6.01	8.04	1007
BOWL	10	G5	10/05/2017 07:34	10/05/2017 15:39	5.74	8.08	958
BOWL	11	F6	11/05/2017 13:10	11/05/2017 20:38	5.62	7.47	887
BOWL	12	F5	17/05/2017 01:22	17/05/2017 07:34	4.64	6.2	884
BOWL	13	E6	18/05/2017 16:09	18/05/2017 22:41	4.24	6.53	1059
BOWL	14	E5	19/05/2017 16:55	19/05/2017 21:44	3.22	4.82	954
BOWL	15	D3	21/05/2017 11:39	21/05/2017 20:05	3.77	8.42	1018
BOWL	16	C4	22/05/2017 14:59	22/05/2017 23:13	4.11	8.24	942
BOWL	17	D5	23/05/2017 20:21	23/05/2017 22:36	2.26	2.26	1130
BOWL	18	D5	25/05/2017 22:33	26/05/2017 07:00	5.27	8.45	1888
BOWL	19	G3	27/05/2017 17:36	28/05/2017 13:30	8.81	19.9	2299
BOWL	20	E8	29/05/2017 21:11	30/05/2017 03:12	3.67	6.02	1091
BOWL	21	D7	30/05/2017 22:58	31/05/2017 05:59	4.71	7.02	1035
BOWL	22	E7	01/06/2017 01:40	01/06/2017 09:09	5.1	7.49	1099
BOWL	23	D8	02/06/2017 03:06	02/06/2017 10:02	4.39	6.94	NA
BOWL	24	J8	03/06/2017 05:44	03/06/2017 09:33	2.93	3.82	1101
BOWL	25	J8	11/06/2017 11:20	11/06/2017 15:25	3.27	4.1	1209
BOWL	26	D6	13/06/2017 03:14	13/06/2017 16:55	7.07	13.69	NA
BOWL	27	C7	14/06/2017 12:51	14/06/2017 22:57	4.82	10.09	838
BOWL	28	B6	16/06/2017 07:02	16/06/2017 15:03	5.38	8.01	1560
BOWL	29	G4	17/06/2017 14:18	17/06/2017 22:08	4.02	7.83	790
BOWL	30	H4	18/06/2017 14:33	18/06/2017 23:07	5.09	8.56	2042
BOWL	31	H5	19/06/2017 20:11	20/06/2017 05:18	6.39	9.11	1186
BOWL	32	J6	20/06/2017 22:43	21/06/2017 06:42	5.53	8	818

Wind farm	Piling bout ID	Tur-bine	Piling bout start time	Piling bout End time	Active piling duration (h)	Piling bout duration (h)	Max hammer energy (kJ)
BOWL	33	D4	22/06/2017 04:21	22/06/2017 13:10	6.21	8.81	999
BOWL	34	E4	01/07/2017 13:13	02/07/2017 05:17	7.96	16.05	1408
BOWL	35	F2	03/07/2017 02:08	03/07/2017 10:50	5.96	8.69	993
BOWL	36	F4	04/07/2017 04:14	04/07/2017 12:25	5.76	8.19	1626
BOWL	37	F12	05/07/2017 13:32	05/07/2017 20:03	4	6.52	819
BOWL	38	H8	06/07/2017 14:39	06/07/2017 20:30	3.52	5.86	740
BOWL	39	G8	07/07/2017 13:35	07/07/2017 20:31	4.42	6.94	1267
BOWL	40	H7	08/07/2017 13:26	08/07/2017 21:42	4.8	8.26	1243
BOWL	41	C6	10/07/2017 00:45	10/07/2017 08:38	5.47	7.87	1082
BOWL	42	C5	11/07/2017 05:11	11/07/2017 13:51	6.35	8.66	1671
BOWL	43	B5	12/07/2017 05:02	12/07/2017 14:01	6.68	8.98	1709
BOWL	44	A5	14/07/2017 02:07	14/07/2017 09:26	5.03	7.3	NA
BOWL	45	E9	15/07/2017 05:56	15/07/2017 12:34	4.42	6.63	799
BOWL	46	D9	16/07/2017 03:44	16/07/2017 13:05	7	9.34	1272
BOWL	47	C8	17/07/2017 04:20	17/07/2017 13:37	5.98	9.28	1054
BOWL	48	B7	18/07/2017 05:19	18/07/2017 14:00	6.54	8.69	1750
BOWL	49	L8	24/07/2017 14:52	24/07/2017 22:38	5.48	7.78	1765
BOWL	50	M9	27/07/2017 15:26	27/07/2017 21:36	3.86	6.18	1805
BOWL	51	M10	28/07/2017 15:10	28/07/2017 21:13	3.82	6.05	1399
BOWL	52	L10	29/07/2017 15:14	29/07/2017 22:50	3.86	7.6	1350
BOWL	53	L9	30/07/2017 17:09	30/07/2017 23:12	3.91	6.06	1577
BOWL	54	K8	31/07/2017 16:51	31/07/2017 23:23	4.41	6.53	1704
BOWL	55	J9	03/08/2017 14:58	03/08/2017 21:41	4.64	6.73	1492
BOWL	56	K9	04/08/2017 23:54	05/08/2017 05:33	3.51	5.66	1647
BOWL	57	J7	05/08/2017 22:51	06/08/2017 06:02	3.95	7.18	1966
BOWL	58	K6	07/08/2017 00:41	07/08/2017 05:57	3.28	5.26	1360
BOWL	59	K7	07/08/2017 21:53	08/08/2017 04:02	4.01	6.16	1608
BOWL	60	L7	08/08/2017 18:36	08/08/2017 23:46	3.15	5.18	1208
BOWL	61	D11	12/08/2017 16:52	13/08/2017 01:42	6.72	8.84	1409
BOWL	62	E12	13/08/2017 17:35	14/08/2017 00:57	5.52	7.36	853
BOWL	63	G12	18/08/2017 12:13	18/08/2017 21:02	3.52	8.82	1029
BOWL	64	G11	19/08/2017 13:08	19/08/2017 20:16	4.63	7.13	965
BOWL	65	K10	20/08/2017 13:36	21/08/2017 02:09	4.35	12.56	1125
BOWL	66	K11	24/08/2017 21:57	25/08/2017 08:18	4.8	10.35	1780
BOWL	67	J11	26/08/2017 01:34	26/08/2017 08:02	4.11	6.46	1462
BOWL	68	J12	26/08/2017 23:21	27/08/2017 06:16	4.68	6.92	1684
BOWL	69	C9	28/08/2017 00:23	28/08/2017 09:29	6.87	9.09	1106
BOWL	70	D10	30/08/2017 23:49	31/08/2017 07:12	5.17	7.38	740
BOWL	71	E10	01/09/2017 00:14	01/09/2017 14:39	6.27	14.43	934
BOWL	72	F11	07/09/2017 03:27	07/09/2017 10:05	4.47	6.63	1356
BOWL	73	H12	08/09/2017 22:52	09/09/2017 06:15	5.03	7.4	993
BOWL	74	F13	10/09/2017 01:20	10/09/2017 06:26	2.92	5.1	1045

Wind farm	Piling bout ID	Tur-bine	Piling bout start time	Piling bout End time	Active piling duration (h)	Piling bout duration (h)	Max hammer energy (kJ)
BOWL	75	G13	12/09/2017 21:02	13/09/2017 04:37	4.85	7.58	1735
BOWL	76	G14	13/09/2017 22:50	14/09/2017 06:22	5.19	7.52	1936
BOWL	77	E11	18/09/2017 15:56	19/09/2017 01:07	6.18	9.18	883
BOWL	78	F10	19/09/2017 17:09	20/09/2017 00:09	4.82	7.01	1096
BOWL	79	G10	20/09/2017 16:44	20/09/2017 23:18	4.44	6.56	1117
BOWL	80	F9	21/09/2017 15:28	21/09/2017 21:41	3.94	6.21	1527
BOWL	81	H13	07/10/2017 02:48	07/10/2017 08:33	3.44	5.76	1045
BOWL	82	J13	08/10/2017 02:11	08/10/2017 08:47	4.44	6.61	1304
BOWL	83	K12	09/10/2017 01:00	09/10/2017 06:54	3.66	5.89	1049
BOWL	84	H11	10/10/2017 00:38	10/10/2017 06:19	3.63	5.69	851
BOWL	85	H10	26/10/2017 18:34	27/10/2017 02:01	4.62	7.45	753
BOWL	86	G9	04/11/2017 05:20	04/11/2017 12:51	5.29	7.52	864
BOWL	87	H9	14/11/2017 20:41	15/11/2017 03:07	4.01	6.42	657
BOWL	88	J10	02/12/2017 16:54	02/12/2017 23:39	4.45	6.75	1278
MEOW	1	K17	20/05/2019 03:30	20/05/2019 04:24	0.9	0.9	815
MEOW	2	K17	26/05/2019 07:02	26/05/2019 12:56	3.35	5.89	1234
MEOW	3	K17	29/05/2019 18:40	30/05/2019 00:28	2.01	5.79	1226
MEOW	4	K16	31/05/2019 12:47	31/05/2019 21:51	4.71	9.07	1310
MEOW	5	J17	02/06/2019 07:06	02/06/2019 16:10	5.62	9.08	1909
MEOW	6	I19	04/06/2019 18:18	05/06/2019 02:26	4.71	8.13	1241
MEOW	7	I20	06/06/2019 21:55	07/06/2019 05:12	3.93	7.28	1463
MEOW	8	H19	08/06/2019 00:54	08/06/2019 10:20	5.69	9.45	1784
MEOW	9	G19	09/06/2019 10:58	09/06/2019 18:23	4.11	7.4	1201
MEOW	10	G18	15/06/2019 04:18	15/06/2019 20:43	4.37	16.42	1199
MEOW	11	G17	16/06/2019 19:15	17/06/2019 14:30	5.32	19.25	1619
MEOW	12	H17	18/06/2019 10:03	18/06/2019 20:21	5.04	10.3	1524
MEOW	13	J18	19/06/2019 21:34	20/06/2019 05:05	4.47	7.51	1638
MEOW	14	J16	20/06/2019 22:53	21/06/2019 12:55	4.51	14.03	913
MEOW	15	H16	22/06/2019 14:52	23/06/2019 07:20	5.26	16.47	1311
MEOW	16	G16	23/06/2019 22:19	24/06/2019 15:15	4.73	16.93	909
MEOW	17	G15	26/06/2019 21:11	27/06/2019 05:38	4.59	8.44	1309
MEOW	18	H14	27/06/2019 23:47	28/06/2019 07:46	5.31	7.99	1011
MEOW	19	J14	29/06/2019 19:11	30/06/2019 10:16	5.08	15.09	1027
MEOW	20	J13	02/07/2019 00:16	02/07/2019 07:33	4.49	7.3	836
MEOW	21	H13	03/07/2019 20:04	04/07/2019 03:00	4.2	6.94	993
MEOW	22	G13	05/07/2019 02:33	05/07/2019 10:36	4.59	8.06	1065
MEOW	23	E14	06/07/2019 22:05	07/07/2019 04:05	4.12	6.02	1402
MEOW	24	C14	07/07/2019 20:47	08/07/2019 02:12	3.67	5.41	1419
MEOW	25	B14	09/07/2019 03:04	09/07/2019 08:20	3.74	5.27	1409
MEOW	26	C15	10/07/2019 00:27	10/07/2019 06:01	3.42	5.57	1123
MEOW	27	D16	11/07/2019 07:04	11/07/2019 12:19	3.55	5.26	1033
MEOW	28	C16	12/07/2019 02:15	12/07/2019 07:29	3.58	5.23	1201

Wind farm	Piling bout ID	Turbine	Piling bout start time	Piling bout End time	Active piling duration (h)	Piling bout duration (h)	Max hammer energy (kJ)
MEOW	29	D17	13/07/2019 02:00	13/07/2019 06:45	3.49	4.76	1217
MEOW	30	E18	13/07/2019 23:06	14/07/2019 06:02	3.91	6.93	1434
MEOW	31	E19	15/07/2019 00:52	15/07/2019 07:42	4.24	6.83	1508
MEOW	32	F21	15/07/2019 20:14	16/07/2019 01:03	3.41	4.81	1523
MEOW	33	G22	16/07/2019 23:07	17/07/2019 03:53	3.06	4.78	1215
MEOW	34	H22	17/07/2019 23:52	18/07/2019 06:35	5.32	6.72	1748
MEOW	35	H21	21/07/2019 04:27	21/07/2019 09:50	3.76	5.38	1411
MEOW	36	G21	22/07/2019 16:04	22/07/2019 22:05	4.42	6.01	1429
MEOW	37	H20	24/07/2019 00:39	24/07/2019 05:36	3.83	4.96	1012
MEOW	38	L12	25/07/2019 00:03	25/07/2019 04:49	3.8	4.77	1102
MEOW	39	L11	26/07/2019 15:54	26/07/2019 20:41	3.7	4.78	1222
MEOW	40	L09	27/07/2019 14:16	27/07/2019 19:01	3.49	4.76	925
MEOW	41	K10	28/07/2019 18:26	29/07/2019 00:04	3.91	5.63	1426
MEOW	42	K11	29/07/2019 15:19	29/07/2019 19:51	3.15	4.53	728
MEOW	43	J10	30/07/2019 12:33	30/07/2019 17:53	4.35	5.33	988
MEOW	44	J10	02/08/2019 15:48	02/08/2019 16:08	0.33	0.33	1016
MEOW	45	J10	03/08/2019 20:59	03/08/2019 21:18	0.33	0.33	1754
MEOW	46	H09	05/08/2019 03:36	05/08/2019 14:45	3.59	11.16	1124
MEOW	47	G09	06/08/2019 03:26	06/08/2019 15:06	4.04	11.68	1933
MEOW	48	G09	07/08/2019 08:49	07/08/2019 11:05	2	2.26	2071
MEOW	49	H18	08/08/2019 05:30	08/08/2019 10:56	4.2	5.42	1371
MEOW	50	I18	17/08/2019 00:39	17/08/2019 05:49	3.97	5.16	1194
MEOW	51	G10	17/08/2019 21:03	18/08/2019 02:39	4.44	5.6	1901
MEOW	52	F15	19/08/2019 02:52	19/08/2019 06:47	2.73	3.91	1420
MEOW	53	A01	20/08/2019 03:19	20/08/2019 07:24	3.08	4.09	1014
MEOW	54	I10	21/08/2019 05:54	21/08/2019 12:23	4.32	6.49	1066
MEOW	55	E06	22/08/2019 05:27	22/08/2019 14:22	4.88	8.93	1394
MEOW	56	E06	23/08/2019 02:37	23/08/2019 06:03	2.41	3.43	1955
MEOW	57	J08	24/08/2019 02:45	24/08/2019 10:58	3.86	8.21	939
MEOW	58	J07	24/08/2019 22:38	25/08/2019 03:26	3.34	4.8	1360
MEOW	59	G07	26/08/2019 07:04	26/08/2019 10:36	2.54	3.52	1555
MEOW	60	G07	28/08/2019 13:09	28/08/2019 18:10	3.66	5.01	2045
MEOW	61	F08	29/08/2019 09:13	29/08/2019 19:13	4.73	10	1660
MEOW	62	C05	30/08/2019 11:44	30/08/2019 16:04	2.58	4.32	917
MEOW	63	B04	01/09/2019 10:22	01/09/2019 14:20	2.89	3.98	1032
MEOW	64	A02	13/10/2019 12:13	13/10/2019 16:44	3.28	4.52	1307
MEOW	65	B05	14/10/2019 08:26	14/10/2019 13:36	3.91	5.17	1408
MEOW	66	C07	16/10/2019 23:40	17/10/2019 04:49	4.19	5.16	1201
MEOW	67	C09	17/10/2019 15:02	17/10/2019 20:09	3.85	5.1	1291
MEOW	68	C04	21/10/2019 05:19	21/10/2019 13:37	2.92	8.29	826
MEOW	69	I06	22/10/2019 18:44	23/10/2019 07:13	3.6	12.48	1325
MEOW	70	C10	28/10/2019 04:13	28/10/2019 09:10	3.14	4.96	973

Wind farm	Piling bout ID	Tur-bine	Piling bout start time	Piling bout End time	Active piling duration (h)	Piling bout duration (h)	Max hammer energy (kJ)
MEOW	71	C11	30/10/2019 03:09	30/10/2019 07:32	3.39	4.39	1526
MEOW	72	C12	31/10/2019 10:23	31/10/2019 14:32	3.28	4.15	1027
MEOW	73	B13	01/11/2019 03:42	01/11/2019 08:37	4.01	4.92	1522
MEOW	74	C02	07/11/2019 08:17	07/11/2019 11:42	2.51	3.42	925
MEOW	75	C02	08/11/2019 07:20	08/11/2019 09:24	1.21	2.07	1211
MEOW	76	D15	13/11/2019 16:47	13/11/2019 20:51	3.15	4.07	1061
MEOW	77	E04	17/11/2019 09:39	17/11/2019 14:22	3.22	4.72	973
MEOW	78	E05	18/11/2019 08:40	18/11/2019 19:05	4.18	10.42	985
MEOW	79	B03	19/11/2019 17:55	20/11/2019 00:52	3.5	6.95	1065
MEOW	80	H05	29/11/2019 19:55	30/11/2019 00:29	3.61	4.58	821
MEOW	81	G05	30/11/2019 21:45	30/11/2019 22:45	1	1	930
MEOW	82	G05	01/12/2019 12:37	01/12/2019 16:38	2.9	4.03	1044
MEOW	83	B02	02/12/2019 11:31	02/12/2019 16:50	4.41	5.31	1309
MEOW	84	D10	03/12/2019 18:27	03/12/2019 22:56	3.61	4.5	1224
MEOW	85	D13	05/12/2019 21:22	06/12/2019 02:37	4.23	5.24	1165
MEOW	86	D09	07/12/2019 02:13	07/12/2019 06:06	2.98	3.89	942
MEOW	87	D08	07/12/2019 16:59	07/12/2019 21:38	3.53	4.64	1472
MEOW	88	D06	14/12/2019 21:49	15/12/2019 01:45	3.01	3.94	628
MEOW	89	D05	16/12/2019 18:26	16/12/2019 22:36	3.16	4.17	1154
MEOW	90	H08	17/12/2019 21:41	18/12/2019 11:38	3.66	13.96	1441
MEOW	91	H11	22/12/2019 05:22	22/12/2019 20:35	5.06	15.22	1919
MEOW	92	G08	23/12/2019 15:34	23/12/2019 20:35	3.95	5.03	1825
MEOW	93	H07	24/12/2019 07:30	24/12/2019 11:59	3.55	4.49	1026
MEOW	94	H06	25/12/2019 03:33	25/12/2019 08:31	4.01	4.97	1626
MEOW	95	I07	25/12/2019 19:08	26/12/2019 00:24	4.38	5.26	1841
MEOW	96	K09	28/12/2019 19:43	28/12/2019 23:06	2.85	3.38	1404
MEOW	97	K09	29/12/2019 14:34	29/12/2019 15:54	1.33	1.33	1715
MEOW	98	L13	30/12/2019 05:05	30/12/2019 09:51	3.62	4.75	1739
MEOW	99	H10	31/12/2019 07:40	31/12/2019 12:53	3.5	5.21	1760
MEOW	100	G11	31/12/2019 23:57	01/01/2020 02:18	1.57	2.36	1419
MEOW	101	G11	04/01/2020 20:57	05/01/2020 00:02	2.25	3.08	1913
MEOW	102	G06	10/01/2020 09:13	10/01/2020 12:09	2.03	2.94	1104
MEOW	103	G06	11/01/2020 19:33	11/01/2020 21:41	1.12	2.13	1428
MEOW	104	C13	19/01/2020 00:30	19/01/2020 10:33	4.01	10.05	1466
MEOW	105	C13	21/01/2020 01:03	21/01/2020 01:55	0.86	0.86	1810
MEOW	106	D07	21/01/2020 19:54	22/01/2020 00:47	4.14	4.89	1299
MEOW	107	C08	22/01/2020 17:29	22/01/2020 21:49	3.51	4.34	1218
MEOW	108	D11	23/01/2020 23:59	24/01/2020 17:47	4.21	17.8	1685
MEOW	109	D04	25/01/2020 18:50	26/01/2020 09:52	5.23	15.03	1844
MEOW	110	F04	28/01/2020 06:32	28/01/2020 15:40	3.28	9.13	1620
MEOW	111	D12	30/01/2020 01:00	30/01/2020 04:13	1.69	3.21	1187
MEOW	112	D12	31/01/2020 10:11	31/01/2020 12:59	1.55	2.81	1839

Wind farm	Piling bout ID	Tur-bine	Piling bout start time	Piling bout End time	Active piling duration (h)	Piling bout duration (h)	Max hammer energy (kJ)
MEOW	113	D14	01/02/2020 18:54	02/02/2020 03:43	3.41	8.81	1513
MEOW	114	J09	04/02/2020 19:27	05/02/2020 10:46	4.63	15.31	1665
MEOW	115	J12	05/02/2020 23:21	06/02/2020 08:57	2.72	9.6	1028
MEOW	116	G20	13/02/2020 00:42	13/02/2020 09:04	2.77	8.37	1228
MEOW	117	J19	26/02/2020 08:55	27/02/2020 01:46	3.53	16.85	1919
MWOW	1	N13	04/10/2023 23:38	05/10/2023 12:18	4.24	12.68	3700
MWOW	2	L11	09/10/2023 17:28	09/10/2023 20:26	2.98	2.98	3768
MWOW	3	L13	16/10/2023 21:48	17/10/2023 00:45	2.95	2.95	4016
MWOW	4	M15	17/10/2023 13:30	17/10/2023 16:25	2.92	2.92	3562
MWOW	5	N16	23/10/2023 13:22	23/10/2023 15:53	2.35	2.52	2280
MWOW	6	M11	31/10/2023 18:43	31/10/2023 22:32	3.41	3.82	4526
MWOW	7	N09	09/11/2023 01:41	09/11/2023 03:56	2.05	2.25	3210
MWOW	8	L12	10/11/2023 02:13	10/11/2023 04:02	1.81	1.81	3820
MWOW	9	L08	15/11/2023 22:03	16/11/2023 00:18	2.24	2.24	4155
MWOW	10	E06	16/11/2023 21:02	16/11/2023 22:31	1.47	1.47	4257
MWOW	11	K14	17/11/2023 19:27	17/11/2023 22:07	2.67	2.67	4277
MWOW	12	P13	26/11/2023 13:53	26/11/2023 16:08	2.25	2.25	4295
MWOW	13	N12	30/11/2023 10:47	30/11/2023 12:45	1.95	1.95	3521
MWOW	14	L14	01/12/2023 13:28	01/12/2023 16:08	2.67	2.67	4228
MWOW	15	G07	02/12/2023 14:45	02/12/2023 16:32	1.78	1.78	4249
MWOW	16	P11	05/12/2023 11:27	05/12/2023 13:45	1.91	2.3	3334
MWOW	17	P14	06/12/2023 08:08	06/12/2023 10:58	2.83	2.83	4265
MWOW	18	N08	18/12/2023 23:00	19/12/2023 02:03	2.86	3.04	1882

Table S2 Summary of the number of piling sites, broadband noise recording sites and piling noise measurements used to investigate the variation in received noise levels at different distances from a subset of piling sites at the Beatrice, Moray East and Moray West offshore wind farms, NE Scotland.

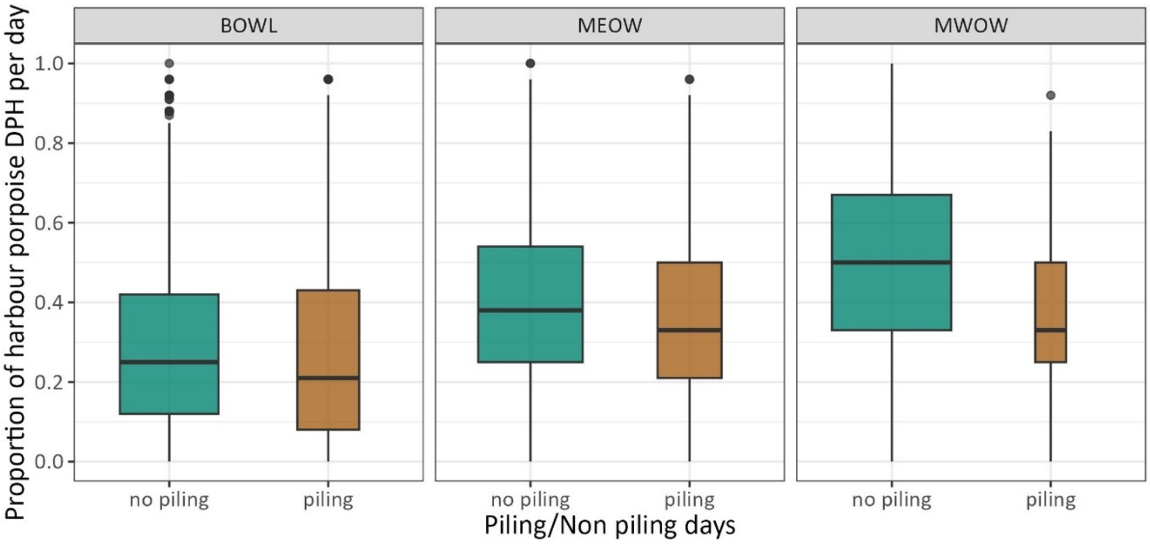
Wind farm	Piling locations	Broadband noise recorder Locations	Sample size
Beatrice	4	4	44,615
Moray East	10	3	184,079
Moray West	13	18	335,975
Total	**27**	**25**	**564,669**

Table S3 Distance between each broadband noise recorder (PAM site ID) and a subset of piling sites (Turbine ID) at the Beatrice, Moray East and Moray West offshore wind farms, NE Scotland.

Wind farm	Turbine ID	PAM site ID	Distance from piling (km)
BOWL	F11	164	8.371
BOWL	F11	201	3.703
BOWL	F11	202	3.741
BOWL	F11	203	3.779
BOWL	F13	164	10.604
BOWL	F13	201	1.515
BOWL	F13	202	1.539
BOWL	F13	203	1.561
BOWL	G13	164	10.957
BOWL	G13	201	0.702
BOWL	G13	202	0.753
BOWL	G13	203	0.806
BOWL	H12	164	10.247
BOWL	H12	201	1.740
BOWL	H12	202	1.793
BOWL	H12	203	1.848
MEOW	F21	247	5.079
MEOW	F21	248	5.045
MEOW	F21	249	4.993
MEOW	G21	247	5.765
MEOW	G21	248	5.728
MEOW	G21	249	5.669
MEOW	G22	247	6.730
MEOW	G22	248	6.694
MEOW	G22	249	6.637
MEOW	H21	247	6.743
MEOW	H21	248	6.705
MEOW	H21	249	6.644
MEOW	H22	247	7.582
MEOW	H22	248	7.545
MEOW	H22	249	7.484
MWOW	E06	ARU 10	2.075
MWOW	E06	ARU11	2.808
MWOW	E06	ARU12	0.814
MWOW	E06	ARU14b	11.098

Wind farm	Turbine ID	PAM site ID	Distance from piling (km)
MWOW	G07	ARU 10b	5.187
MWOW	G07	ARU 11b	5.356
MWOW	G07	ARU 12b	2.533
MWOW	G07	ARU 13b	1.047
MWOW	G07	ARU 17	12.089
MWOW	G07	ARU 18	11.776
MWOW	K14	ARU 10	12.879
MWOW	K14	ARU 11	12.106
MWOW	K14	ARU 12	10.862
MWOW	K14	ARU 13	9.682
MWOW	K14	ARU 14b	0.746
MWOW	L08	ARU 10	11.779
MWOW	L08	ARU 11	11.263
MWOW	L08	ARU 12	8.620
MWOW	L08	ARU 13	7.129
MWOW	L08	ARU 15	0.746
MWOW	L08	ARU 16	1.999
MWOW	L11	ARU 1	0.745
MWOW	L11	ARU 2	1.996
MWOW	L11	ARU 4	1.330
MWOW	L11	ARU 5	3.063
MWOW	L11	ARU 6	5.001
MWOW	L11	ARU 7	5.954
MWOW	L11	ARU 9	2.092
MWOW	L12	ARU 10	12.754
MWOW	L12	ARU 11	12.247
MWOW	L12	ARU 12	10.403
MWOW	L12	ARU 13	9.030
MWOW	L12	ARU 15	3.906
MWOW	L12	ARU 16	3.299
MWOW	L12	ARU 4	0.748
MWOW	L12	ARU 5	2.012
MWOW	L13	ARU 1	1.994
MWOW	L13	ARU 2	0.748
MWOW	L13	ARU 4	1.328
MWOW	L13	ARU 5	1.060
MWOW	L13	ARU 6	2.862
MWOW	L13	ARU 7	4.303
MWOW	L13	ARU 9	3.267

Wind farm	Turbine ID	PAM site ID	Distance from piling (km)
MWOW	L14	ARU 10b	13.963
MWOW	L14	ARU 11b	13.267
MWOW	L14	ARU 12b	11.818
MWOW	L14	ARU 13b	10.554
MWOW	L14	ARU 14b	2.134
MWOW	L14	ARU 5b	0.784
MWOW	M11	ARU 10	13.532
MWOW	M11	ARU 11	13.189
MWOW	M11	ARU 12	11.030
MWOW	M11	ARU 13	9.579
MWOW	M11	ARU 4	1.277
MWOW	M11	ARU 5	3.056
MWOW	M11	ARU 9	0.747
MWOW	M15	ARU 4	3.358
MWOW	M15	ARU 5	1.570
MWOW	M15	ARU 6	0.748
MWOW	M15	ARU 7	1.992
MWOW	M15	ARU 9	4.776
MWOW	N09	ARU 10	14.218
MWOW	N09	ARU 11	14.129
MWOW	N09	ARU 12	11.583
MWOW	N09	ARU 13	10.090
MWOW	N09	ARU 4	3.879
MWOW	N09	ARU 5	5.576
MWOW	N09	ARU 9	2.000
MWOW	N13	ARU 1	3.940
MWOW	N13	ARU 2	2.138
MWOW	N13	ARU 3	0.750
MWOW	N13	ARU 4	2.319
MWOW	N13	ARU 5	2.217
MWOW	N13	ARU 6	3.338
MWOW	N13	ARU 7	2.801
MWOW	N16	ARU 4	4.845
MWOW	N16	ARU 5	3.259
MWOW	N16	ARU 6	2.005
MWOW	N16	ARU 7	0.750
MWOW	N16	ARU 9	5.872



BOWL: 2017-04-01 to 2017-12-04; MEOW: 2019-05-01 to 2020-03-01; MWOW: 2023-08-23 to 2024-02-06

Figure S2 Median (and interquartile range) proportions of harbour porpoise hourly acoustic detections per day during piling and non-piling days at the Beatrice (BOWL), Moray East (MEOW) and Moray West (MWOW) offshore wind farms, NE Scotland, between April 2017 and February 2024. Days with at least 12 h of monitoring were included in the dataset. Piling days are defined as days with at least 25% of hours monitored with piling activities [3-18 h]. Outliers are represented with the black dots.

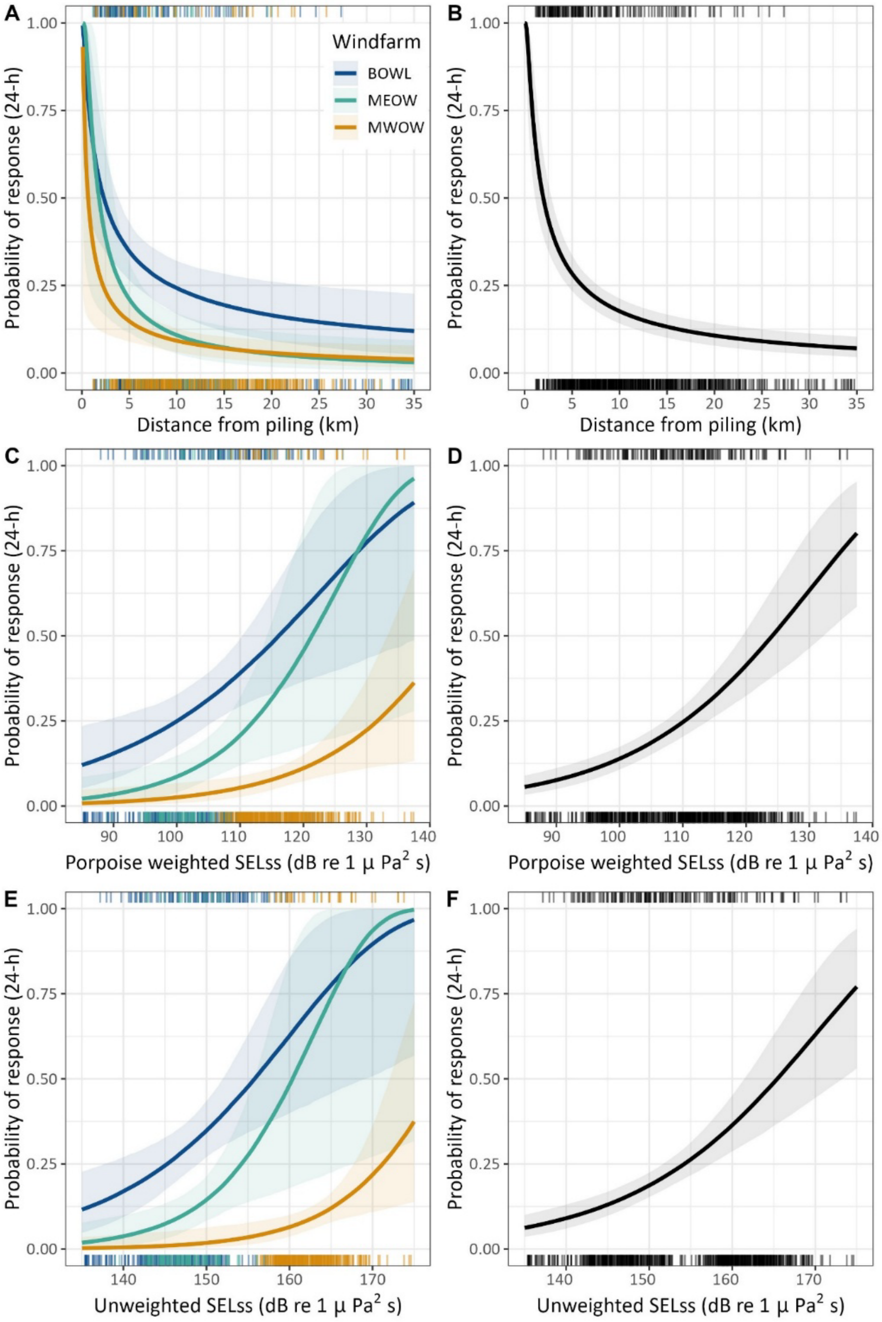


Figure S 3 Variation in the probability of detecting a behavioural response following cessation of piling for *__all piling bouts__* *at three offshore wind farms in the Moray Firth. These panels show the general response across all three sites in relation to A-B) distance from source, C-D) very high frequency (VHF) audiogram-weighted received single-pulse SEL and E-F) estimated received levels of piling noise. All these relationships were predicted assuming no vessels were within 1 km buffer of monitoring sites. Additionally, the panels on the left show the responses for individual wind farm sites (A, C, E) predicted assuming a median active piling duration of 4.7 h at Beatrice (BOWL), 2.8 h at Moray East (MEOW) and 2.9 h at Moray West (MWOW). The panels on the right show the general level of responses during the three piling campaigns, predicted assuming a median maximum hammer energy of 1,356 kJ and a median active piling duration of 3.4 h. Confidence intervals (shaded areas) estimated for uncertainty in fixed effects only. Rug plots show actual response data used in the analyses.*

Table S 4 Summary of the sample size, covariates used in the Generalised Linear Mixed Models (GLMMs), parameters, R50 or D50 values. R50 is the mean distance and D50 is the mean (un)weighted SELss at which there is a 50% probability of harbour porpoise responding to piling at the Beatrice (BOWL), Moray East (MEOW) and Moray West (MWOW) offshore wind farms, NE Scotland. A covariate combining the CPOD identity and monitoring site identity was included as a random effect in the GLMMs.

Wind farm	**N piling bouts**	**Covariates used in GLMMs**	**Values used for predictions**	**R50** (km)
BOWL	2	Log(distance) * active piling duration * wind farm + no. vessels within 1 km	wind farm = BOWL active piling duration = 4.7 h no vessels	6.5
MEOW	2		wind farm = MEOW active piling duration = 2.8 h no vessels	4
MWOW	2		wind farm = MWOW active piling duration = 2.9 h no vessels	5.5
All three	6	Log(distance) + active piling duration + ADD duration + no. vessels within 1 km	active piling duration = 3.4 h ADD duration = 10 mins no vessels	3.2
BOWL	12	Log(distance) * active piling duration * wind farm + no. vessels within 1 km	wind farm = BOWL active piling duration = 4.7 h no vessels	2.4
MEOW	12		wind farm = MEOW active piling duration = 2.8 h no vessels	1.9
MWOW	7		wind farm = MWOW active piling duration = 2.9 h no vessels	0.7
All three	31	Log(distance) + active piling duration + max. hammer energy + no. vessels within 1 km	active piling duration = 3.4 h Max hammer energy = 1356 kJ no vessels	2

Wind farm	**N piling bouts**	**Covariates used in GLMMs**	**Values used for predictions**	**D50** (dB re 1 μ Pa^2 s)
BOWL	2	SELss * active piling duration * wind farm + no. vessels within 1 km	wind farm = BOWL active piling duration = 4.7 h no vessels	148.5
MEOW	2		wind farm = MEOW active piling duration = 2.8 h no vessels	155
MWOW	2		wind farm = MWOW active piling duration = 2.9 h no vessels	166.5
All three	6	SELss + active piling duration + ADD duration + max. hammer energy + no. vessels within 1 km	active piling duration = 3.4 h ADD duration = 10 mins Max hammer energy = 1356 kJ no vessels	157.5
BOWL	12	SELss * active piling duration * wind farm + no. vessels within 1 km	wind farm = BOWL active piling duration = 4.7 h no vessels	155.8

Wind farm	N piling bouts	Covariates used in GLMMs	Values used for predictions	D50 (dB re 1 µ Pa^2 s)
MEOW	12		wind farm = MEOW active piling duration = 2.8 h no vessels	160.4
MWOW	7		wind farm = MWOW active piling duration = 2.9 h no vessels	NA
All three	31	SELss + active piling duration + max. hammer energy + no. vessels within 1 km	active piling duration = 3.4 h Max hammer energy = 1356 kJ no vessels	165.5
BOWL	2	Weighted SELss * active piling duration * wind farm + no. vessels within 1 km	wind farm = BOWL active piling duration = 4.7 h no vessels	105
MEOW	2		wind farm = MEOW active piling duration = 2.8 h no vessels	113.5
MWOW	2		wind farm = MWOW active piling duration = 2.9 h no vessels	123.5
All three	6	Weighted SELss + active piling duration + ADD duration + max. hammer energy + no. vessels within 1 km	active piling duration = 3.4 h ADD duration = 10 mins Max hammer energy = 1356 kJ no vessels	116.5
BOWL	12	Weighted SELss * active piling duration * wind farm + no. vessels within 1 km	wind farm = BOWL active piling duration = 4.7 h no vessels	116.2
MEOW	12		wind farm = MEOW active piling duration = 2.8 h no vessels	121.4
MWOW	7		wind farm = MWOW active piling duration = 2.9 h no vessels	NA
All three	31	Weighted SELss + active piling duration + max. hammer energy + no. vessels within 1 km	active piling duration = 3.4 h Max hammer energy = 1356 kJ no vessels	124.5