PrePARED Report No. 004

Harbour porpoise responses to the installation of XXL monopiles without noise abatement; implications for noise management in the Southern North Sea

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Harbour porpoise responses to the installation of XXL monopiles without noise abatement; implications for noise management in the Southern North Sea

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August 2024

Recommended Citation

Benhemma-Le Gall, A., Hastie, G.D., Brown, A.M., Booth, C.G., Graham, I.M., Fernandez-Betelu, O., Iorio-Merlo, V., Bashford, R., Swanson, H., Cheney, B.J., Abad Oliva, N. & Thompson, P.M. (2024). Harbour porpoise responses to the installation of XXL monopiles without noise abatement; implications for noise management in the Southern North Sea. PrePARED Report, No. 004. August 2024.

Summary

- This report presents the results of PrePARED research that builds upon consent-monitoring undertaken during the installation of monopile foundations at Ocean Winds' Moray West Offshore Wind Farm in 2023. No noise abatement systems were required by regulators for this project, providing an important opportunity to use these data to support management in UK waters.

- The management of impulsive noise in the Southern North Sea Special Area of Conservation (SNS SAC) for harbour porpoises uses time-area thresholds to limit the number of days on which activities producing impulsive noise are permitted. Licencing of these activities is underpinned by Effective Deterrent Ranges (EDR), which are used to assess the spatial scale of disturbance from different noise sources.

- There are no direct estimates of an EDR for monopiles which are being installed without noise abatement systems. Instead, the current EDR for installation of monopile foundations is 26 km, based on early data from pin-piling. More recent data and reviews of the source of this figure highlight that this estimate of EDR is conservative. Reducing this conservatism and associated uncertainty over disturbance from installation of large monopiles would ease management constraints that risk delaying delivery of offshore wind in and around the SNS SAC.

- Data on harbour porpoise detections were collected from a broad-scale array of 60 echolocation detectors (CPODs) moored up to 33.4 km from the pile-driving vessel. Analyses focussed on the installation of seven XXL (9.5 m and 10.0 m diameter) monopiles where responses in the 24 h after piling could be compared with a matched period three days before piling started.

- We used the approach previously used to characterise porpoise responses to piling at the Beatrice Offshore Wind Farm, which informed the EDR used in the SNS SAC for pin pile installation. Despite noise levels for the installation of XXL monopiles being much higher, the response of porpoises to monopile installation at Moray West was similar to that observed in studies of pin-piling at Beatrice. The resulting proxy deterrence function indicates that an EDR based on these new data for monopiles would be 9.4 km.

- Comparison of these results with previous studies highlights the need for broader investigation of existing data and approaches to explore how other factors such as seasonal variation in foraging patterns, vessel traffic, use of acoustic deterrent devices and differences in experimental design shape the magnitude of observed response to different piling noise levels. In the meantime, we suggest that our estimated EDR of < 10 km provides a strong case for reducing the current 26 km EDR for monopiles.

1. Introduction

Offshore wind developments are expected to play a critical role in meeting climate targets. At the same time, delivery of these projects must be balanced against the need to minimise impacts on protected marine wildlife populations. There is consensus that disturbance of marine mammals from pile-driving noise represents a key impact that should be assessed and mitigated when delivering renewable energy projects. However, the approaches taken to manage this trade-off varies between regulators, both internationally and within the UK.

Work packages within the PrePARED project will reduce uncertainties in the frameworks used to assess impacts of impulsive pile-driving noise on marine mammal populations. This research builds upon consent monitoring undertaken at offshore windfarm sites within the Moray Firth, NE Scotland, particularly during the 2023 installation of XXL (9.5 m and 10.0 m diameter) monopile foundations in Ocean Winds' Moray West development. PrePARED studies were designed in response to licencing approaches being used in Scottish waters, where regulators and their statutory advisors have required Environmental Impact Assessments (EIA) to use dose-response relationships to estimate how many individual marine mammals may be disturbed during foundation installation. These data are then used in frameworks such as iPCoD (King et al. 2015) to assess any population consequences of this disturbance. For all protected cetaceans, current advice to Scottish developers is to undertake marine mammal assessments using a dose-response relationship based upon harbour porpoise responses to noise from pin-pile installation at the Beatrice Offshore Windfarm (Graham et al. 2019). PrePARED is extending this earlier work to explore how dose-response relationships vary in relation to habitat type, prey fields and different noise sources.

In addition, PrePARED has been exploring how these emerging data can be analysed and disseminated to maximise their relevance to regulators and developers in other UK waters. Here, managing the trade-off between development and disturbance to marine mammals has been especially problematic within the Southern North Sea (SNS) Special Area of Conservation (SAC) for harbour porpoises. Not only are the porpoises that use this area exposed to impulsive noise from the construction of multiple offshore windfarm developments, but they may also be disturbed by impulsive noise from oil and gas exploration and unexploded ordnance (UXO) clearance.

In contrast to the approach used by Scottish regulators, the management of impulsive noise within the SNS SAC uses a habitat-based approach (JNCC 2020). Regulators must therefore assess and permit all activities that generate impulsive noise to limit the number of days within a given year, or season, in which porpoises may be disturbed over an agreed proportion of the area protected under the SNS SAC. This assessment and licencing process is underpinned by Effective Deterrence Ranges (EDR), which define the spatial extent of disturbance from each of the different noise sources. Current guidance on recommended EDRs is outlined in Table 2 of JNCC

(2020). These vary from 5 km for certain types of geophysical surveys up to 26 km for monopile installation and UXO clearance without noise abatement.

Current recommendations for EDRs in the SNS SAC are based upon available data from just a few studies that have been conducted in German (Dähne et al. 2013; Dähne et al. 2017), Danish (Sarnocińska et al. 2020), Scottish (Graham et al. 2019; Thompson et al. 2013) and US (Crocker and Fratantonio 2016; MacGillivray 2018) waters.

Given the limited evidence base on disturbance ranges, the JNCC guidance highlights the need to incorporate lessons learned from impact and compliance monitoring. In a review for DEFRA on the use of time-area thresholds for managing porpoise SACs, Brown et al. (2023) highlighted the lack of a common definition of EDR among existing studies and the complexity of understanding differences in responses due to variable data collection, analysis and reporting approaches. Brown et al. (2023) recommended a meta-analysis of existing porpoise response data, including the application of a standard approach to estimating EDR corresponding to average habitat loss. The first stage of a planned multi-year project to undertake this work has recently been commissioned by Ørsted in support of efforts to discharge post-consent monitoring conditions on the Hornsea Three project. Additionally, JNCC are currently commissioning an updated review of the recommended EDR's in the light of emerging data and some of the recommendations made in Brown et al. (2023), with anticipated delivery in 2025.

In the meantime, there is concern that delivery of offshore wind projects in the SNS SAC will remain constrained by the recommended EDR (26 km) for pile-driving monopile foundations. This initial EDR was developed by Tougaard et al. (2013), based on published data from studies during pin piling at Germany's first offshore windfarm – Alpha Ventus (Dähne et al. 2013). However, as detailed in Brown et al.'s (2023) review, this EDR is likely to be an overestimate as analyses did not account for high levels of seasonality in porpoise occurrence over the four-year construction period.

Here, we present new data on the responses of porpoises to disturbance during the piling of XXL monopiles that were installed at the Moray West Offshore Windfarm without noise abatement systems. This is anticipated to represent the upper extreme for pile driving noise when using current technology. Planned work within PrePARED will explore these responses in relation to detailed characterisation of received noise levels. This report aims to provide rapid access to new data on disturbance ranges in response to installation of large unabated monopiles. This can then be fed into the decision-making and development of guidance underpinning delivery of offshore wind projects in UK waters.

2. Methods

2.1 General approach

The study was carried out between 1 September and 31 December 2023, during a one-month baseline period and the first three months of foundation installation at the Moray West Offshore Windfarm. Our general approach followed that used in Graham et al.'s (2019) study at the Beatrice Offshore Windfarm, where an array of echolocation detectors was used to assess responses of porpoises to piling events along a gradient of distances from the piling vessel. Like Graham et al. (2019), our analyses focus on a subset of piling events where there were sufficient periods before and after piling to compare responses with a temporally matched baseline. Further details of the construction timelines, passive acoustic monitoring techniques and statistical modelling of data are provided below.

2.2 Moray West construction

The Moray West Offshore Windfarm is located 22 km offshore in the outer Moray Firth, NE Scotland, adjacent to the Beatrice and Moray East Offshore Windfarms (Figure 1). The installation of the 62 Moray West monopiles started on 4 October 2023 and finished on 13 April 2024. Our study was conducted during the first three months of this campaign, during which 18 monopiles were installed during 20 days on which there was some piling activity. There were sufficient gaps in piling activity for responses in the 24 h after piling to be compared with a matched period three days before piling at seven of these locations. Information on each of the 18 piling events highlighting which of the seven locations were used in our analysis is presented in Table S 1.

Monopiles of 9.5 -10.0 m diameter and 74 - 92 m in length were installed through pre-installed scour pads using a 4,400 kJ hydraulic impact hammer (MENCK MHU 4400) deployed from a dynamically positioned (DP) heavy lift vessel (Bokalift 2 [IMO: 9190705]). At four of the 18 locations, piles were first driven to intermediate depths using a vibro-hammer before the impact hammer was used to achieve the final target depth. However, no locations which involved the use of vibro-hammers were included in statistical models due to an insufficient baseline period before these events.

Average durations of active impulse piling at the 18 locations were 2.5 h (range: 1.5 - 4.3 h) and those at the seven focal locations were 2.8 h (range 1.8 - 4.3 h). These periods were sometimes interspersed with breaks in piling due to weather or technical downtime, but all breaks were < 8 h. Following Benhemma-Le Gall et al. (2023), we defined a piling bout as a period of continuous piling at a single location (either vibro- or impact piling) where any break in piling was < 12 h. The average duration of piling bouts at both the 18 locations and the seven focal locations was 4.2 h (range: 2.0 – 12.7 h).

Agreed mitigation measures during monopile installation required the use of an ADD for 10 mins, followed by a 15-min soft start procedure with a maximum hammer energy of 432 kJ (see Thompson et al. 2020). Hammer energy was then ramped up gradually to maintain a steady pile penetration rate (Moray Offshore Windfarm (West) Limited 2023). If any breaks in piling exceeded 6 h, an ADD was again deployed for 10 mins before resuming impulse piling. At those sites where there was a period of vibro-piling prior to impact piling, no ADD was required. No noise abatement systems (see Verfuss et al. 2019) were used in this piling campaign.

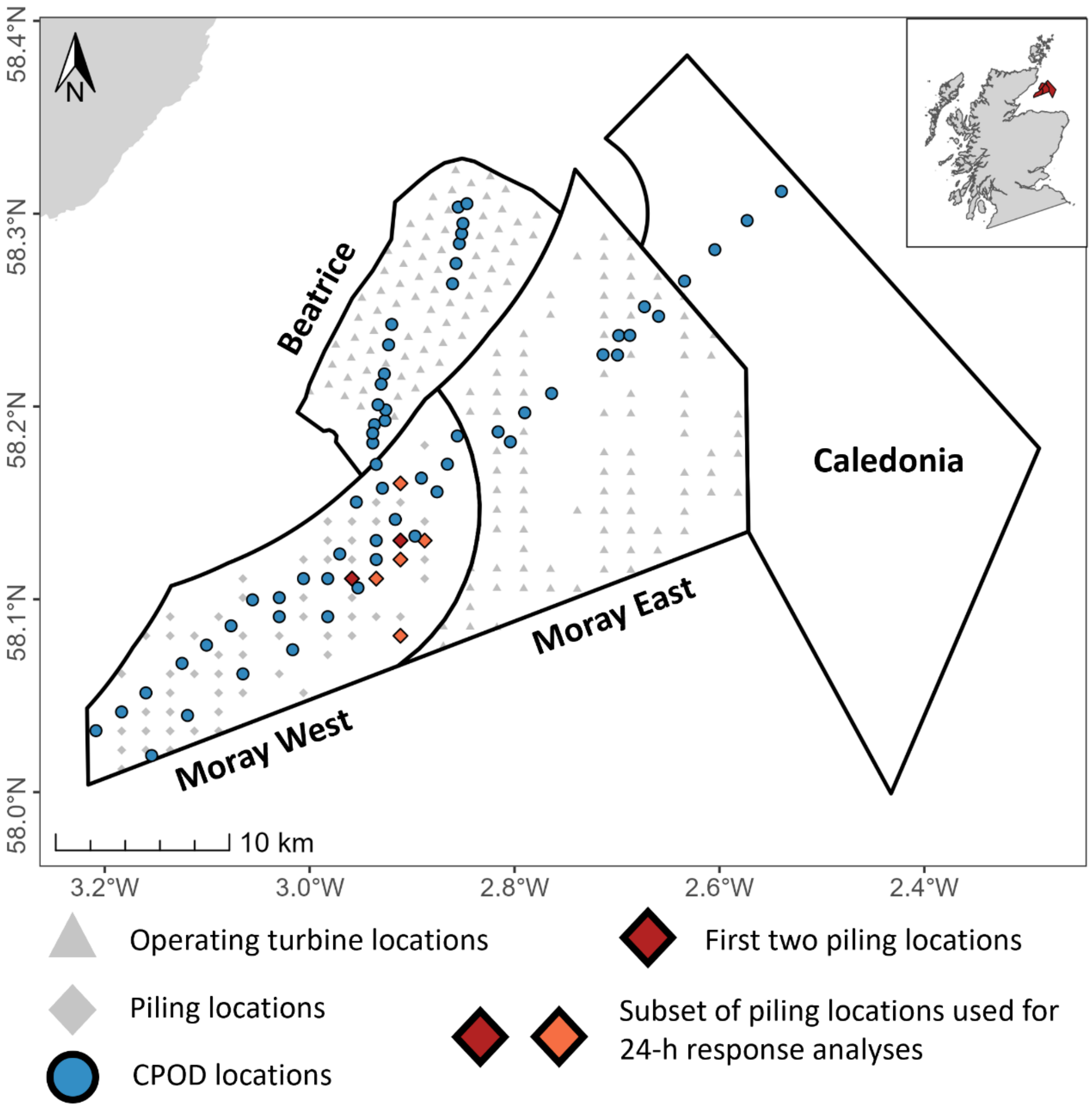

Figure 1 Study area showing the Moray West (under construction), Beatrice and Moray East (operating) and Caledonia (in planning) offshore windfarms in the outer Moray Firth, NE Scotland. The piling locations at Moray West are represented by diamonds (Coloured diamonds are the piling locations used in the analyses, other piling sites appear as smaller grey diamonds). The operating turbine locations at Beatrice and Moray East are represented by grey triangles. The Passive Acoustic Monitoring array (CPODs) used to monitor harbour porpoise acoustic occurrence is represented by blue circles.

2.3 Passive Acoustic Monitoring

Between 1 September and 31 December 2023, an array of 60 moored echolocation click detectors (V.1 CPODs, Chelonia Limited) was deployed across an area that included the Moray West construction site (29 CPODs) and adjacent offshore windfarms that were either operational (Beatrice (17 CPODs) and Moray East (10 CPODs)) or in planning (Caledonia (4 CPODs)) (Figure 1).

Devices were recovered during January - March 2024. At recovery, it was discovered that some moorings had drifted by up to 1.34 km from their deployment locations during severe storms that occurred during the winter of 2023/24. The local impact of the first and largest of these, Storm Babet, started on 18 October. For subsequent spatial analyses, we assume that data recorded before 18 October were collected while CPODs were in their "as laid" position, and data recorded after 20 October were collected at their "as recovered" location.

Data were downloaded from CPODs and processed using the manufacturer's software (CPOD.exe, v.2.044) to identify and extract high and moderate quality Narrow Band High Frequency echolocation click trains emitted by harbour porpoises. For each CPOD, the total number of unfiltered clicks and the number of porpoise click trains were summarised per hour. High levels of background noise at construction sites can saturate CPOD memory and consequently reduce CPOD detection probability (Clausen et al. 2019; Wilson et al. 2013). Following the approach used by Benhemma-Le Gall et al. (2023), data from any CPODs within < 1 km of piling events were discarded from the analyses (n = 3). Additionally, we checked whether the memory was saturated in each one-minute sample and excluded data from CPODs where >1% of minutes during the response period were saturated (i.e. 14 mins for a 24-h response).

Following the methodology described in Graham et al. (2019) and Thompson et al. (2020), we estimated a proxy deterrence function curve by modelling changes in harbour porpoise occurrence after piling in relation to distance from pile-driving activities. Harbour porpoises were considered to have exhibited a behavioural response when the proportional decrease in occurrence compared to baseline was greater than 0.5. This 0.5 threshold was used to create a binary response variable describing the presence or absence of response within a 24-h response period. Whilst our previous studies have explored using other response periods (e.g. 6-h or 12-h), here we focus on the 24-h response given the daily timescale used by JNCC to manage time-area thresholds in English waters.

For each selected piling bout and CPOD, changes in porpoise occurrence in the 24-h period from the end of piling were compared with a baseline period of the same duration that started 48 h prior to the start of the piling bout (for further details on defining response and baseline periods, see Figure 3 in Graham et al. (2019)). To ensure baseline periods were relatively undisturbed, our analyses focussed on the seven piling bouts where piling started after a gap in piling of at least three days. Similarly, these seven selected bouts required a 24-h gap after the end of piling.

Based upon the assumed dates for mooring drift and the criteria used to exclude data, CPOD data on porpoise responses were available from sites located between 1.0 and 33.4 km from the focal subset of seven piling bouts. Of these, the data from the first two piling bouts, prior to Storm Babet, are least likely to be prone to location errors.

2.4 Explanatory covariates

The primary covariate of interest in this analysis is the distance between a CPOD and the piling vessel. However, based on earlier work, we also considered the possibility that piling bout duration, exposure to recent piling events (i.e. those during the Moray West construction period), and the presence of other vessels may influence the deterrence function.

Distance from piling was calculated using the Moray West turbine locations and both the "as laid" and "as recovered" CPOD locations, using the *distVincentyEllipsoid* from the *geosphere* R package (Hijmans 2022). This covariate was included in the model on a logarithmic scale.

To account for the variation in response to piling over time or the duration of piling bouts (Graham et al. 2019), *piling order,* defined as the cumulative number of piling bouts, and *Piling bout duration* were standardised and included in the model.

Finally, vessel-related metrics were included to account for potential disturbance (Benhemma-Le Gall et al. 2021) during both the baseline and response periods. Automated Identification System (AIS) vessel-tracking data from the region were sourced for 2023 from Anatec Ltd. (www.anatec.com). To estimate the level of vessel traffic and residency within a 1 km buffer around each CPOD location, individual vessel tracks were first created over an area representing a 10 km buffer around the PAM array. AIS data were then interpolated at 1-min resolution for each individual vessel track and the total number of interpolated and transmitted AIS positions within 1 km of each CPOD during the baseline and response periods used as the vessel covariates.

All covariates (beside the *distance from piling* covariate) were standardised by subtracting the mean, for each observed value of the covariate, and dividing by the standard deviation.

2.5 Modelling

Porpoise deterrence function curves were estimated for a 24-h response period for the first two piling bouts (before storm Babet) and the subset of seven piling bouts that occurred between October and December 2023 and had sufficient baseline to assess responses.

The presence or absence of any porpoise response to piling was fitted with a binomial distribution and a *cloglog* link function (based on the lowest Akaike Information Criterion (AIC) (Burnham and Anderson 2002)), using Generalized Linear Mixed Models (GLMM Bolker et al. (2009)) and the R package *lme4* (Bates et al. 2015; R Core Team 2022). All models included a random factor that combined the CPOD identifier and deployment location identifier to control for variation in device sensitivity or any site-specific environmental differences.

To identify which covariates to include in the final models, the automated model selection function *dredge* from the R package *MuMIn* (Bartoń 2023) was used to rank the models with different combinations of fixed effect terms. The best fitted models were selected based on the lowest corrected AIC (AICc). To assess the significance of fixed effect terms and their interactions, a sequential analysis of deviance table (Type III Wald chi-squared tests) was computed using the *Anova* function of the R package *car* (Fox and Weisberg 2019). Model validation involved checking for autocorrelation in the model residuals, using *acf* and *pacf* functions (R Core Team 2022), and conducting residuals diagnostics (i.e. uniformity, dispersion tests) with the DHARMa package (Hartig 2020). For each model, the response variable was predicted along a *distance from piling* gradient between 1 and 35 km. A model-based parametric bootstrap of 1,000 simulations was performed using the *bootMer* function of the *lme4* package (Bates et al. 2015) to estimate the mean response and the uncertainty in fixed effects only (based on 2.5% and 97.5% quantiles; 95% confidence interval, CI).

2.6 Effective Deterrence Range

The estimation of porpoise EDR from the unabated impact pile-driving of monopile foundations was based on Tougaard et al. (2013), who defined the EDR as the average temporary habitat loss per individual (see sections 3. and 3.3.1 in Brown et al. 2023). Due, for example, to individual differences in tolerance to noise (Bejder et al. 2009) or behavioural context (Ellison et al. 2012), the level of response to a particular piling event is likely to vary both between and within animals. Consequently, some animals may not exhibit any behavioural responses within an ensonified area, and thus would lose less of their habitat than the population average. Others may react at greater distances and thus would lose more of their habitat. The EDR is essentially the range at which the number of animals exhibiting a response to piling beyond that distance equals the number of animals not responding within that distance (Tyack and Thomas 2019).

To estimate the EDR, we used the deterrence function obtained from the analyses of the 24-h porpoise response to unabated monopile installation. We assumed that harbour porpoise density distribution was uniform across the study area, and that the deterrence area was a circle. Following the method described in Tyack and Thomas (2019), we first derived the probability of response in different distance bands from the deterrence function. Given our assumptions about porpoise density, we then estimated the expected number of animals responding to piling in the area within each of the 50 m distance bands from 1 km to 35 km around the piling event. Finally, for each distance band, we calculated both the cumulative number of animals responding outside the radius and the cumulative number of animals within the radius that did not respond. The distance band at which these two numbers were equal was identified as the EDR.

3. Results

3.1 Broad-scale patterns of occurrence

Detections by the 29 CPODs located within the Moray West construction site demonstrate that harbour porpoises were present throughout the study period. Despite fluctuations in the median proportion of porpoise detection positive hours per day (range: 0.15 – 0.88), there was no evidence of a large-scale temporal trend in occurrence resulting from the foundation piling that occurred on 20 days between October and December 2023 (Figure 2).

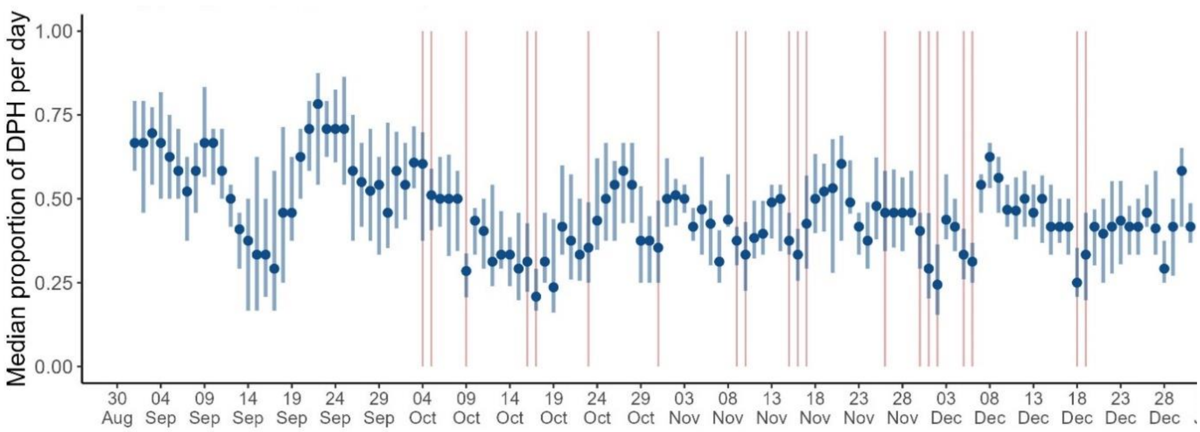

Figure 2 Variation in the daily occurrence of harbour porpoises within the Moray West offshore windfarm construction site between October and December 2023. Data are presented as median proportions of Detection Positive Hours (DPH) per day (± interquartile range) for the 29 CPODs deployed within the site. Red bars indicate the 20 days on which piling occurred.

3.2 Short-term responses to piling events

The response of harbour porpoises over the 24-h following piling events was best explained by the interaction between distance from piling, on a logarithmic scale, and piling duration (Table 1). This was the case both for the first two piling events and the full subset of 7 piling events, although the response to the full subset was weaker. In both cases, porpoise responses decreased with increased distance from piling, and the level of response varied with piling bout duration. Whilst piling duration was selected over piling order, it should be noted that the first piling event was 25% longer than any others, and this is likely to have constrained our power to discriminate between the influence of piling duration and piling order.

Given the stronger response for the first two piling events, and the greater certainty over mooring locations prior to Storm Babet, our results focus here on these two events to provide a conservative estimate of deterrence function (Figure 3) and the resulting EDR. Results for the subset of seven piling events are summarised for comparison and presented in more detail within the supplementary materials (Figure S 1B).

Figure 3 presents the deterrence function for the first two piling events, standardised for the median piling bout duration of 3 h. Based on this relationship, the probability of harbour porpoises responding to piling in the 24-h period after piling was ≥ 50% at distances up to 5 km (95% CI = 2.8 – 7.2). For the subset of 7 piling events, the response was ≥ 50% at distances up to 1.2 km, with an upper 95% CI of 2.5 (Figure S 1B). Given predictions were made on the *distance from piling* range used for the models (i.e. 1 to 35 km) the lower confidence interval could not be calculated for the subset of 7 piling events.

Table 1 Modelled relationships of harbour porpoise behavioural response to piling. Porpoise response to piling was defined as a proportional decrease in porpoise occurrence > 0.5 in the 24-h period after piling. Generalised Linear Mixed Models with a binomial distribution and *cloglog* link function were used to model porpoise response to piling. The explanatory variables selected in the 24-h response models were the distance from piling (km) and piling bout duration (h). All models had a random effect that included the CPOD sampling location combined with the CPOD identifier. R^2 is a marginal R^2, calculated using the *rsquared* function of the piecewiseSEM R package (Lefcheck 2016).

Model	Estimate	Std. error	*z* - *value*	*P*	*R^2*
1. First two piling events					
24-h response ~ log(distance) * duration					**0.35**
(Intercept)	-2.398	1.824	-1.315	0.189	
log(distance) : duration	**1.433**	**0.647**	**2.215**	**0.027**	
log(distance)	0.005	0.684	0.007	0.995	
piling bout duration	-4.125	1.718	-2.401	0.016	
2. Subset of seven piling events					
24-h response ~ log(distance) * duration					**0.15**
(Intercept)	-1.160	0.691	-1.678	0.093	
log(distance) : duration	**0.879**	**0.432**	**2.034**	**0.042**	
log(distance)	-0.507	0.280	-1.810	0.070	
piling bout duration	-2.430	1.177	-2.064	0.039	

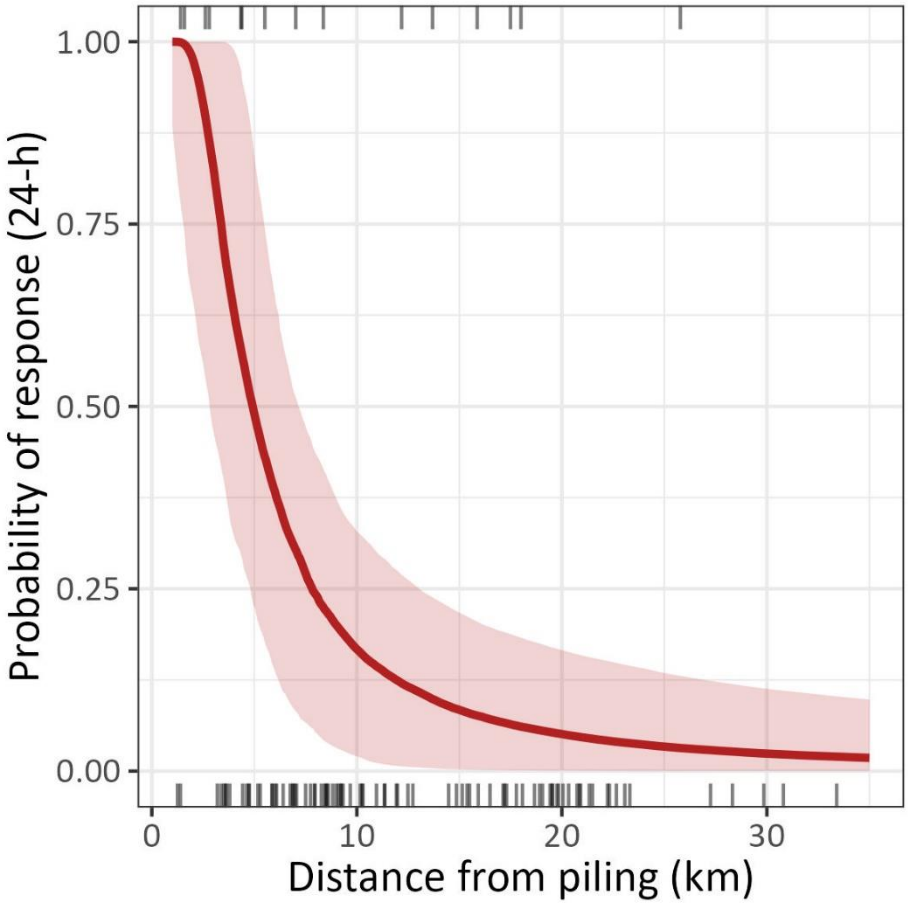

Figure 3 The probability of 24-h harbour porpoise response in relation to the partial contribution of distance from piling at the first two piling events (N13 & L11) (solid red line) at Moray West offshore windfarm, assuming a 3-h piling duration. Confidence intervals (shaded areas) estimated for uncertainty in fixed effects only. Rug plots show actual response data for the first two piling events (black). The estimated response at the extreme of our array is 0.018 and subsequent estimates of EDR assume that this drops to 0.0 beyond 35 km.

3.3 Effective Deterrence Range

Figure 4 presents the cumulative numbers of animals responding and not responding to piling in different distance bands, as based on the deterrence function presented in Figure 3.

Based on these data for a 24-h response after piling the first two monopiles at Moray West, the EDR for piling monopiles with no noise abatement was estimated to be 9.4 km. For comparison, the deterrence function in Figure 3 predicts that there is an 18.6% probability of (24-h) response (CI: 2.7-35.1%) at this distance.

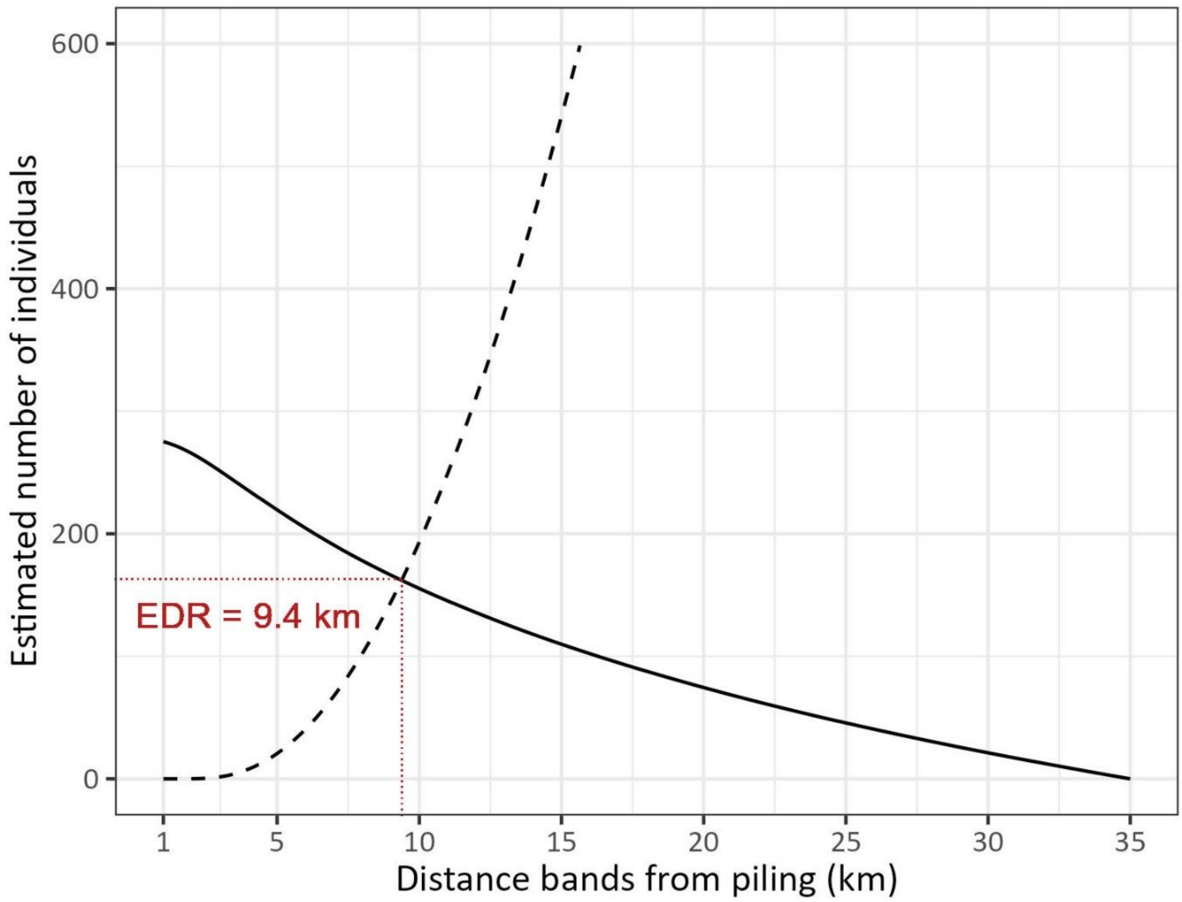

Figure 4 Variation in the estimated numbers of porpoises likely to respond and likely not to respond to piling in relation to distance from piling. Solid line is the number of individuals that respond outside each distance band. Dashed line is the number of animals within the distance band that did not respond. Data are based on the deterrence function for the first two piling events in Figure 3, and an assumed uniform density of one porpoise per km^2. The resulting EDR for monopile installation is based on the point where these two lines cross. Methodology and R code adapted from Tyack and Thomas (2019).

4. Discussion

Over the last decade, passive acoustic monitoring using CPOD echolocation click detectors has become an established and widely used technique for assessing responses of harbour porpoises to a range of anthropogenic stressors (e.g. Brandt et al. 2018; Sarnocińska et al. 2020; Thompson et al. 2013; Todd et al. 2009). Acoustic techniques such as these have their limitations compared to studies of individual behavioural responses using telemetry, but they have been critical to our understanding of harbour porpoise behaviour around offshore windfarm sites given that opportunities to track individuals of this species are rare. Here, we build upon an extensive body of work around North Sea windfarm sites by providing the first direct estimates of porpoise responses to the installation of large diameter monopiles in the absence of any noise abatement measures.

4.1 Scale of response of harbour porpoises to monopile installation

Our studies around monopile installation extend previous research in the Moray Firth which used the same approach to assess responses to seismic surveys (Thompson et al. 2013), pile driving of pin piles (Graham et al. 2019), ADD use (Thompson et al. 2020) and vessel activity during both windfarm construction (Benhemma-Le Gall et al. 2023) and oil and gas decommissioning (Fernandez-Betelu et al. 2024). As seen in these previous studies, particularly during the longer periods of oil and gas exploration and windfarm construction, there was no evidence of broad-scale displacement following the start of construction at Moray West in early October 2023, in which there was intermittent piling activity on 20 of 89 days (Figure 2).

At a finer scale, the level of response to pile driving at Moray West (Figure 3) was similar to that previously observed during the installation of pin piles (Graham et al. 2019). This was unexpected given that noise levels from Moray West's monopile installations, using hammer energies of up to 4,400 kJ, were anticipated to be higher and elicit stronger responses than those observed during installation of smaller pin piles using maximum hammer energies of 2,500 kJ. Emerging results from Moray West's consent monitoring of piling noise indicate that received SEL_{SS} levels at 750 m from the first two piling events were 179 dB re 1µPa^{2}s (Ocean Winds Unpublished Data). This is in line with predicted noise levels for a 9.5 m diameter monopile (see Figure 6 in Verfuss et al. 2023) and considerably louder than noise levels experienced by porpoises during both seismic surveys and pin pile installation. Whilst unexpected, as highlighted by Sarnocińska et al. (2020), it is important to remember that there is still uncertainty over the drivers of animal responses to impulsive noise. For example, response levels may be related to particular noise characteristics (Tougaard et al. 2015) which in turn will vary depending upon a species' hearing characteristics (Southall et al. 2019). Alternatively, response levels could simply be related to an individual's perception of the distance to a source, or whether that source is static or moving towards that individual (Sarnocińska et al. 2020). Disentangling these drivers requires direct experiment or comparison across a broader range of source levels in otherwise similar conditions. An immediate next step within PrePARED is to explore this question by integrating data on porpoise responses and piling noise that have been collected during foundation installation at the three Moray Firth windfarms. In future, these data from the Moray Firth will also be available for projects aiming to integrate data from other North Sea sites to explore this question in more detail, such any planned meta-analyses.

Our results further highlight the need to consider other factors when drawing comparison between different response studies. These include contextual factors such as seasonal changes in prey availability or competitors that may influence responses (Ellison et al. 2012; Gomez et al. 2016). The extent of previous exposure to similar anthropogenic noise may also result in different levels of tolerance or habituation that moderate responses to noise (e.g. Graham et al. 2019). Finally, we recognise that differences in construction methodologies, approaches to mitigation and the experimental design of the studies themselves may all constrain comparison of the results of different response studies.

The response of porpoises to the installation of Moray West monopiles appeared comparable to previous studies (see for example Figure S 1). Analyses integrating similar data from a broader range of windfarm sites are now required to explore how responses vary in relation to different confounding factors. For example, previous studies during the installation of pin piles at Beatrice Offshore Wind Farm suggested that responses declined through the April – December construction period (Graham et al. 2019). However, this pattern is potentially confounded with season, and we recognise that the installation of the first monopile at Moray West occurred in the autumn, when responses at Beatrice were also lower. Investigation of the role of seasonality and baseline porpoise densities will therefore be an important factor to consider in larger comparative analyses.

As highlighted in previous PAM studies of responses to piling (Dähne et al. 2013; Graham et al. 2019), when comparing a response in the period after piling to an earlier baseline, this represents a cumulative response to both piling noise and other disturbance sources associated with pile installation, such as vessel activity or ADDs used to mitigate injury. Given that the range of vessel types used for pile driving include anchored vessels, jack-up vessels and DP heavy lift vessels, this alone is likely to contribute to some of the variation in observed responses.

Understanding how different types of vessels and vessel behaviour moderate disturbance events represents an important area for further work, as this uncertainty currently constrains assessments of the costs and benefits of alternative mitigation measures. For example, some noise abatement systems require additional DP vessels to remain at construction sites for extended periods, thereby increasing continuous noise as a by-product of efforts to reduce impulsive noise. Furthermore, a range of other regulatory measures and operational considerations have resulted in variation in the use of ADDs as a mitigation tool around pile-driving vessels.

Many of the pile-driving events at Alpha Ventus (where Dahne et al. 2013 collected data that underpin the current 26 km EDR) used ADDs for 90 minutes before piling was initiated and continued to deploy ADDs throughout the entire piling period. Mitigation measures developed for Scottish waters recommended that where ADD was used, it should be for just 15 mins before the start of piling to deter porpoises from immediate injury zones. Graham et al. (2019) showed that the presence or absence of this 15-min ADD deployment prior to pin-pile at Beatrice did not influence the 24-h response time that we also used in the Moray West study. However, ADD use did have significant impact on the 12-h response (see Figure 7 in Graham et al. (2019)). Similarly, short experimental exposure to ADD in the absence of piling resulted in significant responses out to several kilometres (Brandt et al. 2013; Thompson et al. 2020). Consequently, recommended ADD use was reduced to 10 mins prior to piling during construction at Moray West (Moray Offshore Windfarm (West) Limited 2023). Thus, reduction in ADD use may have contributed to the weaker responses observed in the present study, particularly when compared to sites in other regions where ADD have been deployed for much longer periods.

In addition to these contextual factors and additional sources of disturbance, modelled deterrence functions may vary between studies due to differences in experimental design. This issue is being explored in a parallel piece of work within PrePARED, where hypothetical PAM arrays are being compared by sub-sampling the larger Beatrice Offshore Wind Farm dataset available from Graham et al. (2019). This work will be reported separately but, for the purposes of this report, it is important to note that modelled deterrence functions may be positively biased when the spatial extent of an array increases. This is because, at greater distances from the piling source, there is a higher probability that positive responses are due to other local disturbances rather than the distant pile driving source (Hastie et al. *in prep*). Future comparisons of data from a broader range of studies should therefore truncate data from larger arrays to provide more robust comparisons of deterrence functions to different sources of disturbance.

4.2 Implications for managing time-area thresholds in the Southern North Sea

The time-area threshold approach to managing noise within the SNS requires information both on the duration and spatial scale of disturbance. Data collected during monopile installation at Moray West could in future be used to provide finer-scale information on the duration of disturbance and reduced foraging activity (Pirotta et al. 2014). However, here we focus on the potential for improving understanding of the spatial scale of disturbance, primarily because this can be more rapidly incorporated into current management frameworks that use a fixed 24 h temporal footprint, but already use flexible EDRs for different activities.

Currently, JNCC (2020) recommend that a 26 km EDR is used in assessments for installing monopiles without noise abatement. This is based on the report from the Expert Group convened by DEFRA's Marine Evidence Group (Tougaard et al 2013), using PAM data from a single wind farm presented in Dahne et al. (2013), which was, in fact, installed with pin-piles. Since then, there have been several studies using similar PAM methods at other offshore windfarm sites. These are reviewed in Brown et al. (2023), which highlights that no subsequent studies reported such strong responses for porpoises exposed to piling noise. Furthermore, Brown et al. (2023) highlight how the approach used to produce the current 26 km EDR likely over-estimates the response because it does not account for underlying seasonal variation during baseline and piling periods.

The Tougaard et al. (2013) report provided an appropriately conservative estimate for monopile EDRs while guidance was being developed. However, JNCC (2020) recognised that new data would need to be incorporated to reduce uncertainties and ensure that the guidance remains based upon the best available evidence. This PrePARED study, based on consent monitoring data from Moray West Offshore Windfarm, has provided the first direct estimate of an EDR for unabated monopile installation. There remain uncertainties over the extent to which response data from the Moray Firth is representative for activities in the SNS. However, recommended EDR's for both pin piles and seismic surveys are also based upon data collected from the Moray Firth. Future analyses that formally integrate other datasets on porpoise responses to different piling events would be valuable to generalise these findings. In the meantime, we suggest that our estimated EDR of approximately 10 km provides a strong case for reducing the current 26 km EDR for unabated impact piling of monopiles.

Acknowledgements

We thank colleagues at the University of Aberdeen and Ocean Winds for support and assistance with data collection, Bill Ruck at Moray First Marine for deploying and recovering moorings, Juliet Shrimpton at RenewableUK and colleagues at DEFRA, MMO and JNCC for discussions on early results and background to the management of the SNS SAC, and Bill Turrell, James Rigby, Nicholas Flores-Martin, Leyre Villota Nieva, Kat Route-Stephens, Nick Brockie, Ashley Leiper, Helen Soubies and Andrew Logie for valuable comments that improved the report.

These analyses were funded by OWEC and Crown Estate Scotland through the PrePARED Project. Field data were collected through the Moray Firth Marine Mammal Monitoring Programme, with funding from Moray Offshore Wind Farm (West) Ltd, Moray Offshore Wind Farm (East) Ltd. and Beatrice Offshore Wind Ltd., using equipment previously purchased by UK Department of Energy & Climate Change, Scottish Government, Oil and Gas UK, COWRIE. We thank Ocean Winds for permission to use the cover photo showing Bokalift 2 installing an XXL pile at Moray West.

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Supplementary Material

Table S 1 Piling information for the locations (Loc.) piled between October and December 2023 at Moray West Offshore Windfarm, NE Scotland. The subset of seven piling locations used for the 24-h response analyses is highlighted in red (for the first two piling events) or in orange (c.f. Figure 1 and Figure S 1B)

Loc.	Start Time (GMT)	Piling bout duration (mins)	Active piling duration (mins)	ADD duration per bout (mins)	Max Energy (kJ)	Vibro-Pile (mins)	Hours since last piling	Hours until next piling	Pile diameter (m)	Pile length (m)	Water depth (m)
N13	04/10/2023 23:38	760	258	3	3700	No	> 500	101.2	9.5	82.9	38.24
L11	09/10/2023 17:28	178	172	1	3768	No	101.2	169.4	9.5	78.9	37.71
L13	16/10/2023 21:48	177	170	1	4016	No	169.4	12.8	9.5	77.4	37.29
M15	17/10/2023 13:30	175	170	1	3562	No	12.8	140.9	9.5	79.42	38.87
N16	23/10/2023 13:22	151	142	1	2280	No	140.9	194.8	9.5	75.72	37.47
M11	31/10/2023 18:43	229	207	1	4526	No	194.8	195.0	9.5	82.17	37.52
N09	09/11/2023 01:31	125	125	1	3210	No	195.0	22.2	9.5	79.33	40.18
L12	10/11/2023 01:51	131	103	2	3820	No	22.2	138.0	10	76.08	36.73
L08	15/11/2023 22:03	421	128	0	4155	42	138.0	20.7	10	84.4	47.15
E06	16/11/2023 21:02	376	90	0	4257	61	20.7	20.9	9.5	88.43	44.71
K14	17/11/2023 19:27	160	154	1	4277	No	20.9	207.8	9.5	76.33	36.38
P13	26/11/2023 13:53	135	127	2	4295	No	207.8	90.7	9.5	79.18	38.03
N12	30/11/2023 10:47	118	111	1	3521	No	90.7	24.7	9.5	78.9	37.73
L14	01/12/2023 13:28	160	153	1	4228	No	24.7	22.6	9.5	83.33	37.68
G07	02/12/2023 14:45	460	100	0	4249	24	22.6	66.9	10	84.62	45.77
P11	05/12/2023 11:27	138	116	1	3334	No	66.9	18.4	9.5	83.02	38.97
P14	06/12/2023 04:49	369	163	0	4265	6	18.4	300.3	9.5	80.8	38.15
N08	18/12/2023 23:00	183	154	1	1882	No	300.3	> 300	10	87.51	43.56

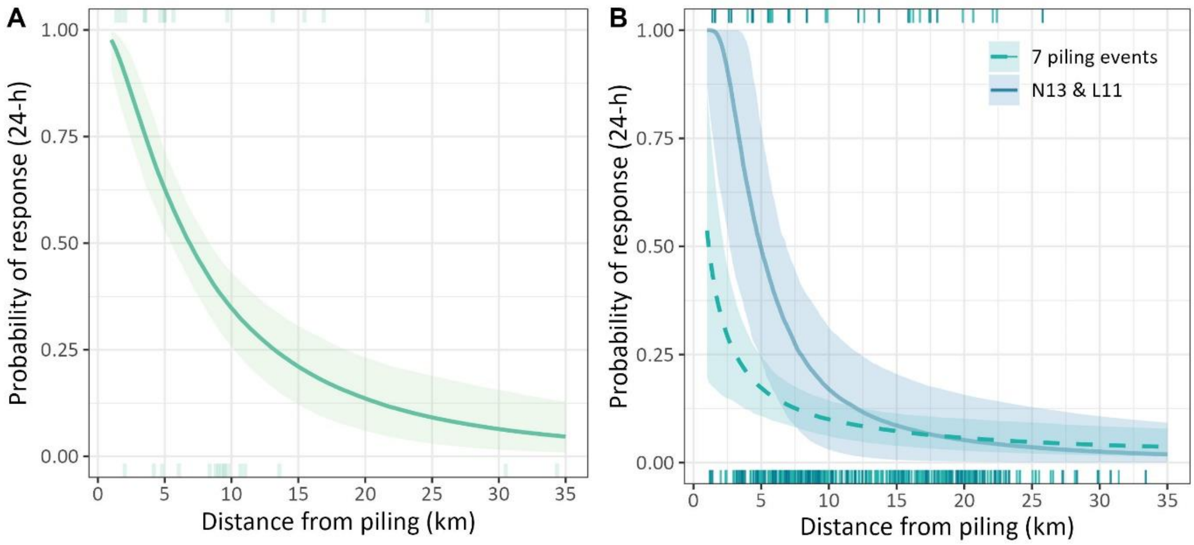

Figure S 1 The probability of 24-h harbour porpoise response in relation to the partial contribution of distance from the installation of A) pin piles at the first piling event at Beatrice offshore windfarm (April 2017); B) monopiles at a subset of 7 piling events (dashed turquoise line) and at the first two piling events (N13 & L11) (solid blue line) at the Moray West offshore windfarm (October-December 2023), assuming a 3-h piling duration. Figure S 1A is similar to Figure 6 of Graham et al. (2019) but remodelled to restrict the data to those PAM sites within 35 km of the piling vessel. Confidence intervals (shaded areas) estimated for uncertainty in fixed effects only. Rug plots show actual response data.