RESEARCH ARTICLE

Ecological Solutions and Evidence | BRITISH ECOLOGICAL SOCIETY

Balancing risks of injury and disturbance to marine mammals when pile driving at offshore windfarms

Paul M. Thompson[1] | Isla M. Graham[1] | Barbara Cheney[1] | Tim R. Barton[1] |
Adrian Farcas[2] | Nathan D. Merchant[2]

[1] Lighthouse Field Station, School of Biological Sciences, University of Aberdeen, Cromarty, Ross-shire, UK

[2] Centre for Environment, Fisheries and Aquaculture Science, Lowestoft, UK

Correspondence
Paul M. Thompson, Lighthouse Field Station, School of Biological Sciences, University of Aberdeen, Cromarty, Ross-shire, IV11 8YL, UK.
Email: lighthouse@abdn.ac.uk

Abstract

1. Offshore windfarms require construction procedures that minimize impacts on protected marine mammals. Uncertainty over the efficacy of existing guidelines for mitigating near-field injury when pile-driving recently resulted in the development of alternative measures, which integrated the routine deployment of acoustic deterrent devices (ADD) into engineering installation procedures without prior monitoring by marine mammal observers.

2. We conducted research around the installation of jacket foundations at the UK's first deep-water offshore windfarm to address data gaps identified by regulators when consenting this new approach. Specifically, we aimed to (a) measure the relationship between noise levels and hammer energy to inform assessments of near-field injury zones and (b) assess the efficacy of ADDs to disperse harbour porpoises from these zones.

3. Distance from piling vessel had the biggest influence on received noise levels but, unexpectedly, received levels at any given distance were highest at low hammer energies. Modelling highlighted that this was because noise from pin pile installations was dominated by the strong negative relationship with pile penetration depth with only a weak positive relationship with hammer energy.

4. Acoustic detections of porpoises along a gradient of ADD exposure decreased in the 3-h following a 15-min ADD playback, with a 50% probability of response within 21.7 km. The minimum time to the first porpoise detection after playbacks was > 2 h for sites within 1 km of the playback.

5. Our data suggest that the current regulatory focus on maximum hammer energies needs review, and future assessments of noise exposure should also consider foundation type. Despite higher piling noise levels than predicted, responses to ADD playback suggest mitigation was sufficiently conservative. Conversely, strong responses of porpoises to ADDs resulted in far-field disturbance beyond that required to mitigate injury. We recommend that risks to marine mammals can be further minimized by (1) optimizing ADD source signals and/or deployment schedules to minimize broad-scale

disturbance; (2) minimizing initial hammer energies when received noise levels were highest; (3) extending the initial phase of soft start with minimum hammer energies and low blow rates.

1 | INTRODUCTION

Offshore windfarm developments are anticipated to provide over 30% of UK electricity needs by 2030 (BEIS 2019). This presents a serious policy dilemma whereby ambitious renewable energy targets must be balanced against the conservation of protected species (Le Lièvre, 2019). Consequently, considerable effort has been invested in the identification of construction and operation procedures that allow renewable energy developments to proceed with minimal environmental impact. Currently, most developments mount offshore wind turbines (OWT) on monopiles or jacket foundations installed into the seabed. Given potential impacts of impulsive underwater noise on marine mammals (Tyack, 2008), attention has focussed on assessing and mitigating the effects of pile-driving noise during construction (Bailey, Brookes, & Thompson, 2014).

Impulsive noise may impact these species in three main ways (see Southall et al., 2007, 2019). Instantaneous death or injury (either physical or auditory) could result from single noise pulses, while accumulated noise doses over longer periods may cause auditory damage. Third, sub-lethal effects may result from behavioural disturbance. Environmental assessments for offshore windfarm developments must assess the areas over which each of these effects might occur using a combination of noise propagation modelling and agreed marine mammal noise exposure criteria (Faulkner, Farcas, & Merchant, 2018). Together with data on local species densities, the number of individuals potentially impacted are then used within various modelling frameworks to predict long-term population consequences of construction in relation to baseline (King et al., 2015; Nabe-Nielsen et al., 2018). Critically, however, these assessments have not generally estimated how many animals might be within the near-field zone of instantaneous death or injury during piling activity. Instead, regulators have assumed that animals will be absent from that injury zone due to mitigation measures that would be integrated into the piling procedure. In the UK, this mitigation has been based upon guidelines that the UK's Joint Nature Conservation Committee (JNCC) produced in 2010 (JNCC 2010). These built upon related guidelines for seismic surveys (Weir & Dolman 2007) and require the use of marine mammal observers (MMOs) to conduct pre-piling surveys over a 500-m mitigation zone for 30 min. If marine mammals are detected, piling should not commence until 20 min after the last detection.

Although a pragmatic first step towards minimizing the risk of injury to marine mammals, reliance on the 2010 guidelines has received criticism in the scientific literature, with calls for more effective mitigation (Parsons et al., 2009). Particularly, it is recognized that the probability of visually detecting marine mammals at sea is extremely low, and the use of passive acoustic monitoring to augment visual observations is not suitable for all species (Evans & Hammond 2004). At the same time, use of the guidelines has presented developers with uncertainty over the potential timelines for piling events. At the planning stage, this can result in economic uncertainty over the cost of construction, potentially affecting project viability, and efforts to meet carbon reduction targets. During construction, this uncertainty may also constrain finer scale optimization of piling events within predicted weather windows, thereby extending the overall construction period and leading to longer-term disturbance from related vessel activity. Balancing these different issues has proved difficult (a) because the efficacy of the JNCC guidelines remains untested and (b) because the guidelines have not used a risk-based approach that considers the likelihood of marine mammal presence in development areas and therefore the degree of caution required for specific projects.

Recent studies indicate that at least one commercially available acoustic deterrent device (ADD) can result in behavioural responses by both seals and cetaceans over ranges which are at least an order of magnitude greater than predicted zones for instantaneous death and injury (Brandt et al., 2013b; Gordon, Blight, Bryant, & Thompson, 2019). Where mitigation aims to maximize the likelihood that marine mammals are outside these predicted impact zones at the start of piling, ADDs may be a more effective tool than MMOs. This approach also provides greater certainty in engineering timelines, avoiding delays due to the onset of darkness, poor weather and MMO detections (McGarry, Boisseau, Stephenson, & Compton, 2017). This alternative approach to mitigation, where ADDs were fully integrated into procedures for piling, was recently implemented at offshore windfarm sites in the Moray Firth, NE Scotland (Beatrice Offshore Windfarm Ltd. [BOWL], 2015). The approach was developed through the Moray Firth Regional Advisory Group (MFRAG); a stakeholder group established by Beatrice Offshore Windfarm Ltd (BOWL) and Moray Offshore Windfarm (East) Ltd as a condition of their 2014 planning consents. Working with regulators and statutory nature conservation advisors, procedures for mitigating the risk of instantaneous injury to marine mammals during piling were developed to balance environmental protection against commercial affordability and practicality. The aim was to integrate mitigation measures into a predictable and efficient engineering process with four key objectives. First, to minimize the risk of instantaneous death or injury to marine mammals, which may result from single noise pulses at close range.

Second, to allow piling to be initiated in darkness, in poor visibility or after breaks in engineering works. Third, to be used safely in an offshore environment in all seasons. Lastly, to minimize the duration of the overall construction period (BOWL, 2015). To achieve this, geotechnical data were used to identify hammer energies that would minimize the risk of pile refusal while avoiding unnecessary activity at high energy. Anticipated hammer energies at the start of each piling sequence were used to estimate noise levels at source based on current understanding of conversion factors (the proportion of hammer energy converted to acoustic energy) (Dahl, de Jong, & Popper, 2015). Predictions of received noise levels across the study site were then related to agreed thresholds for instantaneous auditory injury (Lucke, Siebert, Lepper, & Blanchet, 2009; Southall et al., 2019) to estimate impact areas. Standard operating procedures for integrating ADDs into engineering processes were developed to maximize the likelihood that any marine mammals in the vicinity had fled this near-field injury zone before piling commenced, based on estimated swimming speeds.

These proposed procedures included a risk assessment (BOWL, 2015) that led to regulatory approval to trial this alternative approach to mitigation, subject to research and monitoring programmes being in place to reduce the following key uncertainties encountered during this process. First, estimates of impact ranges were based on limited data on how source levels vary with changes in hammer energy, with previous work focussing on much shallower sites (Dahl & Reinhall 2013; Robinson, Lepper, & Ablitt, 2007). Similarly, uncertainties existed over the source levels of proprietary ADDs, and their efficacy under offshore conditions. Finally, whilst there is growing understanding of the extent to which marine mammals respond to ADD and piling noise (Brandt et al., 2013b, 2018; Graham et al., 2019a), data on the time it takes animals to return to affected areas are required to optimize ADD use during planned and unplanned breaks in piling.

Here, we describe the results of studies that were designed to inform these data gaps during construction of the BOWL windfarm in 2017. Our specific objectives were (1) to measure received noise levels in relation to variation in hammer energy through the piling sequence; (2) to conduct ADD playback experiments prior to the construction period to measure responses of harbour porpoises to ADD noise and assess how long it took animals to return to exposed areas; (3) to characterize source levels of the ADD. These findings were then used to develop recommendations on how these protocols could be further optimized to integrate environmental protection into these engineering processes.

2 | MATERIALS AND METHODS

2.1 | Study system

The study was carried out during the initial phase of construction of eighty-four 7 MW turbines and two offshore transmission modules in depths of 35–45 m at the BOWL windfarm (Figure 1). Prior to the installation of each jacket substructure, four 2.2 m diameter piles of between 35 and 45 m in length were driven into the sediment using
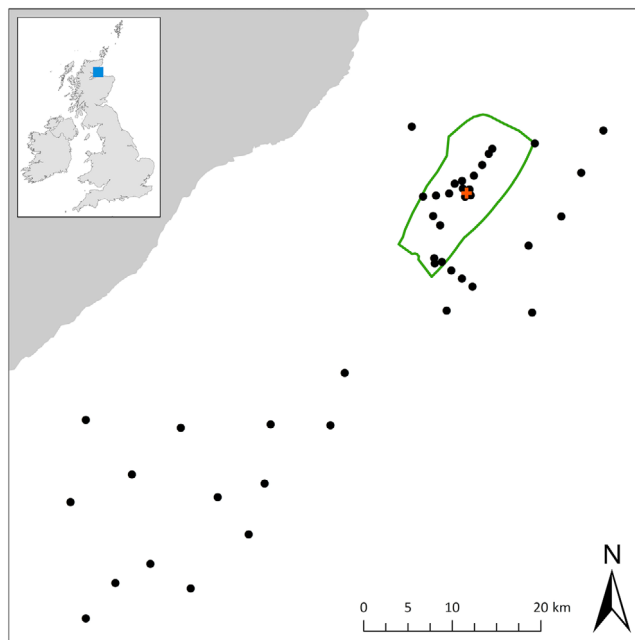

FIGURE 1 Map of the study area showing the boundary of the BOWL development site, the location of the ADD playback (orange cross) on the 3rd March and the locations of moored CPODs (filled circles) that were operating on that date and subsequently used in the porpoise response model

a piling template deployed from an anchored vessel. The integration of ADD-based mitigation measures into this engineering process is illustrated in Figure 2. Briefly, a Lofitech ADD (Lofitech AS, Leknes, Norway) was first deployed at the piling site for 15 min with the intention of displacing marine mammals from the injury zone. This was followed by an agreed soft start sequence for at least 20 min. Hammer energy was then gradually ramped up to levels required to maintain pile movement, whilst keeping within the permitted maximum hammer energy of 2500 kJ. If breaks in piling of > 10 min occurred, the ADD had to be re-deployed for 10–15 min (15 min for longer breaks of > 2.5 h). If breaks of < 10 min in piling occurred, piling could continue at the same hammer energy.

2.2 | Variation in piling noise in relation to hammer energy

Piling noise was 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 turbines (Figure S1 in the Supporting Information). 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 min at a 576 kHz sampling rate. The fourth recorder was moored 8–11 km from piling sites and recorded for 10 min every 30 min at a 96-kHz sampling rate. Sound exposure levels (SEL) and frequency spectra for individual pile strikes were obtained from all recordings of
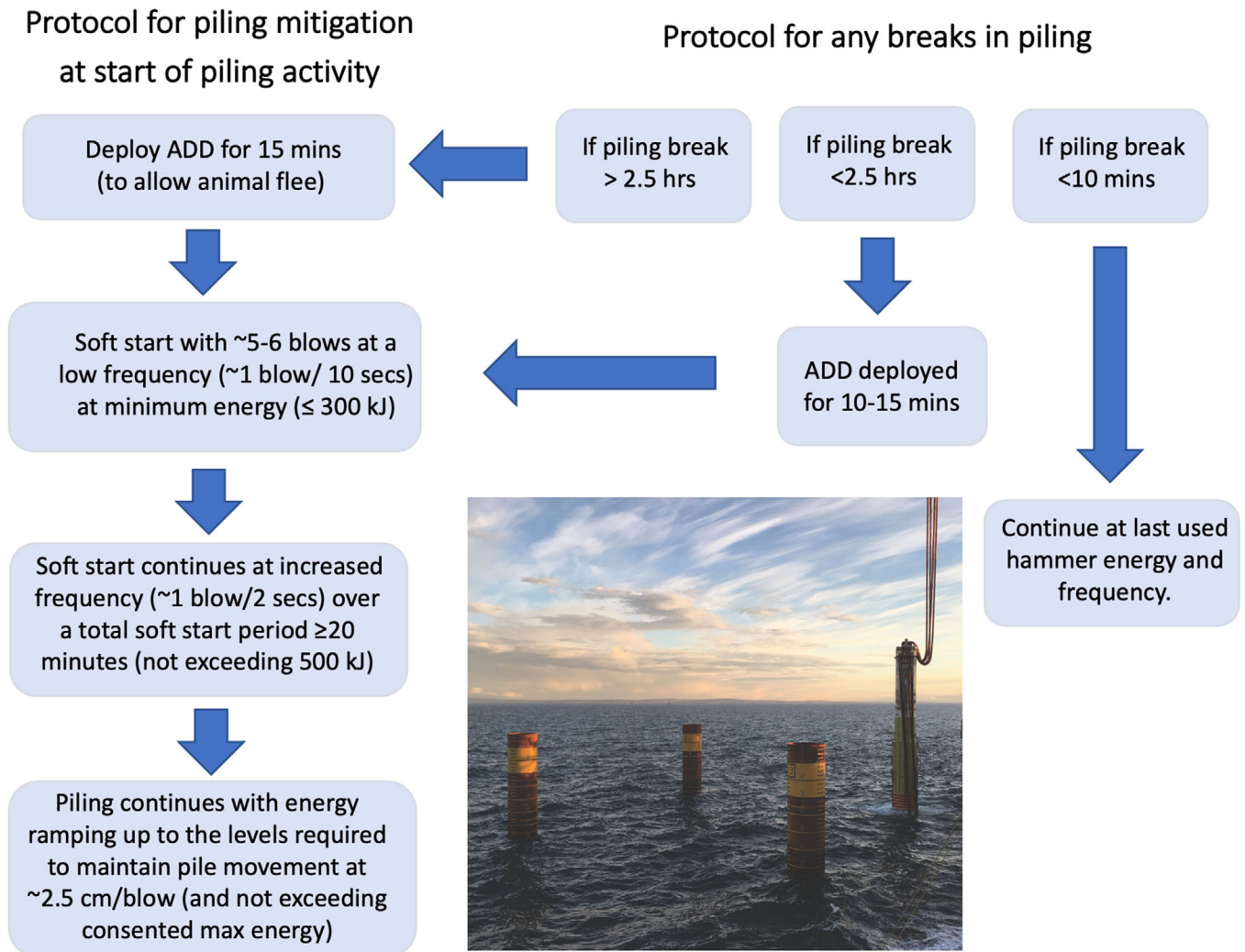
Protocol for piling mitigation at start of piling activity

Protocol for any breaks in piling

Deploy ADD for 15 mins
(to allow animal flee)

If piling break
> 2.5 hrs

If piling break
<2.5 hrs

If piling break
<10 mins

Soft start with ~5-6 blows at a low frequency (~1 blow/ 10 secs) at minimum energy (≤ 300 kJ)

ADD deployed
for 10-15 mins

Soft start continues at increased frequency (~1 blow/2 secs) over a total soft start period ≥20 minutes (not exceeding 500 kJ)

Continue at last used hammer energy and frequency.

Piling continues with energy ramping up to the levels required to maintain pile movement at ~2.5 cm/blow (and not exceeding consented max energy)

FIGURE 2　Schematic showing the alternative mitigation protocols used at the start of pile installation and after any planned or unplanned breaks (adapted from BOWL, 2015). Inset picture shows hammer ready to pile the first of four piles that have been placed in the pile installation frame

the full waveform using a modified version of PAMGuide (Merchant et al., 2015). Pile installation records were provided by developers and linear mixed effects models used to explore how blow by blow received noise levels varied in relation to distance from source, hammer energy, and pile penetration depth. Pile penetration depth was highly correlated with the length of pile exposed in the water column; therefore, only penetration depth was included in models. Received noise measurements at all recording sites were compared with predictions based upon noise propagation modelling (Farcas, Thompson, & Merchant, 2016) that assumed that 0.5% of hammer energy was dissipated into the water column as noise. Further details of this modelling are provided in the electronic Supporting Information.

2.3 | Characterizing ADD signals

Recordings were made using calibrated Soundtraps with a 576-kHz sampling rate during a 15-min experimental ADD exposure on 3 March

2017 (Figure 1). Recorders were moored 2 m above the seabed, 30, 538, 1075, 1546 and 1996 m from the playback location. Three different Lofitech ADD devices were each deployed sequentially at the same location for a 5-min period with their transducers in mid-water (~20 m). We measured 10 randomly selected ADD signals from each recording and calculated the median received SPL at each distance from source. Propagation loss at a peak frequency of 12,840 Hz (see Results) was modelled for each unique source–receiver transect using an energy flux density model and added to the received sound level to estimate source level at a nominal distance of 1 m.

2.4 | Harbour porpoise responses to ADD signals

An array of moored echolocation detectors (V.0 and V.1 CPODs (www.chelonia.co.uk)), deployed to study responses to piling noise (Graham et al., 2019a), was used to assess variation in harbour porpoise detections in relation to experimental ADD exposure prior to

construction (Figure 1). Experimental playbacks were carried out in March 2017 under licence from Scottish Natural Heritage. Data for each playback were available for 43 CPOD deployments from 44 sites (data from two deployments did not cover the entire month). Data were processed using version 2.044 of the manufacturer's software to identify porpoise echolocation clicks. Click trains categorized as high or moderate quality were used for analyses.

Playbacks of the ADD were made from a 14-m survey vessel anchored over selected CPOD moorings, with the engine and echosounder shut down, on the 3, 17 and 23 March 2017. On each day, 15-min experimental exposures were matched with control events when the vessel was anchored and an inactive ADD deployed to midwater for 15-min (Table S1 and Figure S2 in the Supporting Information). On the 3 March, our 15-min exposure consisted of a continuous series of 5-min signals from three different ADD units initiated 15 min after shutdown. One unit was randomly selected for subsequent exposures, which were made 1–2 min after shutdown. Replicate exposures were always >10 km from previous exposures made that day.

We used data from the day in which only a single ADD exposure was made (3 March) to explore how responses varied over different distances and timescales. We compared changes in porpoise occurrence (detection positive hours (DPH); Williamson et al., 2016) at each location in the 3, 6- and 12-h periods from the end of the ADD exposure relative to a baseline occurrence of the same duration 48 h before the exposure. Following Graham et al. (2019a), we characterized baseline variation in occurrence using data from 34 sites from 19 to 28 February 2017 and 43 sites from 7 to 16 March 2017. A null distribution of the baseline proportional change in occurrence (DPH) was produced by randomly sampling 1000 times from 21 to 27 February 2017 and from 9 to 15 March 2017 for each site. We then calculated the proportional change in the number of DPH in the 24-h period following each time relative to the number of DPH in the 24-h period 2 days before (Figure 3). Using the quantile function in R, the 1% quantile of this distribution was calculated. Porpoises were considered to have exhibited a behavioural response to the ADD when the proportional decrease in occurrence was greater than 0.5, the 99th percentile of this baseline distribution (Figure 3). The probability that porpoise occurrence did (1) or did not (0) show a response to ADD was then modelled in relation to distance from source as a binomial response with a probit link function (Williams, Erbe, Ashe, Beerman, & Smith, 2014) using generalized linear models (GLM) in R (R Core Team 2017). Model selection was carried out using Akaike information criterion (AIC) (Burnham & Anderson 2002).

The length of time that it took animals to return to exposed areas following ADD exposure (return time) was determined from the time elapsed between the end of the ADD exposure and the time of the first porpoise detection thereafter. Baseline variation in return times was explored by calculating the time to first porpoise detection following 1000 randomly sampled times between 7 and 15 March 2017 for each of the 43 CPODs recording during this period. Kolmogorov–Smirnov tests were used to test for differences in frequency distributions of return times during the baseline and those for all CPODs within 1 km of playbacks following control and experimental ADD playbacks.
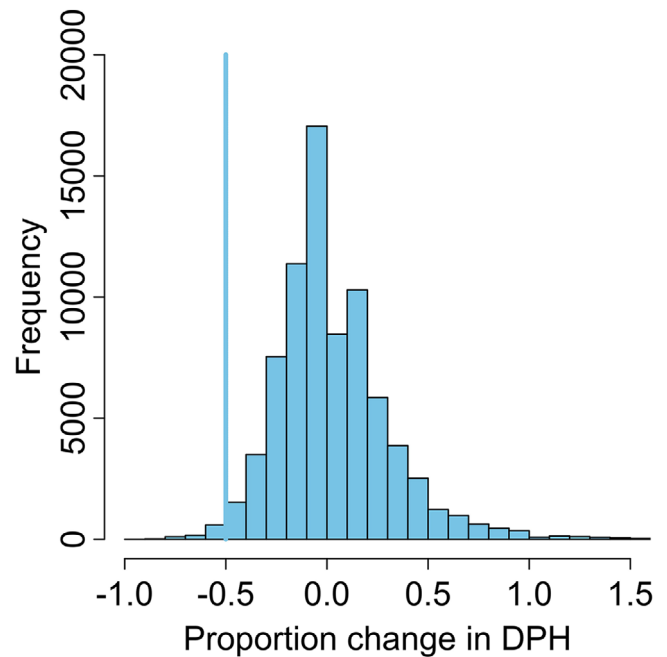

FIGURE 3 Frequency distribution of the proportion change in harbour porpoise occurrence (DPH) for a 24-h period from 1000 randomly sampled times relative to a baseline 48 h before, at 34 sites from 19 February 2017 to 28 February 2017 and 43 sites from 7 March 2017 to 16 March2017. The blue line indicates the first percentile of the distribution

p values were adjusted for multiple comparisons using the Bonferroni correction.

3 | RESULTS

3.1 | Variation in piling noise through the piling sequence

Hammer energies increased from approximately 266 kJ to between 744 and 1735 kJ during the 3990 min that it took to install each of the 16 piles. Unexpectedly, the highest received noise levels were recorded early in each piling sequence, resulting in an inverse relationship between received noise levels and hammer energy (Figure 4). Example power density spectra of the received noise (Figure S3) and sound files are provided in the Supporting Information. Distance from source had the greatest influence on received noise levels (Table 1). The best fitting model also included a positive relationship with hammer energy, but a much stronger negative relationship with penetration depth (Table 1; Figure 5). Consequently, assumed source levels used in noise propagation modelling resulted in predicted received levels giving a poor fit to the data (Figure S4 in the Supporting Information), particularly at the onset of piling. Comparison of predicted and measured SEL indicate that the conversion factor varied by an order of magnitude through the piling sequence. The conversion factor tended towards 1% later in the piling sequence (Figure 4); however, early in
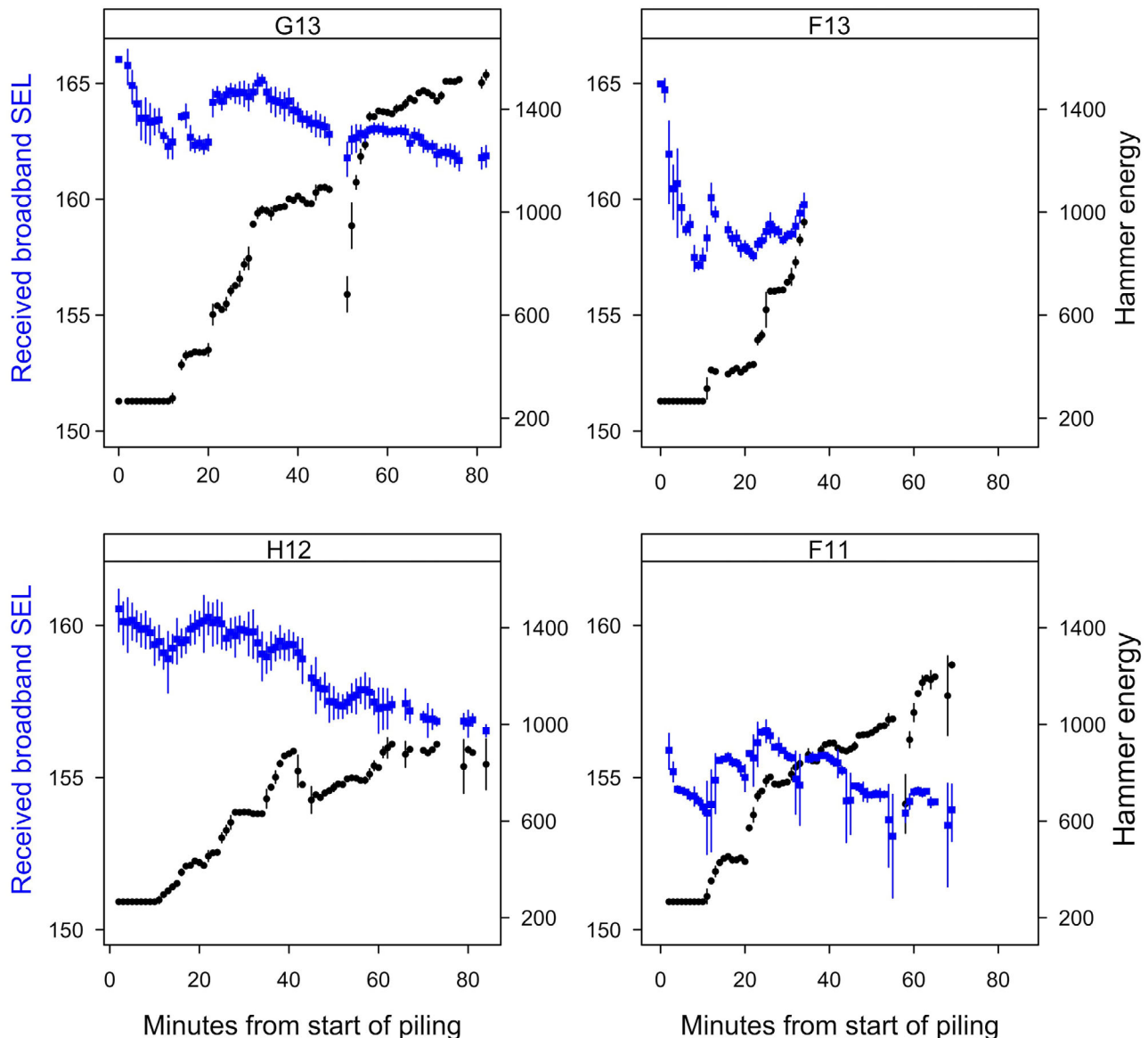
FIGURE 4 Measured received broadband noise levels (SEL; blue squares) and hammer energies (black circles) each minute through the piling sequence for the first pile at the four focal turbine locations. Values are the mean +/- the standard deviation for measurements from three recordings sites < 4 km from piling (see Figure S1 in the Supporting Information)

piling when the penetration depth was lower, observed conversion factors typically exceeded 10% (Figure 6).

3.2 | Harbour porpoise responses to ADD

The median estimate of ADD source levels was a peak–peak sound pressure level (SPL) of 187.2 dB re 1 μPa at 1 m (Table S2) with an observed peak frequency of 12,840 Hz (see spectrogram [Figure S5] and example sound file in the Supporting Information).

Harbour porpoise responses to the first ADD playback on the 3rd March declined with distance from source at all temporal scales (3, 6, 12 h) (Table 2), but there was an inverse relationship between the tem-

poral scale of measurement and estimated spatial scale of response. There was ≥50% chance of harbour porpoises responding to the ADD playback in the 3-h period following the playback at distances up to 21.7 km (95% CI = 13.1–44.2 km) from the ADD, in the 6-h period at distances up to 13.8 km (95% CI = 8.9–22.2 km) and in the 12-h period at distances up to 3.9 km (95% CI = 1.3–7.2 km) (Figure 7; Figure S6 in the Supporting Information).

Return times at all CPODs within 1 km of both ADD playbacks and control playbacks were longer than baseline return times (Table 3), and the spatial scale of responses (Figure 7) was greater than anticipated. However, it is likely that some playbacks and controls were not independent as ADD playbacks were sometimes carried out on the same day (Table S1 in the Supporting Information). The analysis was
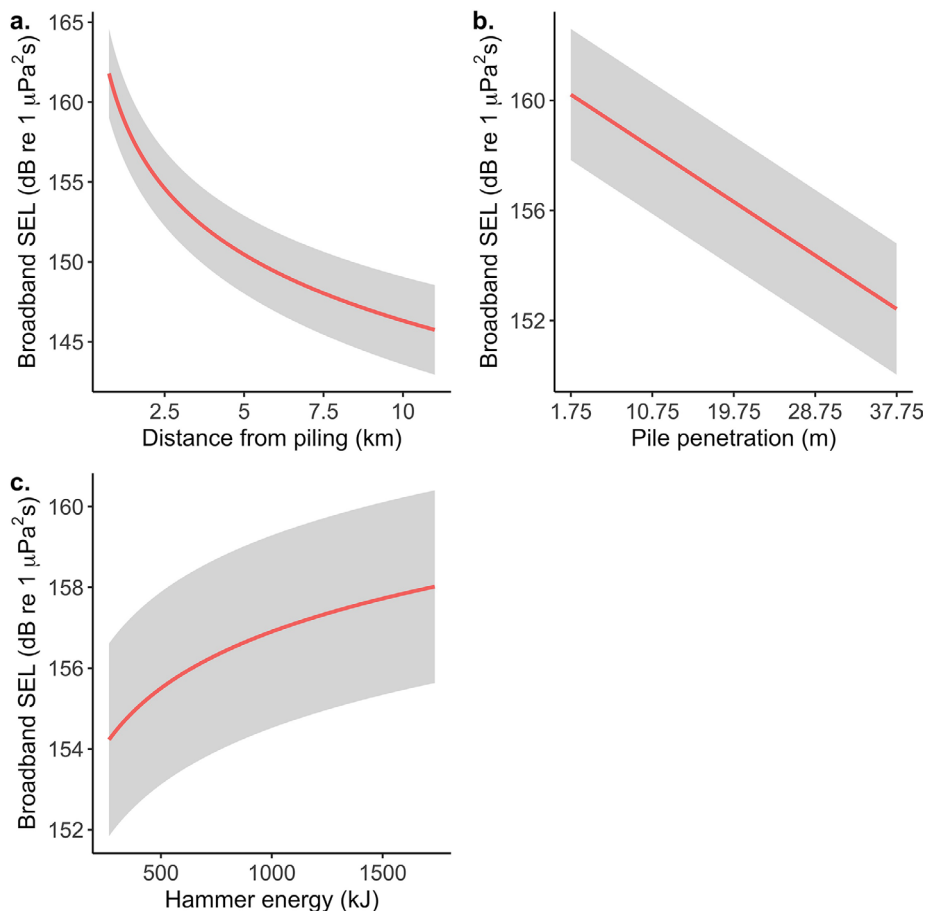
FIGURE 5 Modelled variation in received broadband SELs in relation to the partial contribution of (a) distance from piling, (b) pile penetration and (c) hammer energy. Confidence intervals (shaded areas) estimated for uncertainty in fixed effects only

TABLE 1 Modelled relationship between measured received broadband single-pulse SEL and distance from piling, depth of pile penetration and hammer energy. Relationship was modelled using linear mixed-effects models fitted by REML with a random effect of pile ($n = 53$; SD $= 0.54$) nested within turbine ($n = 15$; SD $= 1.00$) nested within sound recorder identity ($n = 4$; SD $= 2.33$); residual SD $= 0.38$. The model also included a corAR1 correlation structure to allow for autocorrelation in the model residuals

	Estimate	Standard error	DF	t-value	p
(Intercept)	188.436	4.716	40,348	39.95	<0.001
Log (distance)	−5.973	0.573	10	−10.42	<0.001
Pile penetration	−1.686	0.017	40,348	−100.78	<0.001
Log (hammer energy)	2.021	0.035	40,348	58.14	<0.001

therefore repeated including only those instances where the first porpoise detection following playback/control occurred before the next ADD playback, thus excluding long return times that may not be independent (Table S3 in the Supporting Information). The frequency distribution of baseline and control return times did not differ signif-

icantly, and the return times following these ADD playbacks were longer than both baseline and control return times (Table 3; Figure 8). The minimum time to the first porpoise detection following 15-min ADD playback was 133 min for all CPODs within 1 km of playbacks ($n = 15$).

4 | DISCUSSION

Significant resources are invested in mitigation or compensation measures with the aim of protecting biodiversity, but the efficacy of many of these interventions remains unstudied and uncertain (Hill & Arnold 2012; Sutherland, Dicks, Ockendon, Petrovan, & Smith, 2019). Despite this lack of evidence, there is often resistance from regulators and/or stakeholders to adapt or change accepted approaches to mitigation. This can be especially problematic when existing procedures are applied in new ecological or industrial contexts, where the costs and benefits of mitigation measures may differ. The expansion of offshore windfarms requires exploitation of sites in deeper water and further from the coast than previous developments. Uncertainties over the efficacy and cost of applying existing measures for mitigating the risk of injury to marine mammals at sites in NE Scotland led to the routine
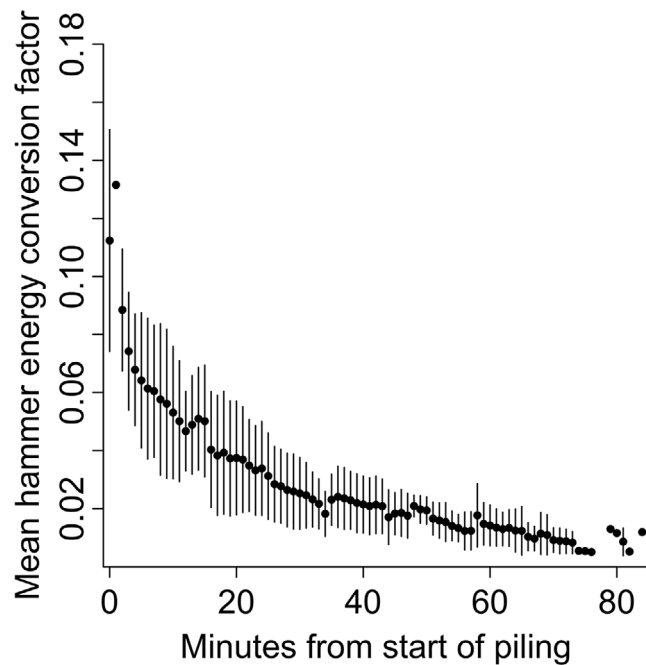
FIGURE 6 Observed mean hammer energy conversion factor per minute from the start of piling for the three sound recorders moored within 4 km of piling sites (see Figure S1 in the Supporting Information)

TABLE 2 Modelled relationships of harbour porpoise responses to ADD playback. Response was defined as a proportional decrease in harbour porpoise occurrence ≥ 0.5, in the 3, 6 or 12 h after the end of the ADD playback. Relationships with distance to playback were modelled using GLM with a binomial error distribution and the probit link function. ΔAIC gives the difference in AIC between the intercept only model, for that response length, and the model in the table

Model	Estimate	Standard error	z value	p	Δ AIC
(a) 12-h response ~ log(distance)					−17.1
(Intercept)	1.0723	0.4891	2.192	0.0283	
Log(distance)	−0.7844	0.2237	−3.507	<0.001	
(b) 6-h response ~ log(distance)					−29.8
(Intercept)	3.5795	0.9706	3.688	<0.001	
Log(distance)	−1.3639	0.3619	−3.769	<0.001	
(c) 3-h response ~ log(distance)					−19.0
(Intercept)	3.2553	0.8918	3.650	<0.001	
Log(distance)	−1.0578	0.2995	−3.532	<0.001	

FIGURE 7 The probability of a harbour porpoise response in relation to distance from ADD playback for the first ADD playback on 3 March 2017 over a period of: 12 h (solid red line), 6 h (long-dash orange line) and 3 h (short-dash yellow line). Harbour porpoise occurrence was considered to have responded to ADD exposure when the proportional decrease in occurrence (DPH) exceeded a threshold of 0.5. (See Figure S3, in the Supporting Information, for separate graphs showing actual response data and confidence intervals)

TABLE 3 Results of Kolmogorov–Smirnov tests between the frequency distributions of return times following ADD playbacks, controls and random times during the baseline period, for all CPODs within 1 km of the playback, control or randomized event. p values were adjusted for multiple comparisons using the Bonferroni correction

Kolmogorov–Smirnov test	All CPODs		CPODs with detection before next playback	
	D	p	D	p
Playback vs control	0.3125	1.00	1	0.0093
Playback vs baseline	0.8999	<0.001	0.8999	<0.001
Control vs baseline	0.6180	<0.001	0.4797	1.00

4.1 | Variation in piling noise through the piling sequence

Estimates of noise exposure from offshore pile-driving have assumed that a consistent proportion of hammer energy is converted into water-borne acoustic energy, and the highest source levels therefore occur at maximum hammer energies. Reviewing available empirical measurements, Dahl et al. (2015) suggest this conversion factor is typically ~0.5%, and this figure has been used in several UK environmental assessments. In contrast, we recorded the highest received levels at

integration of ADDs into pile-driving procedures to deter animals from potential injury zones. Our study was designed to address key uncertainties and data gaps identified during this process. The results provide new information that better inform efforts to balance requirements to mitigate risk of injury with other environmental impacts of construction and reveal inconsistencies in the assumptions used within assessments of broader impacts of pile-driving noise.
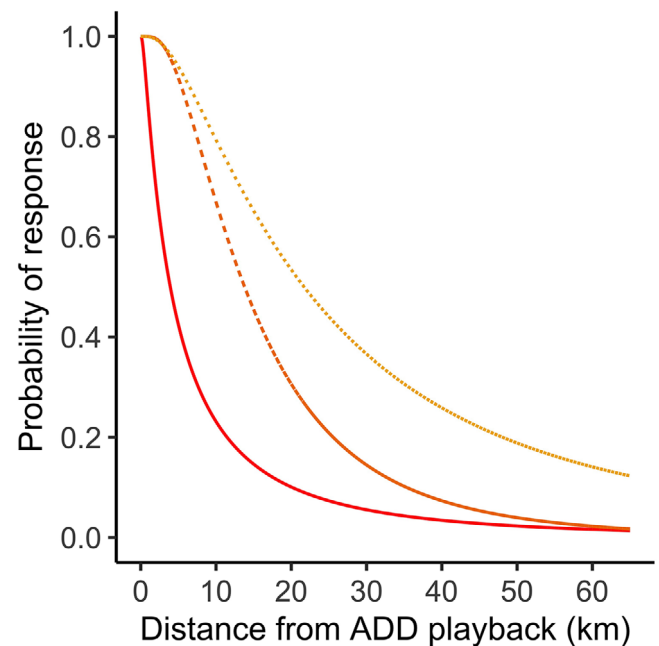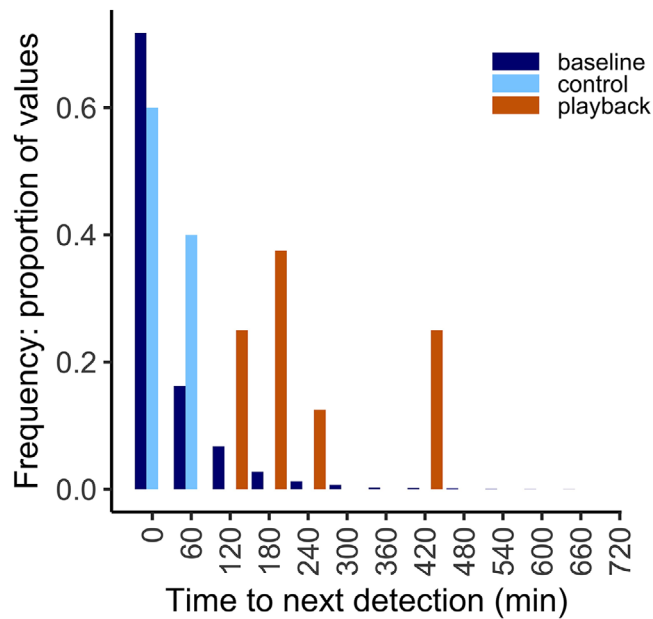
FIGURE 8 Frequency distribution of time to next detection, expressed as a proportion of the total, following ADD control and playback experiments, in comparison to random times during the baseline period, from 7 March 2017 to 15 March 2017

lower hammer energies (Figure 4). Conversion factors in our study therefore varied by more than an order of magnitude through a piling cycle (Figure 6) and exceeded 10% during the piling soft starts designed to minimize noise exposure at the beginning of each sequence. Previous use of the 0.5% conversion factor has been based largely upon two empirical studies (Robinson et al., 2007; Dahl & Reinhall 2013), both in shallow waters of <15 m. In each case, there were important differences in pile installation techniques that may explain why our observed conversion factors were higher when using pin piles to install jackets in deeper waters. In Robinson et al. (2007) near-field measurements made during the installation of a 65 m × 2 m pile at an experimental test site reported that 0.3% of hammer energy was converted to sound with a highly linear relationship between pulse energy and hammer energy (see Figure 10 in Robinson et al. [2007]). However, less than 40% of the pile was within the water column during the entire measurement period, meaning an unknown percentage of hammer energy was dissipated as sound in air (particularly during the soft start) or into the sediment (at higher hammer energies). Dahl and Reinhall (2013) made near-field measurements from a vertical array of hydrophones during the final stages of the installation of three 32 m × 0.76 m piles at a coastal harbour. Here, approximately 1% of hammer energy was radiated into the water column, but acoustic measurements were made only after each pile had been pre-driven to over 95% of the planned installation depth into the sediment (~14 m). Thus, the critical soft-start period (when we found higher conversion factors) was not studied and only 40% of the pile length was within the water column throughout the measurement period. Both these study systems differ markedly from the engineering processes now being used to install pin-pile jackets at deeper offshore windfarm sites. For example, in our study, piles

of between 35 and 45 m were driven to within 2 m of the seabed using a submersible hammer in depths of up to 45 m. Thus, during soft starts, the entire pile could be within the water column. While at the highest hammer energies, most of the pile was embedded in the sediment.

The predominant mechanism producing piling noise is the Mach wave effect, where a compression wave travels down the length of the pile (Reinhall & Dahl 2011). Recent efforts to improve predictions of spatial variation in received levels of pile-driving noise have focussed on developing more complex underwater propagation models (e.g. Lippert & von Estorff 2014) rather than exploring factors affecting variation in source characteristics. Further work is now required to explore how observed variation in both the magnitude and frequency spectra of source levels influences estimates of cumulative noise exposure. In the meantime, our observations have important implications for the assessment and mitigation of potential impacts of pile-driving noise on protected wildlife populations.

Currently, the maximum hammer energy used during the installation of offshore windfarms is tightly regulated, and therefore a major focus within all environmental assessments (Faulkner et al., 2018; Merchant, 2019). Given that hammer energy has been considered to relate directly to underwater noise levels, environmental assessments have aimed to identify maximum hammer energies that provide developers with flexibility over future engineering processes, whilst minimizing any risk to regulatory consent. Subsequently, however, if new geophysical data or engineering solutions require greater hammer energies, consented developments have had to re-submit revised environmental assessments, increasing project costs and timelines. Our findings suggest that the regulatory focus on maximum hammer energies should be reviewed. This requires consideration both of procedures for assessing exposure to piling noise and of approaches for mitigating potential impacts. Received levels of piling noise were highest at the very beginning of each pile installation (Figure 4). A soft start using low hammer energies is required by engineers when the pile first enters the sediment (Dahl et al., 2015). However, based on the perception that source levels are lower at this stage, regulators often require an extended mitigation soft start to give animals longer to flee before they are exposed to noise from higher hammer energies. Paradoxically, our findings raise the possibility that extending the soft start beyond that required by engineers may increase cumulative doses to wildlife. Instead, we recommend that efforts to mitigate the effects of noise exposure through regulation of piling schedules should focus on two other areas. First, environmental benefits of the current soft start procedures (see Figure 2) may be improved by extending the initial phase where the blow rate is reduced. Second, and more critically, there now appear to be significant benefits in further reducing hammer energy during these initial pile strikes. At the Beatrice development, the choice of piling vessel and hammer system meant that it was not technically feasible to initiate piling at lower hammer energies. However, more modern piling vessels and hammer systems now provide the potential to initiate the installation of similar sized piles at much lower hammer energies. We suggest that regulators therefore consider limiting initial hammer energies and encourage the use of installation systems that best minimize these.

4.2 | Harbour porpoise responses to ADD

Reductions in initial hammer energies will help reduce the risk of injury to wildlife, but this approach must be integrated with pre-exposure to acoustic deterrents to minimize the occurrence of animals within potential injury zones. Data from our study can now be used to improve assessments both of the extent of the potential injury zone, and of the efficacy of these ADDs to disperse harbour porpoises. Measurements of higher than expected noise levels at the start of piling resulted in a predicted zone of instantaneous injury from the first pile strike out to 290 m. This was over five times greater than original prediction of 56 m based upon 0.5% of hammer energy, but still within the range of distances that a porpoise can flee at 1.5 ms^{-1} in the 15-min that the ADD was in operation.

Observed changes in detections of harbour porpoises across our array of echolocation detectors confirmed that this species exhibited a strong behavioural response to ADD playbacks. This was consistent with previous studies on the effects of ADD mitigation on both harbour porpoises (Brandt et al., 2013a; Graham et al., 2019a; Mikkelsen, Hermannsen, Beedholm, Madsen, & Tougaard, 2017) and minke whales (McGarry et al., 2017), although harbour seal responses to ADDs appear more equivocal (Gordon et al., 2019; Mikkelsen et al., 2017). One limitation of passive acoustic methods such as ours is that a lack of detections may represent either a change in distribution or in vocal behaviour. However, acoustic responses in several studies have been reported alongside visual confirmations of displacement, further suggesting that ADDs are effective for mitigating the risk of injury to protected cetaceans. A second limitation of our approach is that other factors may confound either the characterization of baseline variation (Figure 3) or the identification of a behavioural response to ADD playbacks (Figure 7). Given consistent spatial variation in porpoise occurrence in previous acoustic and aerial surveys within this study area (see Brookes, Bailey, & Thompson, 2013; Williamson et al., 2016), we characterized baseline variation at each site with data from different time periods; thereby assuming that other factors, such as seasonal migrations, caused no major temporal changes in baseline occurrence during our 4–5 week study. Similarly, our models assume that observed behavioural responses were all in response to the ADD playback, whereas some may be responses to other disturbance sources such as vessel traffic (Wisniewska et al., 2018). Indeed, it seems likely that the few responses that we detected at >40 km were due to other sources, given that harbour porpoises are unlikely to detect ADD signals above background noise at these distances (Rose et al., 2019). Nevertheless, removing all data from locations > 40 km from source made little difference to the modelled relationship (Figure S7 in the Supporting Information), indicating that the spatial extent of porpoise responses to ADD mitigation was large (Figure 7) and of similar magnitude to reported responses to pile-driving noise (Dahne, Tougaard, Carstensen, Rose, & Nabe-Nielsen, 2017; Graham et al., 2019a). Consequently, there is a need to optimize the duration of ADD playbacks depending upon local densities and sensitivities of different target species. The duration of ADD mitigation must be sufficient to allow animals time to flee from the near-field but be minimized to avoid unnecessary far-field behavioural disturbance. Given the strong observed response to the Lofitech ADD used in this development, we recommend further evaluation of alternative ADD systems such as FaunaGuard (Van der Meij, Kastelein, Van Eekelen, & Van Koningsveld, 2015), which offer the potential to minimize both near-field injury risks and avoid broader-scale behavioural displacement. Another critical consideration is any requirements for re-deployment of ADDs following planned or unplanned breaks in piling. For the BOWL piling strategy, a precautionary approach was to re-deploy ADDs when breaks exceeded 10 min. We found that porpoises were not detected on CPODs within 1 km of playbacks for more than 2 h after ADD playbacks (Figure 8). On the basis of this finding, we recommend that broader-scale disturbance could be further reduced by requiring the re-application of ADD mitigation only after longer breaks in piling.

Our findings on variability in the relationship between piling hammer energy and underwater noise levels can help focus efforts to mitigate adverse impacts of underwater noise on marine mammals. Critically, there needs to be recognition that future assessments of noise exposure should consider foundation type when regulating hammer energy. Analysis of underwater noise levels from a broader suite of engineering designs and construction scenarios is now required to fully characterize this variability. Further work on changes in the frequency spectra of underwater noise through the piling sequence for both pin piles and monopiles would also provide more robust estimates of cumulative levels of noise in frequencies most likely to impact marine mammal hearing (Southall et al., 2019). However, estimates of the effects of cumulative exposure from both pile-driving noise and ADD use will require the development of new approaches that integrate exposure levels and thresholds from both impulsive and continuous noise sources (see also Hastie et al., 2019). In the meantime, we recommend that risks to marine mammals can be further minimized through efforts to (1) optimize ADD source signals and/or deployment schedules to maximize dispersion from near-field injury zones while minimizing broad-scale disturbance; (2) minimize hammer energies at the start of piling when received noise levels were highest; (3) identify opportunities to extend the initial phase of soft start with minimum hammer energies and low blow rates.

Our observations of far-field responses of porpoises to ADDs highlight the challenge of optimizing these mitigation measures to balance potential risks from injury and disturbance. Here, we focussed on the use of ADDs as a tool to mitigate direct injuries because water depths and current regimes at this site precluded the use of current noise abatement technologies such as bubble curtains (see Dahne et al., 2017). At other sites, or with future technical developments, noise abatement techniques may provide an additional tool to mitigate these impacts. Nevertheless, even where source levels can be reduced during the intense but relatively short piling periods, this may require additional vessels and/or extended construction timelines; potentially resulting in broader-scale chronic disturbance over much longer timescales. Minimizing population level impacts from these different pathways requires a risk-based assessment of mitigation options, where risks of near-field injury and disturbance from noise sources that operate on different spatio-temporal scales are fully

integrated into existing assessment frameworks (e.g. King et al., 2015; Nabe-Nielsen et al., 2018). In turn, this requires recognition, amongst both regulators and stakeholders, that there is unlikely to be a one size fits all approach for mitigating the effects of piling noise. Instead, these procedures will need optimizing both for different design options and for areas with different communities and local densities of marine mammals.

AUTHORS' CONTRIBUTIONS

P.T., I.G and N.M. conceived and designed the study. T.B. managed data collection. I.G. and B.C. processed data. N.M. and A.F. analysed noise data. I.G. conducted data analysis. P.T. and I.G. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

All data are available from the Dryad Digital Repository. Data from echolocation recorders can be found at: https://doi.org/10.5061/dryad.5qg30sd (Graham et al., 2019b). Other data and R code used for all analyses are available at https://doi.org/10.5061/dryad.34tmpg4hs (Thompson et al., 2020).

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1002/2688-8319.12034.

ORCID

Paul M. Thompson https://orcid.org/0000-0001-6195-3284
Nathan D. Merchant https://orcid.org/0000-0002-1090-0016

REFERENCES

Bailey, H., Brookes, K. L., & Thompson, P. M. (2014). Assessing environmental impacts of offshore wind farms: Lessons learned and recommendations for the future. *Aquatic Biosystems*, 10, 8. https://doi.org/10.1186/2046-9063-10-8

BEIS (2019). UK Government Department of Business, Energy and Industrial Strategy Offshore Wind Sector Deal. HM Government. Available at: https://www.gov.uk/government/publications/offshore-wind-sector-deal. Accessed October 20, 2020.

BOWL (2015). Beatrice offshore wind farm consent plan; Piling strategy. Retrieved from http://marine.gov.scot/sites/default/files/00490632.pdf

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

Brandt, M. J., Höschle, C., Diederichs, A., Betke, K., Matuschek, R., & Nehls, G. (2013a). Seal scarers as a tool to deter harbour porpoises from offshore construction sites. *Marine Ecology Progress Series*, 475, 291–302. https://doi.org/10.3354/meps10100

Brandt, M. J., Höschle, C., Diederichs, A., Betke, K., Matuschek, R., Witte, S., & Nehls, G. (2013b). Far-reaching effects of a seal scarer on harbour porpoises, Phocoena phocoena. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 23, 222–232. https://doi.org/10.1002/aqc.2311

Brookes, K. L., Bailey, H., & Thompson, P. M. (2013). Predictions from harbor porpoise habitat association models are confirmed by long-term passive acoustic monitoring. *Journal of the Acoustical Society of America*, 134, 2523–2533. https://doi.org/10.1121/1.4816577

Burnham, K. P., & Anderson, D. R. (2002). *Model selection and multimodel inference: A practical information-theoretic approach (2nd ed.)*. New York, NY: Springer.

Dahl, P. H., de Jong, C. A., & Popper, A. N. (2015). The underwater sound field from impact pile driving and its potential effects on marine life. *Acoustics Today*, 11, 18–25. Retrieved from https://acousticstoday.org/wp-content/uploads/2015/06/The-Underwater-Sound-Field-from-Impact-Pile-Driving-and-Its-Potential-Effects-on-Marine-Life-Peter-H.-Dahl-Christ-A.-F.-de-Jong-and-Arthur-N.-Popper.pdf

Dahl, P. H., & Reinhall, P. G. (2013). Beam forming of the underwater sound field from impact pile driving. *Journal of the Acoustical Society of America*, 134, El1–El6. https://asa.scitation.org/doi/pdf/10.1121/1.4807430

Dahne, M., Tougaard, J., Carstensen, J., Rose, A., & Nabe-Nielsen, J. (2017). Bubble curtains attenuate noise from offshore wind farm construction and reduce temporary habitat loss for harbour porpoises. *Marine Ecology Progress Series*, 580, 221–237. https://doi.org/10.3354/meps12257

Evans, P. G. H., & Hammond, P. S. (2004). Monitoring cetaceans in European waters. *Mammal Review*, 34, 131–156. https://doi.org/10.1046/j.0305-1838.2003.00027.x

Farcas, A., Thompson, P. M., & Merchant, N. D. (2016). Underwater noise modelling for environmental impact assessment. *Environmental Impact Assessment Review*, 57, 114–122. https://doi.org/10.1016/j.eiar.2015.11.012

Faulkner, R. C., Farcas, A., & Merchant, N. D. (2018). Guiding principles for assessing the impact of underwater noise. *Journal of Applied Ecology*, 55, 2531–2536. https://doi.org/10.1111/1365-2664.13161

Gordon, J., Blight, C., Bryant, E., & Thompson, D. (2019). Measuring responses of harbour seals to potential aversive acoustic mitigation signals using controlled exposure behavioural response studies. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 29, 157–177. https://doi.org/10.1002/aqc.3150

Graham, I. M., Merchant, N. D., Farcas, A., Barton, T. R., Cheney, B., Bono, S., & Thompson, P. M. (2019a). Harbour porpoise responses to pile-driving diminish over time. *Royal Society Open Science*, 6, 190335. https://doi.org/10.1098/rsos.190335

Graham, I. M., Merchant, N. D., Farcas, A., Barton, T. R., Cheney, B., Bono, S., & Thompson, P. M. (2019b). Data from: Harbour porpoise responses to pile-driving diminish over time, *Dryad Digital Repository*. https://doi.org/10.5061/dryad.5qg30sd

Hastie, G., Merchant, N. D., Götz, T., Russell, D. J. F., Thompson, P., & Janik, V. M. (2019). Effects of impulsive noise on marine mammals: Investigating range-dependent risk. *Ecological Applications*, 29, e01906. https://doi.org/10.1002/eap.1906

Hill, D., & Arnold, R. (2012). Building the evidence base for ecological impact assessment and mitigation. *Journal of Applied Ecology*, 49, 6–9. https://doi.org/10.1111/j.1365-2664.2011.02095.x

JNCC (2010). *Statutory nature conservation agency protocol for minimising the risk of injury to marine mammals from piling noise*. 14. Peterborough:. Retrieved from https://hub.jncc.gov.uk/assets/31662b6a-19ed-4918-9fab-8fbcff752046

King, S. L., Schick, R. S., Donovan, C., Booth, C. G., Burgman, M., Thomas, L., & Kurle, C. (2015). An interim framework for assessing the population consequences of disturbance. *Methods in Ecology and Evolution*, 6, 1150–1158. https://doi.org/10.1111/2041-210X.12411

Le Lièvre, C. (2019). Sustainably reconciling offshore renewable energy with Natura 2000 sites: An interim adaptive management framework. *Energy Policy*, 129, 491–501. https://doi.org/10.1016/j.enpol.2019.02.007

Lippert, T., & von Estorff, O. (2014). The significance of parameter uncertainties for the prediction of offshore pile driving noise. *Journal of the Acoustical Society of America*, 136, 2463–2471. https://doi.org/10.1121/1.4896458

Lucke, K., Siebert, U., Lepper, P. A., & Blanchet, M.-A. (2009). Temporary shift in masked hearing thresholds in a harbor porpoise (Phocoena phocoena) after exposure to seismic airgun stimuli. *Journal of the Acoustical Society of America*, 125, 4060–4070. https://doi.org/10.1121/1.3117443

McGarry, T., Boisseau, O., Stephenson, S., & Compton, R. (2017). Understanding the effectiveness of acoustic deterrent devices on minke whale (*Balaenoptera acutorostrata*), a low frequency cetacean. ORJIP Project 4, Phase 2. RPS Report EOR0692. Prepared on behalf of The Carbon Trust. Retrieved from https://www.carbontrust.com/resources/understanding-the-effectiveness-of-acoustic-deterrent-devices-on-minke-whale

Merchant, N. D. (2019). Underwater noise abatement: Economic factors and policy options. *Environmental Science & Policy*, 92, 116–123. https://doi.org/10.1016/j.envsci.2018.11.014

Merchant, N. D., Fristrup, K. M., Johnson, M. P., Tyack, P. L., Witt, M. J., Blondel, P., & Parks, S. E. (2015). Measuring acoustic habitats. *Methods in Ecology and Evolution*, 6, 257–265. https://doi.org/10.1111/2041-210X.12330

Mikkelsen, L., Hermannsen, L., Beedholm, K., Madsen, P. T., & Tougaard, J. (2017). Simulated seal scarer sounds scare porpoises, but not seals: Species-specific responses to 12 kHz deterrence sounds. *Royal Society Open Science*, 4, 170286. https://doi.org/10.1098/rsos.170286

Nabe-Nielsen, J., van Beest, F. M., Grimm, V., Sibly, R. M., Teilmann, J., & Thompson, P. M. (2018). Predicting the impacts of anthropogenic disturbances on marine populations. *Conservation Letters*, 11, e12563. https://doi.org/10.1111/conl.12563

Parsons, E. C. M., Dolman, S. J., Jasny, M., Rose, N. A., Simmonds, M. P., & Wright, A. J. (2009). A critique of the UK's JNCC seismic survey guidelines for minimising acoustic disturbance to marine mammals: Best practise? *Marine Pollution Bulletin*, 58, 643–651. https://doi.org/10.1016/j.marpolbul.2009.02.024

R Core Team (2017). *R: A language and environment for statistical computing*. Vienna, Austria R Foundation for Statistical Computing .

Reinhall, P. G., & Dahl, P. H. (2011). Underwater Mach wave radiation from impact pile driving: Theory and observation. *Journal of the Acoustical Society of America*, 130, 1209–1216. https://doi.org/10.1121/1.3614540

Robinson, S., Lepper, P. A., & Ablitt, J. (2007). The measurement of the underwater radiated noise from marine piling including characterisation of a "soft start" period. In *Proceedings of the Oceans Conference* (pp. 732–737). Piscataway, NJ: IEEE Press. https://doi.org/10.1109/OCEANSE.2007.4302326

Rose, A., Brandt, M., Vilela, R., Diederichs, A., Schubert, A., Kosarev, V., & Piper, W. (2019). Effects of noise mitigated offshore pile driving on harbour porpoise abundance in the German Bight 2014–2016 (Gescha2). Retrieved from https://www.bwo-offshorewind.de/wp-content/uploads/2019/07/study-on-the-effects-of-noise-mitigated-construction-works-on-the-harbour-porpoise-population-in-the-german-north-sea.pdf

Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Jr, C. R. G., & Tyack, P. L. (2007). Marine mammal noise exposure criteria: Initial scientific recommendations. *Aquatic Mammals*, 33, 411–521. https://doi.org/10.1080/09524622.2008.9753846

Southall, B. L., Finneran, J. J., Reichmuth, C., Nachtigall, P. E., Ketten, D. R., Bowles, A. E., & Tyack, P. L. (2019). Marine Mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects. *Aquatic Mammals*, 45, 125–232. https://doi.org/10.1578/AM.45.2.2019.125

Sutherland, W., Dicks, L., Ockendon, N., Petrovan, S., & Smith, R. (2019). *What works in conservation 2019*. Cambridge, UK: Open Book Publishers. doi:10.11647/OBP.0179

Thompson, P. M., Graham, I. M., Cheney, B., Barton, T. R., Farcas, A., & Merchant, N. D. (2020). *Data from: Balancing risks of injury and disturbance to marine mammals when pile driving at offshore windfarms*. Dryad Digital Repository. https://doi.org/10.5061/dryad.34tmpg4hs

Tyack, P. L. (2008). Implications for marine mammals of large-scale changes in the marine acoustic environment. *Journal of Mammalogy*, 89, 549–558. https://doi.org/10.1644/07-MAMM-S-307R.1

Van der Meij, H., Kastelein, R., Van Eekelen, E., & Van Koningsveld, M. (2015). Faunaguard: A scientific method for deterring marine fauna. *Terra et Aqua*, 138, 17–24. Retrieved from https://www.iadc-dredging.com/article/faunaguard-scientific-method-deterring-marine-fauna/

Weir, C. R., & Dolman, S. J. (2007). Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. *Journal of International Wildlife Law & Policy*, 10, 1–27. https://doi.org/10.1080/13880290701229838

Williams, R., Erbe, C., Ashe, E., Beerman, A., & Smith, J. (2014). Severity of killer whale behavioral responses to ship noise: A dose–response study. *Marine Pollution Bulletin*, 79, 254–260. https://doi.org/10.1016/j.marpolbul.2013.12.004

Williamson, L. D., Brookes, K. L., Scott, B. E., Graham, I. M., Bradbury, G., Hammond, P. S., & Thompson, P. M. (2016). Echolocation detections and digital video surveys provide reliable estimates of the relative density of harbour porpoises. *Methods in Ecology and Evolution*, 7, 762–769. https://doi.org/10.1111/2041-210X.12538

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

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.