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Vessel noise prior to pile driving at offshore windfarm sites deters harbour porpoises from potential injury zones

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ABSTRACT

Efforts to meet climate change targets are resulting in rapid and global expansion of offshore windfarms. In many regions, development areas are also used by protected marine mammals, requiring the assessment and mitigation of any risk of injury during construction and operation. For small cetaceans such as the harbour porpoise, there is particular concern over the risk of injury from impulsive noise should individuals remain within near-field injury zones during the installation of pile driven turbine foundations. Currently, this risk is assessed by comparing predicted noise levels at the start of piling with baseline estimates of animal density, which are, in turn, based on data collected at least one year earlier. However, vessel-based preparation work immediately prior to piling may displace animals, thus reducing any risk of injury when pile-driving begins. We investigated the effects of pre-piling activities on local soundscapes and harbour porpoise occurrence during the construction of two deep-water offshore windfarms in NE Scotland. Arrays of echolocation click detectors deployed at a sub-set of turbine sites were used to assess porpoise occurrence within a 5 km buffer during a 48-h period prior to the initiation of piling. In parallel, we characterised local vessel activity using AIS data and underwater broadband noise levels. We then used daily engineering records to characterise variation in construction activities and explore how porpoise occurrence varied during the 48 h prior to piling. On average, vessels arrived onsite 11–15 h before the start of pile-driving activities at both windfarms. In both installation campaigns, harbour porpoise acoustic detection gradually declined by up to 33% during the 48 h prior to piling. This decrease in detections was associated with increased levels of vessel and pre-piling installation activities, and increased local underwater broadband noise levels. These results provide strong evidence of porpoise displacement prior to active mitigation activities, highlighting the need to account for disturbance from multiple sources when optimising mitigation measures aimed at reducing impacts of windfarm construction on protected marine mammal populations.

1. Introduction

The offshore windfarm industry is expanding rapidly to support many nations' net zero ambitions, requiring the development of installation techniques and mitigation measures to minimise environmental impacts (Le Lièvre, 2019). Concern over potential impacts upon marine mammals has typically focussed on assessing and mitigating the effects of intense impulsive underwater noise during pile-driving (Tougaard et al., 2003; Carstensen et al., 2006; Brandt et al., 2011; Teilmann and Carstensen, 2012; Dähne et al., 2013; Russell et al., 2016; Dähne et al., 2017; Brandt et al., 2018; Graham et al., 2019; Thompson et al., 2020; Whyte et al., 2020). Near field, these impulsive noise sources have the potential to instantaneously injure marine mammals (Southall et al., 2008; Southall et al., 2019). In the far-field, disturbance is a concern (e.g. Graham et al. (2019)), since it may reduce foraging opportunities (Wisniewska et al., 2018; Benhemma-Le Gall et al., 2021) and have population level impacts that must be assessed by regulators to meet environmental legislation (Booth et al., 2017; Nabe-Nielsen et al., 2018).

Where marine mammals may occur within construction sites and predicted injury zones, mitigation measures must be integrated into the engineering procedures to reduce the risk of near-field injury from pile-driving noise. The measures used vary within different regulatory systems, but typically aim either to: 1) ensure animals are absent from a potential injury zone before piling is initiated by conducting visual or

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acoustic observations prior to piling (JNCC, 2010); 2) deter animals from the potential injury zone by using Acoustic Deterrent Devices (ADDs) and soft start protocols (Thompson et al., 2020); or 3) attenuate pile-driving noise using noise abatement techniques (e.g. bubble curtains) (Dähne et al., 2017; Brandt et al., 2018). However, there are difficult trade-offs to balance when choosing and implementing mitigation measures (Abramic et al., 2022). Both visual and passive acoustic monitoring may fail to detect animals that enter the injury zone (JNCC, 2010). The efficacy of ADDs for many species remains uncertain and, where effective, ADDs may have far-field disturbance effects (Brandt et al., 2013b; Gordon et al., 2019; Thompson et al., 2020; Findlay et al., 2021). The efficacy of noise abatement techniques also remains uncertain, particularly in deeper waters (Verfuss et al., 2019; Wagenknecht, 2021). Noise abatement techniques may also require additional vessels onsite (Brandt et al., 2018) or extend construction schedules, which could impact marine mammals through altered underwater soundscapes and have broader environmental impacts.

Mitigation measures should be optimised using a risk-based approach. In particular, the level of mitigation required should be based on the likelihood of individuals of different species being present within potential injury zones at the start of piling activity. Currently, such decisions are made using baseline data that are collected at least one year before construction. However, pre-piling activities have the potential to disturb marine mammals through increased levels of background noise and vessel activity and thus are likely to change baseline distribution of animals. For example, harbour porpoise detections declined in the three hours prior to piling activities at eleven offshore windfarms in the German Bight (Rose et al., 2019). This was assumed to be related to construction traffic, but empirical data on vessels were not available to test this assumption (Brandt et al., 2018; Rose et al., 2019). The impact of vessel noise, occurrence and/or activity on harbour porpoise behaviour has been extensively reported in coastal waters (Hermannsen et al., 2014; Dyndo et al., 2015; Oakley et al., 2017; Wisniewska et al., 2018; Hermannsen et al., 2019), and at offshore

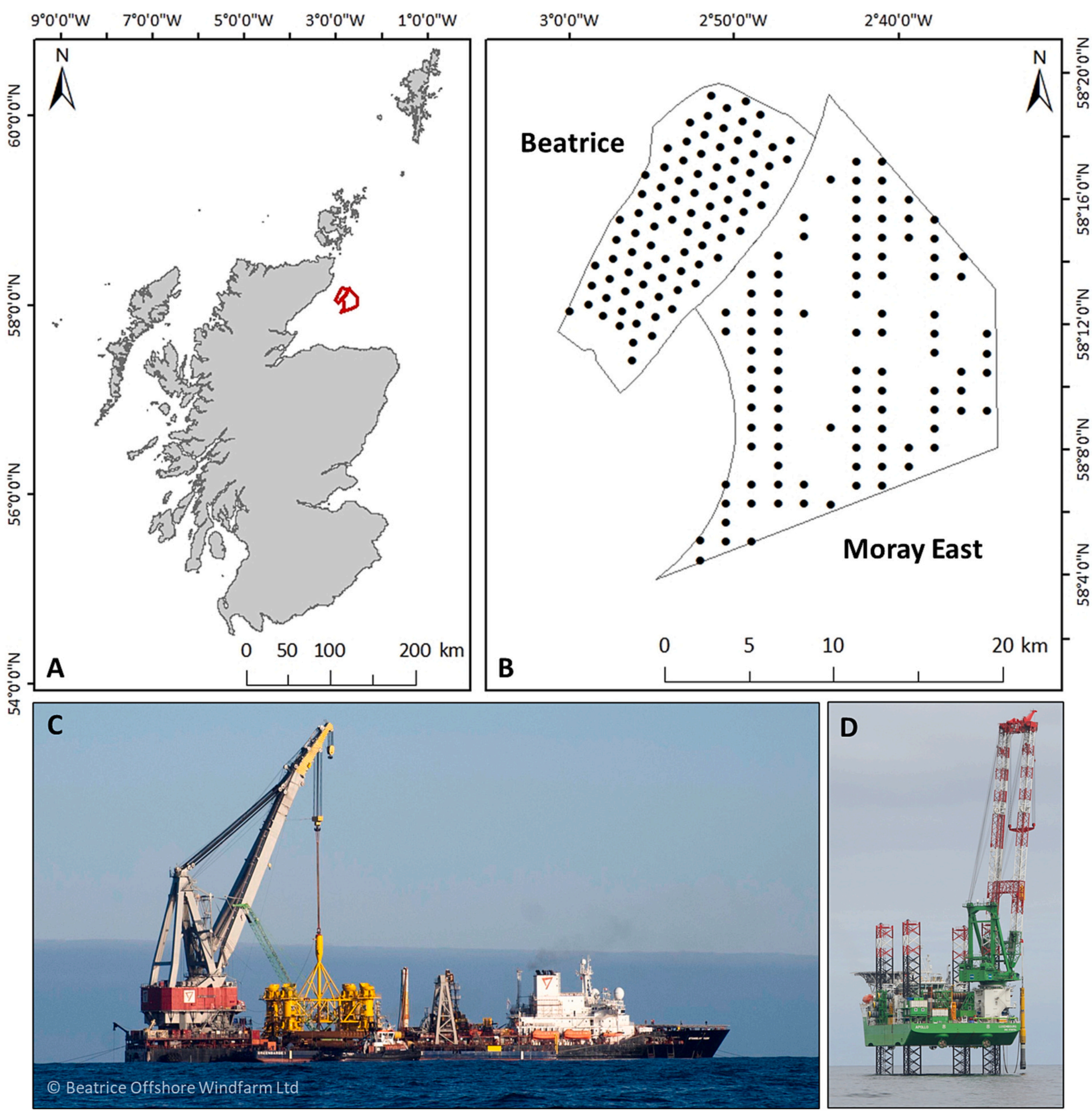

Fig. 1. A) Beatrice and Moray East offshore windfarms in red are located in the outer Moray Firth, NE Scotland; B) Beatrice and Moray East offshore windfarms (black lines) and piling sites (black dots); C) Heavy lift piling vessel deploying the pile installation frame (PIF) at Beatrice offshore windfarm; D) Heavy lift jack-up piling vessel deploying the hammer at Moray East offshore windfarm.

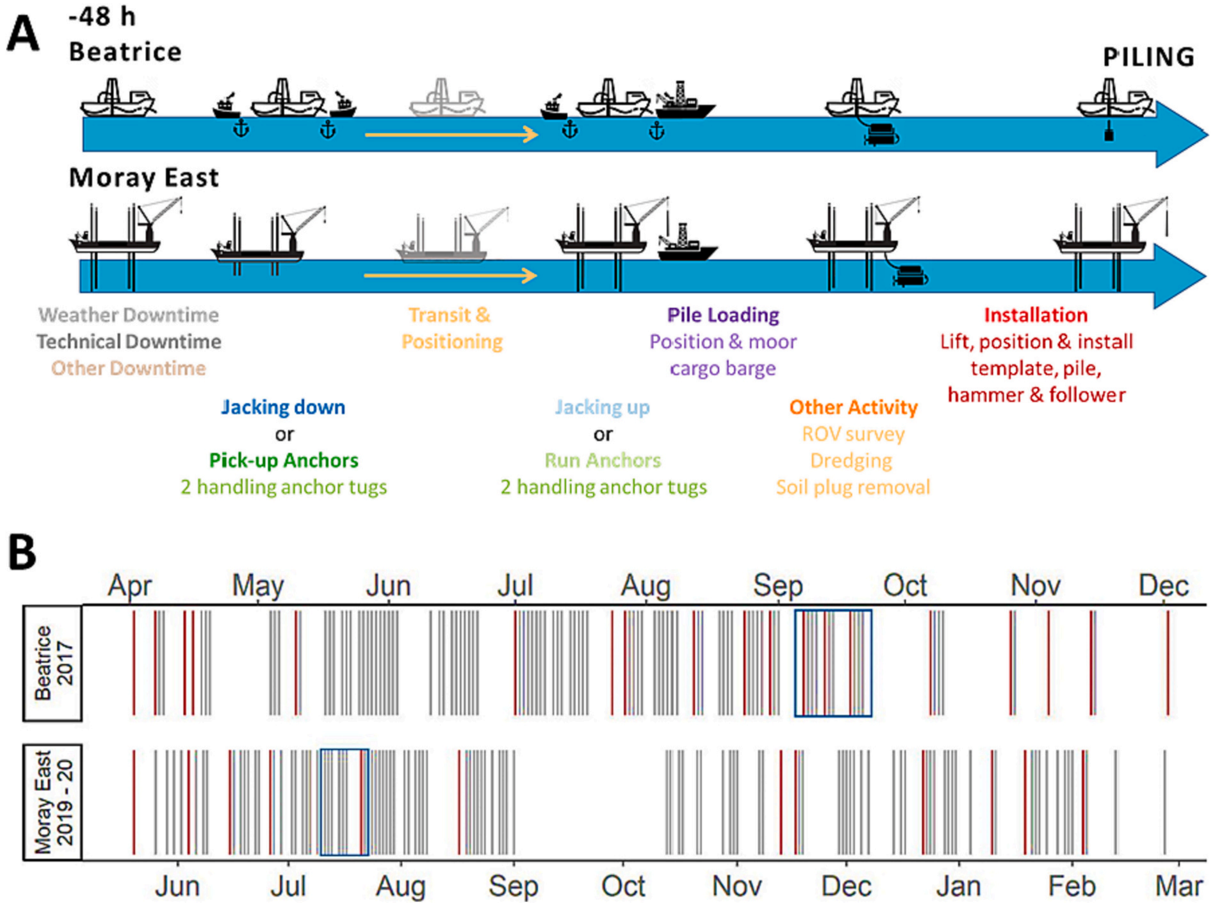

Fig. 2. A) Schematic of activities conducted by the piling and ancillary vessels prior to piling at Beatrice and Moray East offshore windfarms. B) Pile-driving timeline with the lines representing piling bouts and the red lines those bouts selected for the study; the blue rectangle indicates the time period during which underwater noise recordings were collected.

windfarm sites (Brandt et al., 2018; Graham et al., 2019; Benhemma-Le Gall et al., 2021). The increase in vessel activity prior to piling is expected to disturb porpoises and could potentially act as deterrent. Additionally, better understanding of variation in marine mammal occurrence prior to the start of impulsive noise activities would reduce the uncertainty in the number of individuals likely to be in the injury zone when piling is initiated. Mitigation measures can then be optimised to ensure near-field animal displacement while minimizing unnecessary far-field disturbance (Thompson et al., 2020).

Here, we address this data gap by investigating variation in harbour porpoise occurrence, levels of vessel activity and underwater broadband noise during the 48-h period prior to pile-driving at the UK's first two large-scale deep-water offshore windfarms. We characterise the different activities conducted by the piling and ancillary vessels. Finally, we discuss the wider management implications of the results and provide recommendations for optimising construction work while integrating context-dependent, adaptive mitigation measures.

2. Material and methods

2.1. Characterisation of construction activities

The study was conducted around the Beatrice and Moray East offshore windfarms, at the Smith Bank, in the outer Moray Firth, NE Scotland (Fig. 1A) (for details see Benhemma-Le Gall et al. (2021)). These two windfarms are located 15 km offshore on a shallow sand bank, the Smith Bank, with water depths ranging between 35 and 68 m (Fig. S1A). Sediment type slightly varied between the two windfarms (Fig. S1B). Harbour porpoises are distributed throughout the Moray Firth, but higher densities have been recorded at the Smith Bank (Brookes et al., 2013; Williamson et al., 2016; Williamson et al., 2021). At both windfarms, turbines were installed on jacket structures that were pin-piled to the seabed, but differences in the type of installation vessels used (anchored vs jack-up) (Fig. 1C and Fig. 1D) provided valuable comparative data on sound levels from each installation method.

Piling at the Beatrice windfarm occurred on 103 days, between 2nd April and 2nd December 2017, and required impulsive pile driving techniques to install a set of four piles at each of the 84-wind turbine and two-Offshore Transformer Module locations (Graham et al., 2019) (Fig. 1B and Fig. 2B).

Prior to the pile installation works, the heavy lift vessel *Stanislav Yudin* was positioned by two dedicated anchor handling tugs using an eight-point anchor spread and a pile installation frame (PIF) was lowered onto the seabed (Fig. 1C). A cargo barge delivered the four piles to the piling vessel, which then placed each pile in the PIF sleeves. Piling at the Moray East offshore windfarm occurred on 132 days, between 19th May 2019 and the 27th February 2020. Similar impulsive pile driving techniques were used to install a set of three piles at each of the 100-wind turbine and three-Offshore Substation Platform locations. Prior to piling operations, the heavy lift jack-up vessel *Apollo* was dynamically positioned and jacked up to operational draft (Fig. 1D). At every two locations, a supply vessel delivered six pin piles to the piling platform, which loaded them onto the deck. As at Beatrice, the PIF was lowered onto the seabed and the three piles were positioned into the PIF sleeves. At both windfarms, mitigation required an Acoustic Deterrent Device

(ADD) to be deployed to deter marine mammals from the predicted near-field injury zone and a soft start piling procedure implemented prior to the start of piling (for more details see Thompson et al. (2020)).

A schematic of the sequence of activities undertaken prior to the deployment of the ADD mitigation and pile-driving is provided in Fig. 2A. Information on the type and duration of vessel activities during this pre-piling phase of installation were extracted from engineering logs, and details are presented in the Supplementary Materials (Table S 1 and Table S 2).

No other piling or seismic activities occurred in the Moray Firth during the study period.

2.2. Piling timeline

As outlined in Thompson et al. (2020), ADDs were deployed, at both windfarms, for 15 mins prior to the start of piling, followed by a soft start. On some occasions, piling events at individual turbine locations were spread across several days due to weather or technical downtime. For this study, we focussed on piling bouts that occurred at the same turbine location with no breaks in piling of >12 h. Additionally, we considered only the subset of turbine locations where piling bouts had at least a two-day gap between the end of piling at the previous turbine location and the start of piling at the focal turbine location (Fig. 2B). Preliminary analyses of engineering logs showed that the piling vessel arrived onsite on average 11.2 h (first and third quartiles (Q1-Q3): 10.7–14.5 h) before the start of pile-driving activities at Beatrice, and around 15.1 h (Q1-Q3: 9.6–23.3 h) at Moray East. Based on these findings, our main analyses focussed on the period 48 h prior to the start of piling at each location. Locations at which the piling vessel arrived onsite >48 h prior to the start of piling were excluded from these analyses. At the 22 sites remaining in the analyses (Fig. 3), vessel data were considered in relation to the Hour Relative to Piling (HRP) ranging from −48 to 0 h. The start of hour 0 was taken from the time at which the ADD was activated. Therefore, hour 0 represents the hour in which active mitigation measures (ADD and piling soft start) were conducted prior to the start of piling.

2.3. Spatial analysis of vessel-tracking data

Vessel activity around turbine locations was extracted for all months in which piling took place using 1 and 5 min-resolution Automatic Identification System (AIS) vessel-tracking datasets (Astra Paging Ltd. and Anatec Ltd.). Following the procedure used by Benhemma-Le Gall et al. (2021), vessel-tracking data were processed to produce an hourly index of vessel intensity within a 5 km buffer around each piling location, to be used as the response variable in the *vessel model* (see section 2.6). A 5 km buffer was chosen, as Benhemma-Le Gall et al. (2021) found that increased vessel activity influenced porpoise occurrence at distances up to 4 km. Georeferenced AIS data, and piling locations were first projected into WGS84 UTM 30 N using the *sf* package in R (Pebesma, 2018; R Core Team, 2019). AIS data were then interpolated either every 1 min for the noise analyses or every 5 min for the other analyses, and spatially filtered to retain data within a 5 km buffer around each location. The interpolated vessel locations were then temporally filtered to extract vessel locations that were recorded in each HRP. To highlight the magnitude of vessel intensity from ancillary vessels around construction sites, we focused this analysis on additional vessels that were within the 5 km buffer around piling locations and excluded the piling vessel at both windfarms.

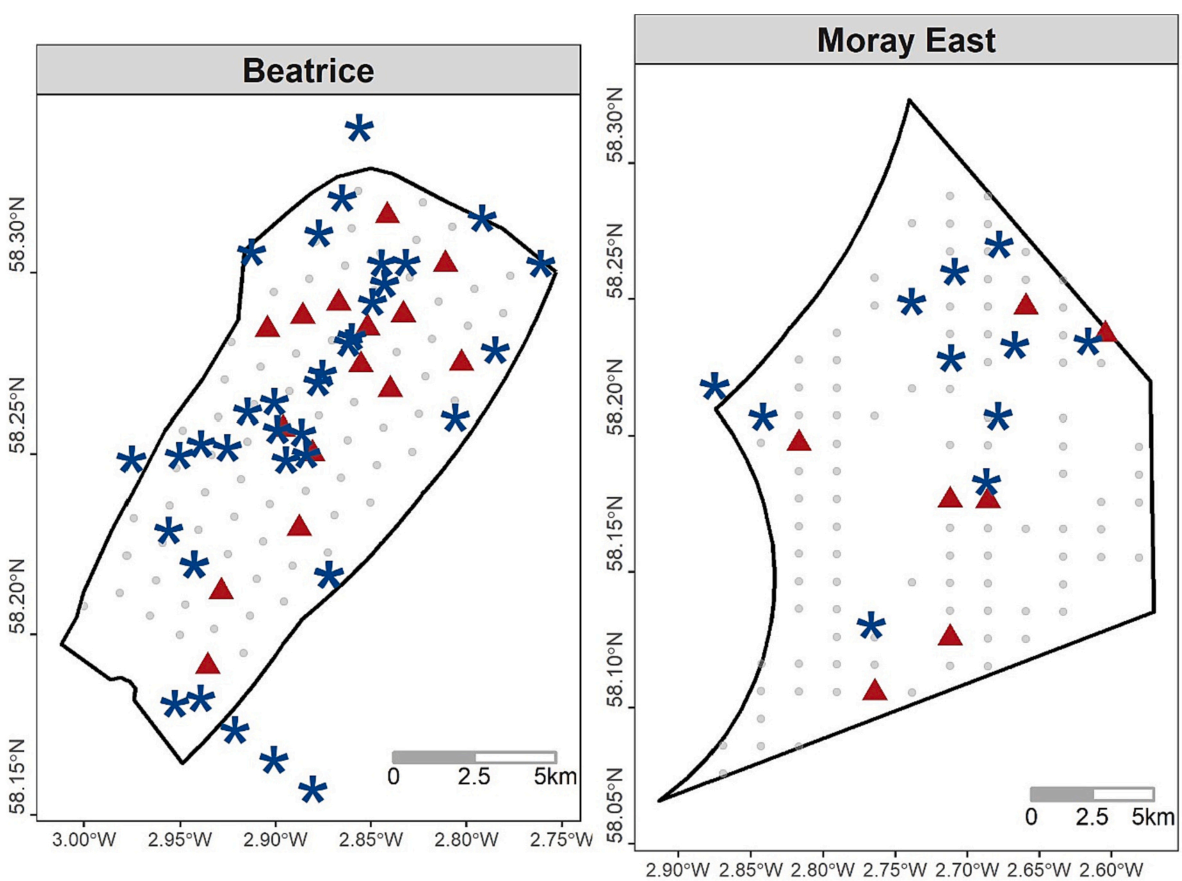

Fig. 3. Spatial distribution of the echolocation clicks detectors (CPODs; blue stars) within 5 km of the subset of piling locations (red triangles) selected for the study at Beatrice and Moray East offshore windfarms; grey circles represent the turbine and substation layouts at both windfarms.

2.4. Passive acoustic monitoring

During both piling campaigns, an array of echolocation click detectors (V.0 ($n = 3$), and V.1 ($n = 52$) CPODs; www.chelonia.co.uk) was deployed within the two windfarm sites, following the sampling design used in Graham et al. (2019). A subset of these data from within 5 km of active piling locations were used here to investigate variation in harbour porpoise occurrence during pre-piling activities at each windfarm site (Fig. 3). Data were processed and extracted with the manufacturer's software CPOD.exe (v2.044). High and moderate quality Narrow Band High Frequency echolocation click trains of porpoise origin were identified and filtered using the standard "KERNO" classifier. For each CPOD, the number of porpoise echolocation clicks was exported, summarised and converted into presence-absence of detections per HRP for each piling location, to be used as the response variable in the *porpoise models* (see section 2.6).

To ensure that high levels of background noise did not saturate memory and prevent the CPODs from logging clicks (Wilson et al., 2013; Clausen et al., 2019), we only kept data from hours which recorded clicks in all 60-min samples within the hour. Additionally, to prevent any masking effect of vessel noise on porpoise echolocation click detections, we only included hours during which the minimum vessel distance from CPOD locations was >1 km. This threshold was based upon previous analysis of data from NE Scotland which suggested that vessel noise was unlikely to saturate the CPOD click threshold beyond 1 km (Pirotta et al. (2014)'s Supplementary material).

In separate models (i.e., *Beatrice* and *Moray East Control-Impact porpoise models*), we used PAM sites that were outside the 5 km buffer around the construction sites as reference sites to compare variation in harbour porpoise occurrence within vs outside the 5 km "impact" zones, for each windfarm (see Supplementary Material, Figs. S 4A and S 4B).

2.5. Variation in broadband noise levels

Calibrated measurements of underwater broadband noise levels were made for 7–19 days in September 2017 at Beatrice and for 12 days in July 2019 at Moray East. In each case, three bottom-mounted noise recorders (Ocean Instruments SoundTrap, ST300HF) were moored at distances of 0.5 to 5 km from piling locations (Fig. 4). At Beatrice, recorders were duty cycled (1/10 mins) with a sampling rate of 576 kHz. At Moray East, continuous recordings were made with a sampling rate of 48 kHz (see Table S 4 for details). During these short-term deployments, eight turbine locations were piled at Beatrice and seven at Moray East (Fig. 4). Data were processed through MATLAB following Merchant et al. (2015) and broadband Sound Pressure Levels (SPL) were extracted at 1-min resolution.

To compare pre-piling broadband noise levels at the two windfarm sites, we selected a subset of 6 piling locations (three for each site) for which there was a gap of at least 24 h between piling events. We summarised the mean broadband noise levels per hour relative to piling, from 24 h prior to the start of piling and deterrence activities, to allow comparison with the hourly variation in porpoise occurrence and vessel intensity prior to piling, and to be used as the response variable in the *noise model* (see section 2.6). For each one-minute sample, Euclidean distances between the noise recorder deployment sites and 1) the piling vessel and 2) any other vessels within a 5 km buffer around the noise recorder were calculated. Inspection of the AIS data revealed that the majority of vessels within the windfarm sites were involved in construction and did not transit long distances within an hour. Therefore, the mean distance to the piling vessel and the minimum distance to any other vessels were summarised per hour relative to piling and then log-transformed. These metrics were included in models as the background noise levels were likely influenced by the presence and distance from

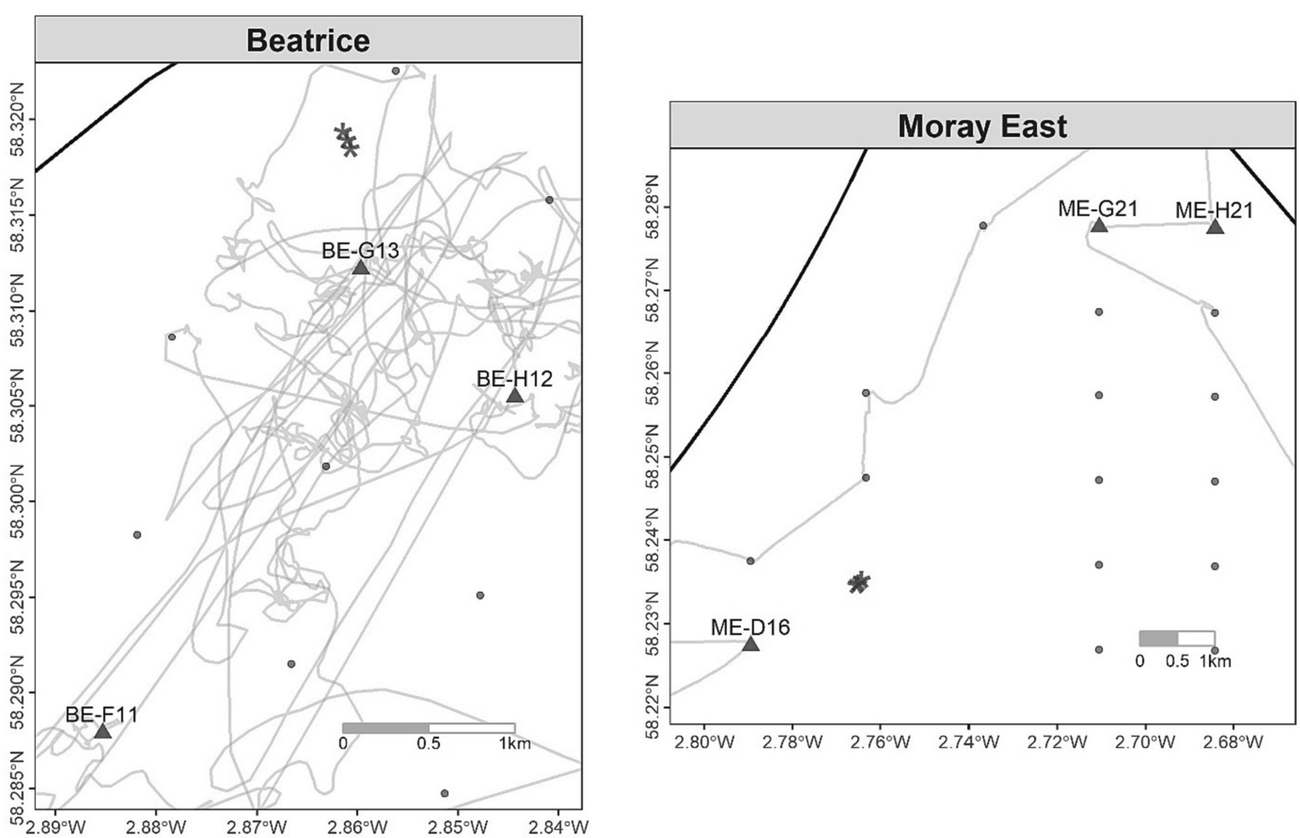

Fig. 4. Maps of the turbine sites piled at Beatrice offshore windfarm between 5 and 23 September 2017 and at Moray East offshore windfarm between 10 and 24 July 2019 (triangles), used for the noise analyses. Noise recorder deployment sites are represented as stars; the grey lines represent the piling vessel track line during the indicated time period; the dots are the turbine sites piled outside the indicated time period.

other noise sources such as other vessels.

2.6. Modelling

Overall differences in harbour porpoise acoustic detections and levels of vessel intensity in the 48-h period prior to piling were compared between the two windfarms using a Mann-Whitney *U* test (Mann and Whitney, 1947). Generalised Additive Models (GAMs) were used to characterise variation in porpoise detections and vessel intensity during the 48 h before to the first hour of deterrence and piling activities at each windfarm. In the *porpoise models*, the binary presence/absence of porpoise detections per HRP (see section 2.4) was fitted with a binomial distribution and a *probit* link function using the *gam* function of the *mgcv* R package (Wood, 2011). Similarly, in the *vessel model*, the vessel intensity (see section 2.3), ranging from 0.0 to 4.9 min.km^{-2}, was squared-rooted and then used as the response variable and fitted to a Tweedie distribution. The continuous variable *HRP*, ranging from −48 to 0, defined by a cubic regression spline, was included as the explanatory variable in interaction with the factor *windfarm ID* in the *porpoise* and *vessel* models. Two additional *porpoise* models were fitted for the data for each windfarm separately, the *Control-Impact porpoise* models. In these two models, the factor *Control-Impact* was included as an explanatory variable in interaction with the continuous variable *HRP*.

A GAM was also used to characterise variation in mean broadband noise levels during the 24 h to the first hour before piling activities at each windfarm. In the *noise model*, the mean broadband SPLs (see section 2.5), ranging from 101.1 to 142.1 dB re 1 μPa, were used as the response variable and fitted to a Gamma distribution, with the *inverse* link function. The explanatory variables used for this model were the continuous variable *HRP*, ranging from −24 to −1, in interaction with the factor *windfarm ID*.

To avoid under- or overfitting the GAM models, the basis dimension *k* was arbitrarily set large and then reduced based on the model diagnosis tool of the *gam.check* function. A double penalty approach and the Restricted Maximum Likelihood (REML) method were used for automatic term and smoothness selection. To account for potential temporal autocorrelation in porpoise detections between hours relative to piling for each piling bout, a temporal autocorrelation *corA1* was used.

To compare variation in broadband noise levels between windfarm construction sites from 24 h to the first hour of piling activities, a linear model was used with the mean SPLs as response variable. The log *(mean distance)* to the piling vessel, and the factor windfarm in interaction with the *log (*min *distance)* to any vessels were the explanatory variables.

3. Results

At our sub-set of turbine locations, piling vessels arrived onsite and started anchoring or jacking up on average between 11 and 15 h prior to piling (Table 1). At Beatrice, 32 PAM sites within 5 km of the 15 turbine locations (*n* = 4320 h) were used to estimate variation in porpoise detections. Sample sizes at Moray East were slightly smaller, with 11 PAM sites within 5 km of 7 turbine locations (*n* = 555 h, Table S 5). Overall, harbour porpoise occurrence was higher at Moray East, with a mean porpoise detection probability per hour of 0.37 against 0.25 at Beatrice (W = 1,063,905, $p < 0.0001$). Additionally, levels of vessel intensity were significantly higher at Beatrice with an averaged vessel intensity of 1.30 min.km^{-2} against 0.93 min.km^{-2} at Moray East (W = 1,692,352, $p < 0.0001$).

Table 1
Sample size, sampling effort, overall vessel intensity, porpoise detection probability at selected piling locations at the Beatrice and Moray East offshore windfarms; PAM stands for Passive Acoustic Monitoring; for further information on the sample size per hours relative to piling (HRP) see Table S 5.

Windfarm	Turbine Locations (N)	PAM Sites (N)	Vessel intensity (min. km^{-2}) Mean [min; max]	Piling vessel time of arrival (hour) Median	Porpoise detection probability per hour
Beatrice	15	32	1.30 [0.00; 4.9]	−11.23	0.25
Moray East	7	11	0.93 [0.13; 2.8]	−15.09	0.37

3.1. Variation in construction activity, vessels and porpoise occurrence prior to piling activity

During the 48-h pre-piling phase, the main activity recorded at both windfarms was *Weather Downtime*. Levels of downtime decreased to <50% about 12 h before piling at Beatrice and 6 h at Moray East, while in parallel, levels of *Anchoring*, *Pile Loading* and *Installation* activities increased (Fig. 5A). The higher proportions of *Running Anchors, Pile Loading* and *Installation* activities were coincident with an increase in vessel intensity and with a 24% (± 3%) decrease in porpoise occurrence at Beatrice from −18 HRP (see Fig. 5A, Fig. 5B and Fig. 5C; Fig. S 3). At Moray East, higher levels of vessel intensity were associated with *Pile Loading* and *Installation* activities (Fig. 5A; Fig. S 3) and porpoise occurrence started decreasing from −25 HRP by up to 18% (± 10%) (Fig. 5C). The decrease in porpoise occurrence from around −8 to 0 HRP at both windfarms was closely associated with a large increase in installation activities and was not observed at the reference sites that were >5 km from the construction site (Fig. S 4). Overall, in the pre-mitigation phase, when no mitigation measures were used (between −48 and − 1 HRP), porpoise acoustic detection decreased by 32.8% (±4.4%) at Beatrice and by 13.2% (±2.1%) at Moray East. An additional decrease of 1.2% (±0%) at Beatrice and of 1.2% (±0.7%) at Moray East were recorded between −1 HRP and the active mitigation phase (0 HRP), during which ADD and soft start procedures were undertaken.

3.2. Soundscape in the vicinity of a subset of piling locations

A total of 365 h were used to investigate variation in broadband noise levels. Broadband noise levels varied significantly through the 24 h prior to the start of piling at Beatrice ($F_{5.52,\,6} = 30.43$, $p < 0.0001$) but not at Moray East ($F_{1.1,\,6} = 0.51$, $p = 0.06$) (Fig. 6). At Beatrice, for the three piling locations investigated in this analysis, a peak in mean SPLs, ranging between 120.3 and 126.2 dB re 1 μPa, was detected between −13 and − 8 HRP (Fig. 6A) during which the main activities were *Running* and/or *Picking up anchors*, and *Mooring cargo barge.*

Furthermore, overall broadband noise levels during the 24 h period before piling differed with the log*(mean distance)* to the piling vessel ($F_{1,\,351} = 9.29$, $p < 0.003$) and between windfarm sites in interaction with the *log(min distance)* to any vessels within a 5 km-radius around noise recorder locations ($F_{1,\,351} = 15.66$, $p < 0.0001$). Noise levels were estimated to be 4.2 dB louder at Moray East than at Beatrice, when standardised with the piling vessel at 3.5 km and other vessels at 2.5 km from noise recorders (Fig. 6B). Noise levels were negatively related to the distance from the piling vessel and from any other vessels (Fig. S 5).

4. Discussion

Efforts to assess and mitigate environmental impacts of proposed offshore windfarms require good understanding of different construction procedures and responses of key receptors such as marine mammals. As a relatively new industry, with rapidly evolving infrastructure, this has led to significant uncertainties during consenting. Previous strategic monitoring in Scottish (Graham et al., 2019; Thompson et al., 2020) and other regions (Tougaard et al., 2003; Teilmann and Carstensen, 2012; Dähne et al., 2013; Brandt et al., 2018) has focused primarily on marine mammal responses to pile-driving and deterrence activities. Here, we specifically focused on assessing cumulative effects

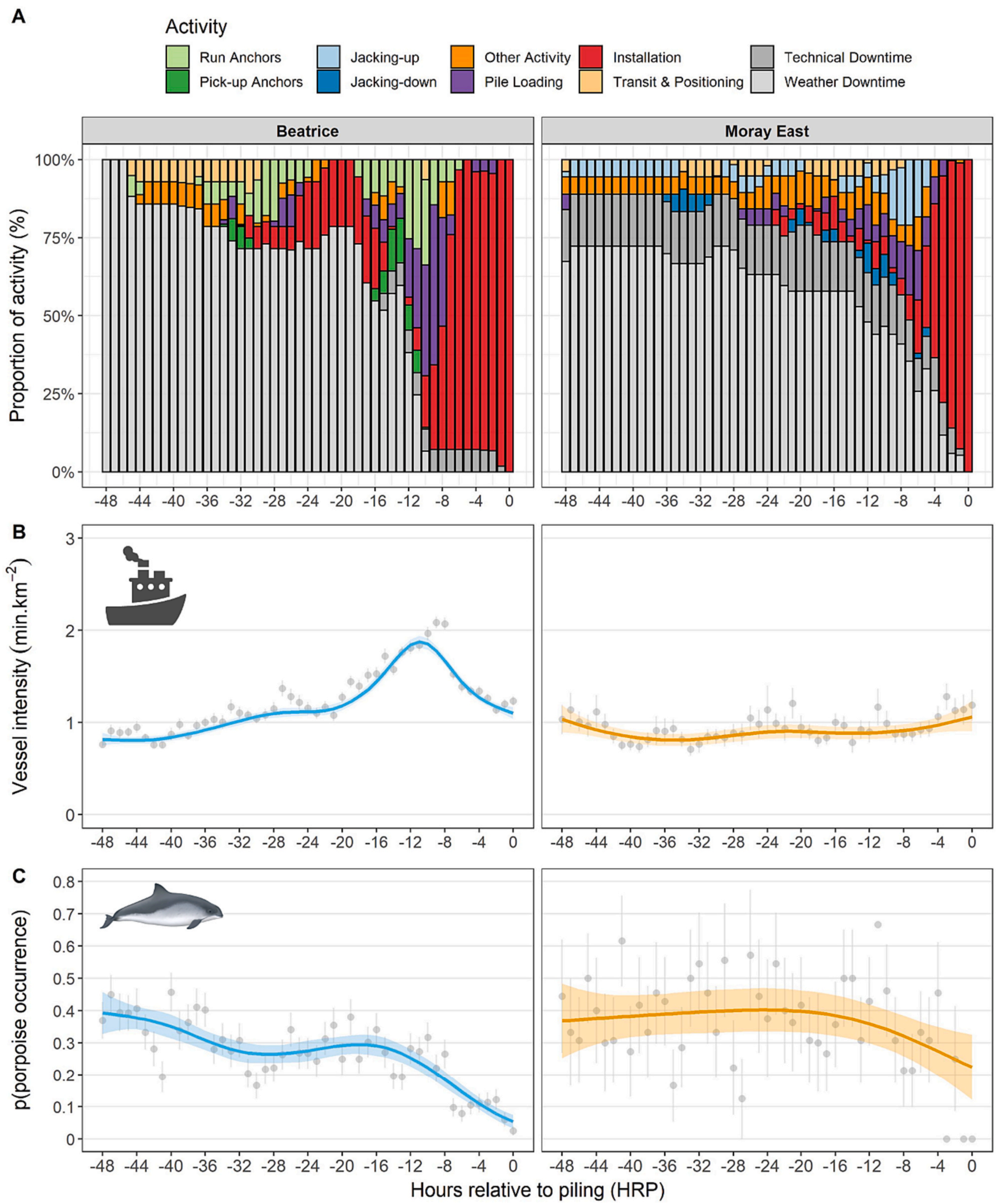

Fig. 5. Variation in A) percentage of time spent undertaking specific construction activities B) vessel intensity (min.km^{-2}) and C) probability of porpoise occurrence throughout the 48 h prior to the start of pile-driving activities at a subset of piling locations at Beatrice and Moray East offshore windfarms. In figs. B and C, grey dots represent the mean of observed data, the line range represents the standard error; the blue and yellow lines are the GAM fitted lines and the shaded areas represent the 95% confidence intervals to estimate the uncertainty. For further information on the sample sizes in each hour relative to piling see Table S 5.

of pre-piling activities to optimise mitigation of piling impacts. These data highlight how differences in construction vessels and operational procedures may, to some extent, influence variation in the local soundscape and in harbour porpoise occurrence at those construction sites.

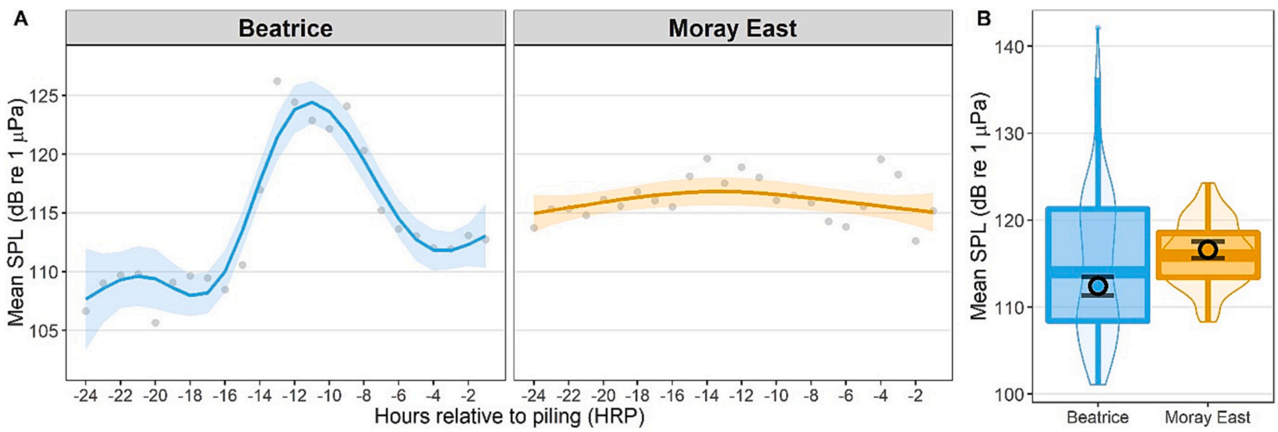

Fig. 6. A) Mean broadband sound pressure levels (SPLs) per hours relative to piling (i.e. from 24 h to the first hour before the start of pile-driving activities) at three piling locations at both the Beatrice and Moray East offshore windfarms ($n = 6$); the grey dots represent the mean values of observed data; the blue and yellow lines are the GAM fitted lines and the shaded areas represent the 95% confidence intervals to estimate the uncertainty; B) Observed (boxplot and violin plot) and estimated (black circle and error bar) mean SPLs per windfarm, when the mean distance from the piling vessel is fixed at 3.5 km and the minimum distance to any vessel is fixed at 2.5 km.

4.1. Construction activities throughout the piling campaign

Whilst both windfarms used pin-piled jacket structures for their foundations, the piling vessels and engineering processes used were markedly different; with Beatrice using an anchored piling vessel and Moray East a jack-up vessel. These different procedures led to variations in the time spent undertaking key construction activities (e.g. *Installation, Pile Loading, Anchoring/Jacking-up* and *down*) between the two piling campaigns (Table S 3). During *Pile Loading*, six piles were delivered to the piling vessel at Moray East against four at Beatrice, resulting in longer times undertaking this activity at Moray East. On the other hand, jacket structures required only three pin-piles at Moray East against four at Beatrice, and *Installation* activities were shorter at Moray East. Using an installation vessel that was jacked-up and down at Moray East took slightly less time than running and picking up anchors at Beatrice. Both piling vessels spent much of their time in weather downtime (51% of the time at Beatrice and 38% at Moray East) highlighting the logistical and financial challenges of construction work offshore (Table S 3). Although observed differences in time spent in other activities at the two windfarms were small, these data highlight how the choice of vessel type or procedures may influence overall costs and timings of piling campaigns.

4.2. Variation in vessel activity at the two windfarms

Higher levels of vessel intensity were observed at Beatrice compared to Moray East, but a peak in intensity in the period before piling was observed at both sites (Fig. 5B). Higher vessel activity at Beatrice was primarily due to anchoring activities requiring two anchor handling tugs. For both developments, *Pile Loading* and *Installation* activities were also associated with higher levels of vessel intensity (Fig. S 3) but the frequency of pile loading activities varied between the two campaigns. This again highlights how differences in vessels and installation techniques may influence spatio-temporal variation in soundscapes both within the sites and around associated shipping lanes and ports. The piling vessel at Beatrice was not anchored during weather downtime, whereas the Moray East vessel was jacked up, thus reducing the spatial footprint of vessel activity (see Fig. 4). Choices over piling vessel and scheduling of equipment supply or crew transfers therefore provide opportunities to manage both vessel intensity and soundscapes during construction, though this must be balanced against overall costs and carbon emissions associated with different options. In this study, all vessels involved in construction were detected through their use of AIS, but decisions over management of other marine activities within construction sites may also affect levels of vessel activity and underwater soundscapes. We were unable to fully investigate this because some fisheries activity continued within both construction sites, but this could not be quantified because inshore fishing vessels often operated without using AIS.

4.3. Variation in harbour porpoise occurrence and background noise levels

During eleven windfarm developments in German waters, a 14–16% decrease in porpoise detection rates was observed in the three hours before piling within a 5 km buffer around construction sites (Rose et al., 2019). Rose et al. (2019) suggested that this drop in porpoise occurrence was related to vessel traffic, but they were not able to quantify variation in vessel activity to explore this further. In our study, harbour porpoise acoustic detection decreased by 32.8% (±4.4%) at Beatrice and by 13.2% (±2.1%) at Moray East, in the 48 h before the start of mitigation measures and piling (from −48 to −1 HRP) (Fig. 5C). Using AIS vessel tracking data and daily engineering records, we were able to associate these declines with increased levels in vessel intensity, especially at Beatrice offshore windfarm (Fig. 5B), but also with the increase in installation activities (Fig. 5A). Thus, during the pre-mitigation phase, the combination of both increased levels of vessel intensity and installation activities may act as a deterrent. Harbour porpoise acoustic detection decreased by an additional 1.2%, within 5 km buffer around construction sites, during the active mitigation phase, when ADD and soft start procedures were conducted. Whilst these mitigation measures aimed to disperse animals from the near-field injury zone (Thompson et al., 2020), vessels and installation activities are likely to have displaced animals, prior to the start of mitigation. The pre-mitigation phase can therefore provide opportunities for self-mitigation in construction preparation and optimization. Furthermore, at the subset of piling locations studied, broadband noise levels increased between 8 h and 13 h before piling activities at Beatrice (Fig. 6A). This peak in noise levels likely coincided with increased numbers of vessels and louder activities such as running anchors and/or pile loading. In contrast, no consistent pattern in noise levels were detected at Moray East in the 24 h before piling. Based on the sample of three sites within each development, noise levels associated with Moray East were on average 4.2 dB louder than at Beatrice (Fig. 6B). Although broadband noise levels averaged over 24 h period were higher at Moray East, this metric does not reveal subtle changes in noise levels that may trigger porpoise responses nor peak noise levels that were higher at Beatrice. Higher levels of broadband noise at Moray East may be due to differences in the noise profiles of construction activities at the two sites. Alternatively, this difference may have been due to elevated ambient noise from natural or other anthropogenic noise sources, such as wind and wave action, operational wind farm noise from Beatrice, or undetected fisheries activity (Farcas et al., 2020). Finally, the difference in predicted broadband noise levels between the two sites, when distances to piling and other vessels are held constant, may be attributable to variation in underwater radiated noise levels from vessels (MacGillivray et al., 2022), or to variation in the sound propagation characteristics (Farcas et al., 2016), e.g., varying sediment properties between the study sites. Thus, this limits direct comparison of the noise profiles of specific pre-piling activities in these two developments but highlights the need for additional characterisation of noise profiles for different construction activities, operational windfarms and other natural or anthropogenic factors contributing to averaged ambient noise levels in these offshore environments.

Despite differences in vessel intensity, noise levels and baseline detection rate, the decline in porpoise detections was similar for both windfarms. Harbour porpoises may therefore respond to higher levels of disturbance from increased vessel traffic and/or underwater noise levels associated with activities that were common to both developments. The decrease in porpoise occurrence, prior to piling, at both windfarms may represent a response to the cumulative impact of several construction activities, and the installation activities in particular, including PIF installation and pile loading and installation (see Fig. 5). An individual's decision to leave and/or return to an exposed area likely depends on its fitness, energetic status and perception of predation risk (Frid and Dill, 2002; Beale and Monaghan, 2004). Some activities may trigger a stereotypical response, displacing some animals away from the noise source, while other individuals remain in the exposed area. Although the magnitude of response is likely to be site specific and context dependent (Gill et al., 2001; van Beest et al., 2018), these results can be used to modify baseline estimates of animal densities within the predicted impact zones at the start of piling. This, in turn, can support efforts to optimise mitigation measures that seek to minimise the risk of near-field injury from pile-driving (Thompson et al., 2020).

4.4. Implications for developers and regulators

Efforts to reduce potential impacts of pile-driving on marine mammals have typically focussed on reducing noise levels at source (Dähne et al., 2017) or ensuring that animals are either not present (JNCC, 2010) or deterred (Brandt et al., 2013a) from the site. However, these measures to mitigate any risk of near-field injury may result in other environmental pressures; for example, where use of ADD may increase far-field disturbance (Brandt et al., 2013b; Thompson et al., 2020), although newer devices may reduce the extent of disturbance (Voß et al., 2023) or noise abatement results in additional vessel traffic. Similarly, area/time disturbance thresholds used in English waters (JNCC, 2020) may reduce the spatial footprint of piling at any one time, but extend the temporal spread of construction activity. Uncertainty over the relative importance of these risks has meant that regulatory guidance in different countries may vary in its emphasis on different mitigation measures (e.g., Thompson et al. (2020); Juretzek et al. (2021); Danish Energy Agency (2022)). Our results help inform this trade-off between different impacts, highlighting the contribution of self-mitigation when optimising additional mitigation measures (Abramic et al., 2022) to reduce overall cumulative impacts. Nowadays construction vessels are more likely to use dynamic positioning (DP) than e.g., an eight-point anchor spread system, which may reduce both vessel spatial footprint of disturbance and the overall duration in peak noise levels of certain construction activities. In future, ancillary and support vessels' behaviour and spatial distribution could be managed to minimise the spatial footprint of disturbance from construction vessels (Findlay et al., 2023), and vessel management plans developed to reduce potential impacts. This highlights the need for a better understanding of the noise profiles of different construction and support vessels and how these vary depending on vessel speed and activity. Such information may be especially important for assessing and managing underwater soundscapes as new technologies such as floating windfarms become more widespread. Similarly, this will require better assessment of noise profiles from vessels engaged in other anthropogenic activities, such as fisheries, to provide baseline for assessments (Dyndo et al., 2015; Merchant et al., 2016; Erbe et al., 2019; Hermannsen et al., 2019), management plans and efforts to maintain buffer areas with lower levels of disturbances where cetaceans displaced from ensonified areas can forage (Forney et al., 2017).

To mitigate the risk of instantaneous death and injury to marine mammals during pile-driving activities, the use of ADD was integrated into the engineering processes during the Beatrice and Moray East piling campaigns (Thompson et al., 2020). Although our study indicates that harbour porpoises were still acoustically detected in the vicinity of construction sites prior to the start of piling, the overall detection rate dropped by up to 33% from 48 h before to the start of ADD and piling activities. These results can be used to modify estimates of the number of individuals likely to be in the vicinity of construction sites prior to piling activities to optimise mitigation measures.

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Author contributions

A.B., I.G and P.T. conceived and designed the study based on data collection that has been led by P.T. and I.G. N.M. analysed all the noise data. A.B. processed the data, carried out the data analysis and prepared all the tables and figures, under the supervision of I.G. and P.T. A.B., I.G. and P.T. drafted the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

CRediT authorship contribution statement

Aude Benhemma-Le Gall: Conceptualization, Methodology, Formal analysis, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Paul Thompson:** Conceptualization, Project administration, Funding acquisition, Supervision, Writing – review & editing. **Nathan Merchant:** Formal analysis, Writing – review & editing. **Isla Graham:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors have no known conflict of interest. This study was partly funded by two commercial developers, BOWL and MOWEL. However, these funding bodies had no input into data collection, analysis and interpretation nor into the paper redaction. The aims, scope and sampling design of the study were agreed by the statutory advisors represented on the Moray Firth Advisory Group (MFRAG) and the regulator Marine Scotland Licensing and Operations Team.

Data availability

The datasets and R codes, used in this study, are available through the Dryad Digital Repository at: https://doi.org/10.5061/dryad.tdz08kq37

Variation in soundscapes and harbour porpoise occurrence prior to pile-driving at two offshore windfarms (Original data)

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Appendix A. Supplementary data

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