Marine Pollution Bulletin 200 (2024) 116083

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Characterising underwater noise and changes in harbour porpoise behaviour during the decommissioning of an oil and gas platform

Oihane Fernandez-Betelu [a,*], Isla M. Graham [a,1], Freya Malcher [b], Emily Webster [b], Sei-Him Cheong [b], Lian Wang [b], Virginia Iorio-Merlo [a], Stephen Robinson [b], Paul M. Thompson [a]

[a] Lighthouse Field Station, School of Biological Sciences, University of Aberdeen, Aberdeen IV11 8YL, United Kingdom
[b] National Physical Laboratory, Hampton Road, Teddington, Middlesex TW11 0LW, United Kingdom

ARTICLE INFO

Keywords:
Oil and gas
Man-made marine structures (MMS)
Decommissioning
Underwater noise
Harbour porpoise
North Sea

ABSTRACT

Many man-made marine structures (MMS) will have to be decommissioned in the coming decades. While studies on the impacts of construction of MMS on marine mammals exist, no research has been done on the effects of their decommissioning. The complete removal of an oil and gas platform in Scotland in 2021 provided an opportunity to investigate the response of harbour porpoises to decommissioning. Arrays of broadband noise recorders and echolocation detectors were used to describe noise characteristics produced by decommissioning activities and assess porpoise behaviour. During decommissioning, sound pressure spectral density levels in the frequency range 100 Hz to 48 kHz were 30–40 dB higher than baseline, with vessel presence being the main source of noise. The study detected small-scale (< 2 km) and short-term porpoise displacement during decommissioning, with porpoise occurrence increasing immediately after this. These findings can inform the consenting process for future decommissioning projects.

1. Introduction

An increasing number of offshore oil and gas (O&G) and wind energy structures will be decommissioned in the next decades as they reach the end of their production life (Smyth et al., 2015; Fowler et al., 2020). Decommissioning man-made marine structures (MMS) involves a series of complex and expensive activities to ensure both the safety of the operation and the protection of the environment (Topham and McMillan, 2017; Capobianco et al., 2021). There are many options available for decommissioning MMS, which range from complete removal to leaving the structures in place (Li and Hu, 2022). However, these are limited by regulators, stakeholders and the available technology, but, in general, each region has its own preferred option (Hamzah, 2003). For instance, in the Northeast Atlantic, international regulations currently mandate the complete removal of MMS upon reaching the end of their operational life (OSPAR, 1998).

The removal of an MMS involves various activities that have the potential to impact marine life (Burdon et al., 2018). For the benthic and epibenthic communities that grow on subsea foundations, the removal of these structures leads to habitat loss and changes in local environment (Hall et al., 2022). Impacts may also occur due to the alteration of underwater noise during decommissioning activities. Activities required for the removal of MMS, such as cutting, may increase underwater noise levels, and therefore, have the potential to impact sensitive species (Hall et al., 2022). Furthermore, it is known that both the presence of vessels and the noise generated by them have adverse effects on marine mammals and fish during the construction phase of MMS (Reeve, 2019; Benhemma-Le Gall et al., 2021). Considering that heavy-lifting vessels are required for the removal of MMS (Tan et al., 2021), similar impacts from vessels may also arise during the decommissioning phase.

In many regions, disturbance to protected marine mammal populations has been a key issue when assessing potential impacts of offshore construction activity. Recent work has also shown that MMS can be attractive to marine mammals (Todd et al., 2020; Clausen et al., 2021; Fernandez-Betelu et al., 2022). Consequently, future plans for decommissioning these structures must consider the potential effects on marine mammal receptors and, if required, identify mitigation actions to minimise those effects (Hall et al., 2022). Marine mammals use sounds to communicate, facilitating hunting, traveling, and breeding, and therefore, are sensitive to the noise produced by human activities (Erbe

* Corresponding author.
E-mail address: oihane.fernandez@abdn.ac.uk (O. Fernandez-Betelu).
[1] Present address: Cairngorms National Park Authority, Grantown on Spey PH26 3HG, United Kingdom.

https://doi.org/10.1016/j.marpolbul.2024.116083
Received 11 October 2023; Received in revised form 26 January 2024; Accepted 27 January 2024
Available online 9 February 2024
0025-326X/

et al., 2018). Although there have been many studies on disturbance to marine mammals from construction of MMS, particularly where the installation process has required the use of impulsive pile driving (Dähne et al., 2013; Brandt et al., 2018; Graham et al., 2019), no studies have yet been conducted on the effects of decommissioning. Furthermore, any future assessment of these impacts is constrained by the lack of information about the likely noise profiles of decommissioning activities (Fowler et al., 2020; Lemasson et al., 2021; Hall et al., 2022).

Noise profiles from decommissioning activity will depend on both the type and the size of infrastructure being decommissioned, as well as the specific techniques used for removal. However, given that both O&G platforms and offshore wind structures often use similar foundations and subsea infrastructures, it is reasonable to anticipate that similar approaches will be taken in their decommissioning. Consequently, the knowledge gained from decommissioning activities related to O&G platforms can be valuable and transferable to the offshore wind industry (Parente et al., 2006). Evidence gathered from current O&G decommissioning projects, will allow the marine renewable sector to enhance future decommissioning practices, facilitating the implementation of more effective and environmentally responsible approaches (Murray et al., 2018). During 2021, the Jacky Wellhead, a small suction piled oil production facility was decommissioned in the Moray Firth (NE Scotland). Harbour porpoises are widely distributed in this area (Brookes et al., 2013), and several previous studies have characterised the responses of this species to different offshore energy activities (Thompson et al., 2013; Graham et al., 2019). Furthermore, a recent study in the area found that this and other MMS, had a reef-effect on harbour porpoises, which used these sites to forage (Fernandez-Betelu et al., 2022). This decommissioning operation therefore provided an opportunity to gather information on underwater noise during decommissioning activities and the responses of harbour porpoises to this discrete event. Here, we described the characteristics of noise produced during the 5-day decommissioning period using broadband noise recordings. Additionally, we assessed the extent to which harbour porpoises responded to this event using an array of echolocation click detectors. In particular, the study aimed to characterise 1) underwater noise produced during decommissioning and 2) variation in harbour porpoise occurrence and foraging activity before, during and after decommissioning.

2. Material and methods

2.1. Study area and decommissioning activities

The study was conducted in 2021 during the decommissioning of the Jacky Wellhead O&G platform (NE Scotland, Fig. 1). The Jacky Wellhead was a monopile structure installed in 2008 (jacket weight: 596 t; Supplementary material Fig. S.2) with three suction piles, a foundation system used in both O&G installations and the offshore wind industry (Bang et al., 2000). Beatrice Bravo O&G platform, located at 4.7 km from Jacky Wellhead, was installed in 1983 and has 10 leg piles and 4 skirt-piles (total jacket weight: 2946 t, Fig. 1). Both O&G installations within the study area, Jacky Wellhead and Beatrice Bravo, were non-operational and therefore not contributing significantly to the local soundscape.

The Jacky Wellhead was decommissioned between the 2nd and the 6th of September 2021. Following current legislation (OSPAR Commission decision 98/3), both the platform and its foundations were completely removed from the seabed. The topside of the platform was removed on the 3rd of September and its frame and suction piles were removed on the 5th of September. Three vessels were involved in these activities: a crane ship that conducted the activities linked with the removal of the platform (Fig. 1), a support vessel, and a safety vessel (Table 1). The crane vessel remained continuously on dynamic positioning during decommissioning activities (Supplementary material Fig. S.1).

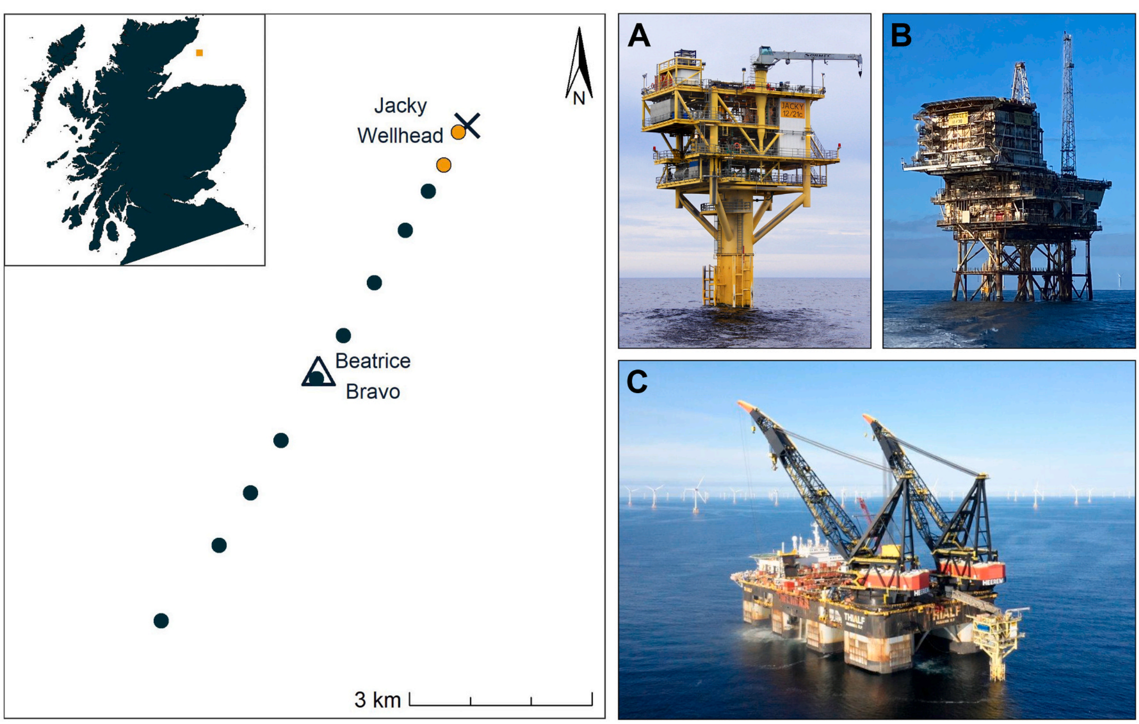

Fig. 1. Map of the study area showing the locations of man-made marine structures (X: Jacky Wellhead; △: Beatrice Bravo), CPODs (dark points) and CPOD+SoundTraps (orange points). Pictures: A) Jacky Wellhead O&G platform (© Stephen Hurrell), B) Beatrice Bravo O&G platform (© Repsol Sinopec Resources UK LTD) and C) Thialf crane ship during decommissioning activities (© Ithaca). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Vessels involved in Jacky decommissioning activities, including their unique nine-digit identifiers known as Maritime Mobile Service Identity (MMSI).

Vessel type	Vessel name	Vessel unique identifier (MMSI)	Arrival time in Jacky Field (GMT)	Departure time from Jacky Field (GMT)	Total hours on site
Crane ship	Thialf	353979000	02/09/2021 11:43	06/09/2021 01:18	85.6
Safety vessel	Grampian Deliverance	235108934	30/08/2021 09:51	06/09/2021 01:33	126.4
Support vessel	Bylgia	244740210	02/09/2021 11:40	06/09/2021 00:18	56.8

2.2. Characterising variation in underwater noise during decommissioning

Variation in underwater noise levels was measured from recordings made at two locations, ca. 184 m and 751 m from the Jacky platform, between 28th August and 12th September 2021 (Fig. 1). Devices were attached to a mooring approximately 3 m from the seabed in water depths of approximately 36 m. Recordings were made continuously at a 96 kHz sampling rate using broadband noise recorders (SoundTrap ST600HF, Ocean Instruments). Therefore, all noise analyses were based on a 48 kHz limiting frequency. It was not possible within the scope of the project to undertake a full free-field calibration of the recorder. To ensure the accuracy of the recorder and hydrophone measurements, after their recovery the devices were calibrated at 25 Hz – 315 Hz using a pressure comparison method in a closed coupler at the UK National Physical Laboratory (NPL,IEC 60565–2:2019 standard; Hayman et al., 2016; Hayman et al., 2017). The sensitivity determined at 315 Hz (uncertainty, 0.5 dB) was used as the nominal sensitivity for frequencies up to 10 kHz with an additional uncertainty of 1 dB, and to 48 kHz with an additional uncertainty of 2 dB. This calibration provided the scale factors which were used to convert the digital recordings into absolute sound pressure in pascals before all subsequent analysis.

Underwater noise recordings were analysed to characterise variations in frequency characteristics and noise levels during different decommissioning activities that were identified from operator activity logs. A chart showing how these activities of interest varied over time is shown in Supplementary material (Fig. S.1).

Total broadband sound pressure levels (SPL) were extracted for the recorder located 751 m from the Jacky platform to characterise noise levels. Broadband SPL values in 30-min bins were calculated using the sum of the square pressure magnitude values from a FFT of the signal across the whole frequency range (from 100 Hz to 48 kHz). First, the extent to which underwater noise levels increased during the decommissioning activities was investigated. The 30-min SPL values were averaged to a daily scale using the *meandB* function from the *seewave* R package (Sueur et al., 2008). Average daily SPL values were then allocated to three decommissioning periods: *Before* (28th August to 1st September), *During* (2nd to 6th September) and *After* (7th to 11th September). Average daily SPL values were modelled as a function of decommissioning period (*Before/During/After*) in a gaussian linear model. Second, a more detailed investigation of the noise produced by underwater cutting activities was conducted given that these had the potential to be the highest source of noise (Pangerc et al., 2016; Ithaca Energy (UK) Limited, 2018). Using information from the decommissioning operations log (Supplementary material Fig. S.1), the noise produced by different decommissioning activities was compared (*Cutting/Drilling/ROV test dive/Other/No activity logged*; note, drilling refers to the drilling of holes in the steel structure to facilitate lifting). The 30-min SPL values during different decommissioning activities were modelled in a gaussian linear model.

Calibrated recordings were converted into sound pressure spectral density level, calculated as a function of time, to plot spectrograms for periods of interest. A scaled fast Fourier transform (FFT) (calculated for a 15-min period) was used to observe the sound pressure spectral density level for different activities and the variation in sound levels across these activities. The choice of a resolution period of 15-min was motivated by a desire to isolate the sound signatures of individual sources. The data analysis was done in conformance with the procedures developed in the EU JOMOPANS project and the analysis was checked using the benchmarked data developed for that project (Basan et al., 2024).

2.3. Variation in harbour porpoise occurrence and foraging activity

Between August and September 2021, an array of 11 echolocation detectors (CPODs; www.chelonia.co.uk) was deployed along a gradient of exposure to study the responses of harbour porpoises to decommissioning noise (Fig. 1). CPODs were located between 0.2 and 9.5 km from the decommissioning activities and included two devices in close proximity to MMS: one CPOD at 184 m from the Jacky Wellhead platform and another CPOD at 70 m from the Beatrice Bravo O&G platform (Supplementary material Table S.2).

To reduce memory requirements, all the CPODs were set to record a maximum of 4096 clicks per minute (scan limit). This means that, when the scan limit was reached, most likely due to high levels of background noise (Clausen et al., 2019), CPODs stopped recording for the rest of the minute and then started recording again at the beginning of the subsequent minute. To minimise false-negative detections, subsequent analyses excluded hours with >100,000 recorded clicks h^{-1} and with >2 min h^{-1} in which the scan limit was reached (Brandt et al., 2018).

CPOD data were processed using the CPOD custom software (cpod.exe v. 2.044). Following the manufacturer's manual, only echolocation clicks classified as high or moderate quality by the built-in "KERNO" classifier were included in the analyses. Detection positive hours were defined as hours containing echolocation clicks that were classified as porpoise clicks, and this metric was used as a proxy for porpoise occurrence (Thompson et al., 2013; Graham et al., 2019). The presence of buzzes was then identified within each of these hours by fitting a Gaussian mixture model to log transformed echolocation inter-click intervals (ICIs; Pirotta et al., 2014b). Buzz positive hours were defined as hours in which at least one buzz was detected. Harbour porpoises use buzzes for both feeding and social communication (Clausen et al., 2011; Sørensen et al., 2018), but it is not possible to distinguish between these behaviours with CPOD data. Therefore, in line with previous work, it was assumed that buzzes could be used as a proxy for foraging (Pirotta et al., 2014a; Williamson et al., 2017; Benhemma-Le Gall et al., 2021).

To investigate the effect of decommissioning on harbour porpoise occurrence and foraging activity, 15 days of data (5 days before/during/after decommissioning activities) were analysed within two generalised additive models (GAMs; Wood, 2006) and two generalised linear models (GLM; Nelder and Wedderburn, 1972).

To assess the extent of the effect of decommissioning activities on porpoises, the proportion of detection positive hours per day (proxy for occurrence) and the proportion of buzz positive hours per number of hours present (proxy for foraging activity; Stedt et al., 2023) were modelled as a function of the interaction between the distance to Jacky and the decommissioning period (three levels: *before/during/after*). Since porpoises are attracted to MMS in this area (Fernandez-Betelu et al., 2022), two GAMs with a binomial family distribution (probit link function) were fitted to allow more flexibility in the predictions.

To further assess the effect of decommissioning activities on porpoises at a nearby MMS, the proportion of detection positive hours per day and the proportion of buzz positive hours per number of hours present were modelled as a function of the interaction between each MMS (two levels: *Jacky/Beatrice Bravo*) and the decommissioning period (three levels: *Before/During/After*). This analysis only considered the two CPODs deployed within 200 m of each MMS, located at 70 m and 184 m from Beatrice Bravo and Jacky respectively (Supplementary material Table S.2). Two GLMs with a binomial family distribution (probit link function) were fitted and Tukey Honestly Significant Difference tests (Tukey HSD; Tukey, 1991) used as a post-hoc test to identify significant differences between group means.

Data processing and analyses were conducted in R (R Core Team, 2022) using the packages *mgcv* (GAM modelling; Wood, 2015) and *DHARMa* (Model validation and residual diagnostics; Hartig, 2017).

3. Results

3.1. Characterising variation in underwater noise during decommissioning

Broadband sound pressure spectral density levels were significantly higher during the 5-day decommissioning period compared to the 5-day periods before and after decommissioning (Tukey HSD p-value <0.001). The average daily SPL increased by between 30 dB and 40 dB in the frequency range from around 100 Hz up to around 48 kHz during decommissioning compared to the 5 days before decommissioning activities took place (from a 5-day average of 108.3 dB re 1 μPa before to 141.0 dB re 1 μPa during decommissioning activities; Fig. 2A). This increase in underwater noise levels matched the time of arrival and departure of the crane ship, whereas there was no observable rise in noise levels associated with the arrival of the safety vessel, two days before decommissioning started (Table 1).

In contrast, there was no obvious finer-scale variation in sound pressure spectral density levels within those five days during decommissioning activities that had been anticipated to generate additional noise. In particular, no significant difference in the sound pressure levels was found between cutting and other decommissioning activities (Tukey HSD p-value >0.05 for all comparisons, Supplementary material Table S.1). Instead, the sound pressure spectral density levels measured during periods of cutting activity were similar to the levels during other decommissioning activities which, for example, included ROV testing and visual inspection of the subsea structure (Fig. 3A). Similarly, there were no obvious differences in the sound spectral density spectrum of each of the investigated activities (Fig. 3B). The dominant source of noise during the decommissioning period appeared to be associated with the presence of the vessels carrying out the decommissioning activities rather specific activities such as cutting per se (Fig. 3B).

3.2. Variation in harbour porpoise occurrence and foraging activity

Harbour porpoises were detected every day throughout the 15-day study period for a median of 17 h per day. A total of 173 h were excluded from the analyses (4.4 % of the total dataset) because the scan limit was reached in >2 min h^{-1} or $>100{,}000$ clicks h^{-1} were recorded. The complete dataset comprised 165 data days from 11 CPODs

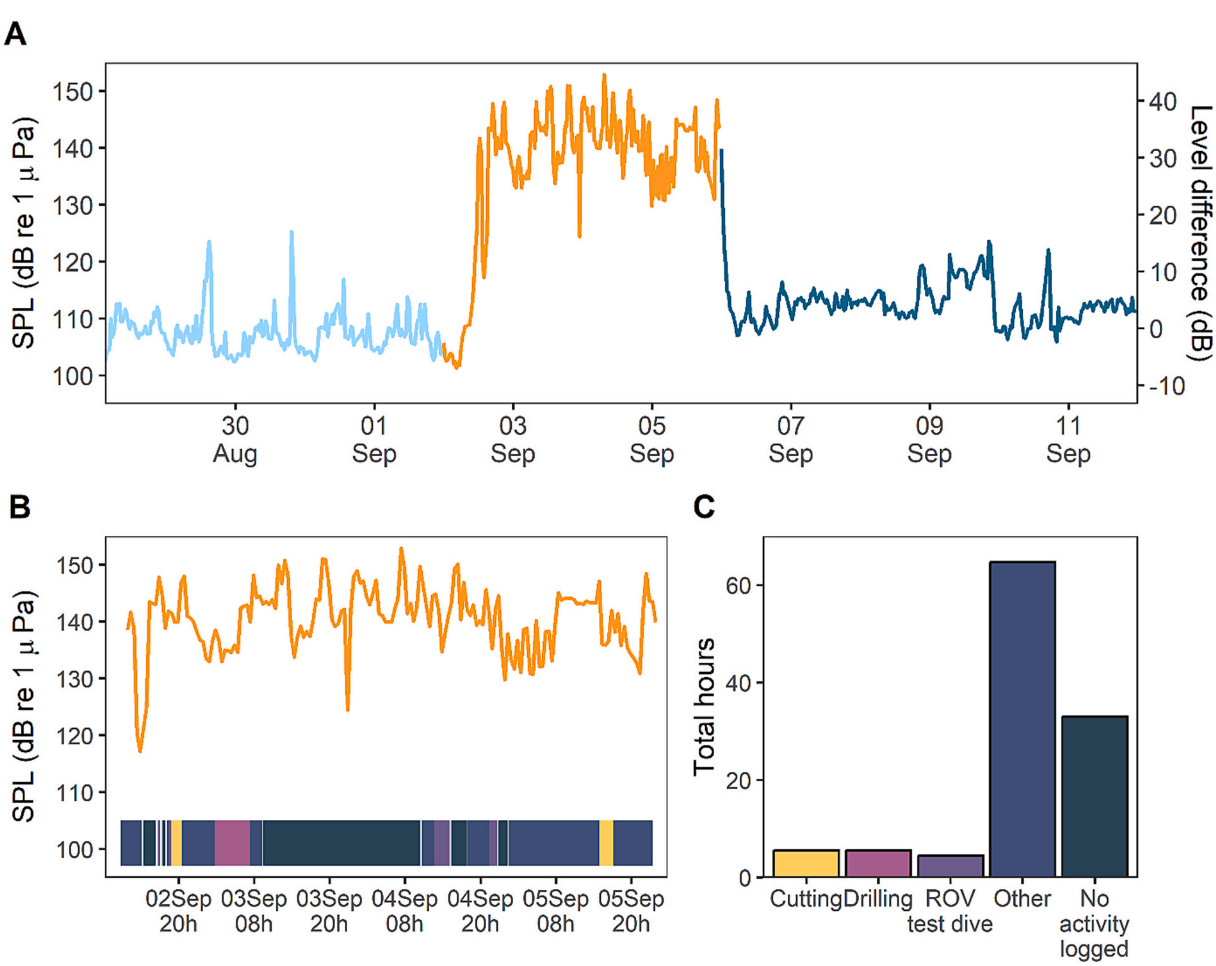

Fig. 2. A) Total broadband sound pressure level (SPL) over 15 days from the SoundTrap deployed 751 m away from Jacky. Total broadband SPL levels were calculated using the sum of the square pressure magnitude values from an FFT of the broadband signal over a 30 min period. The level difference was calculated by normalising the total broadband SPL levels by the average over the 5 days before decommissioning activities took place. Colours represent decommissioning periods: light blue - Before (28th August to 1st September); orange - During (2nd to 6th September 2021); dark blue - After (7th to 11th September). B) Broadband SPL during decommissioning (orange line) including the timeline of key decommissioning activities (bottom coloured bar). C) Total number of hours per decommissioning activity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

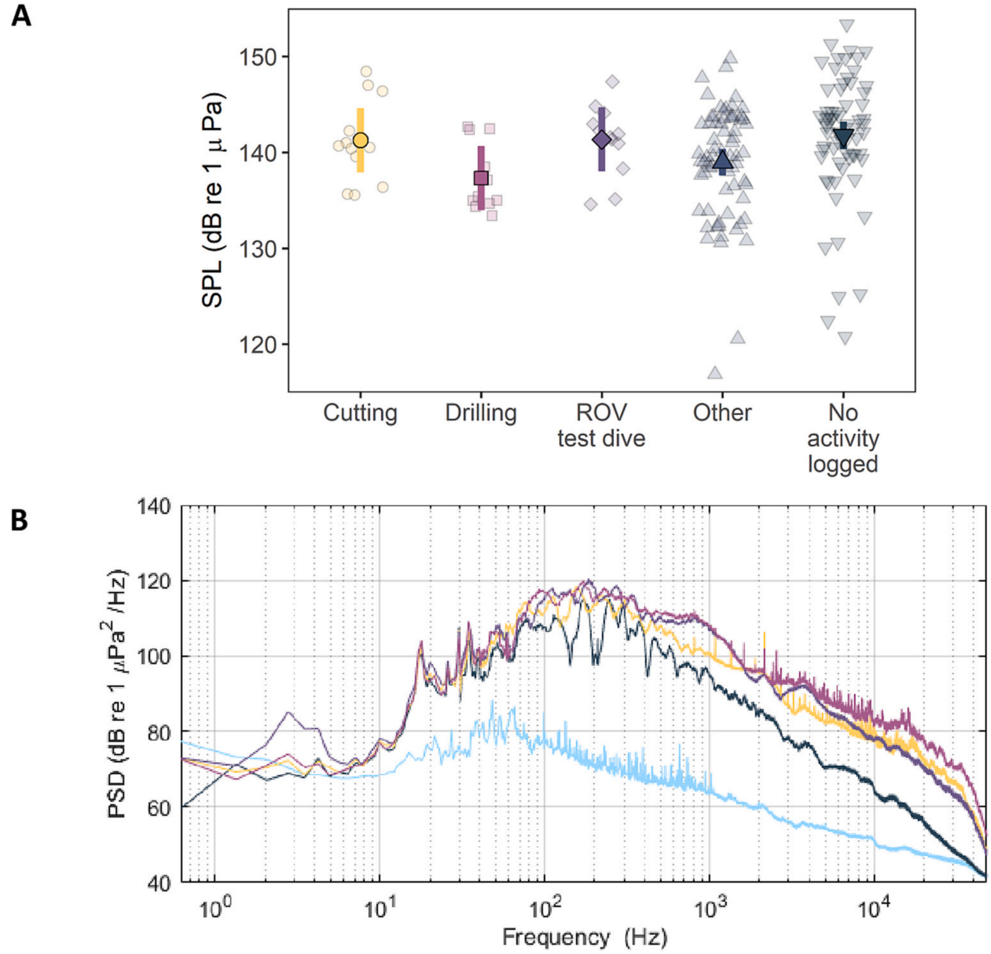

Fig. 3. A) Predicted mean and standard error SPL (point error bar) for each decommissioning activity, including 30-min SPL values (translucid data points) extracted from the recorder located 751 m away from Jacky. B) Sound pressure spectral density spectrum from the recorder located 751 m away from Jacky. The spectrum was calculated for a 15-min period and then down sampled by a factor of 1000 to give a frequency resolution of 0.72 Hz. Figure includes the sound pressure spectral density spectrum: Light blue, before decommissioning activities (1st Sep 03:00); Pink, during decommissioning - drilling (3rd Sep 6:10 am); Yellow, during decommissioning – cutting (2nd Sep 19:00); Purple, during decommissioning – ROV test drive (2nd Sep 16:40); Black, during decommissioning – no activity logged (3rd Sep 16:00). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

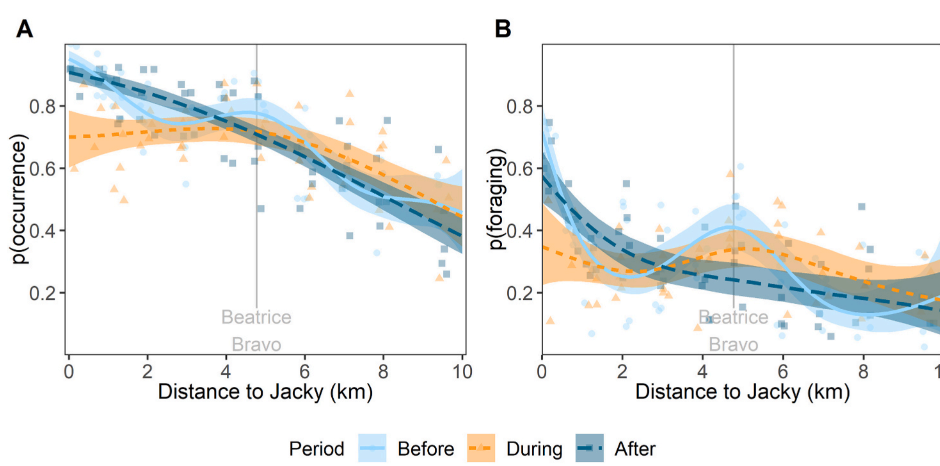

Fig. 4. Predicted probability of (A) harbour porpoise occurrence and (B) foraging activity, in relation to distance to Jacky platform and decommissioning period (light blue solid line: before decommissioning activities; orange dotted line: during; dark blue dashed line: after). Plots include raw data points and the distance at which Beatrice Bravo O&G platform is found (vertical grey line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Supplementary material Table S.2). A Gaussian model with four components led to the identification of the three ICI groups, including buzz ICIs (mean buzz ICI 2 ms; Supplementary material Fig. S.3).

In the GAM analyses, variation in both porpoise occurrence (Fig. 4A) and foraging activity (Fig. 4B) were best explained by the interaction between decommissioning period and distance to the Jacky Wellhead platform. During the decommissioning of this platform, the probability of harbour porpoise occurrence near decommissioning activities (< 2 km) was significantly lower compared to the occurrence before and after the decommissioning (Fig. 4A). There were no significant differences in porpoise occurrence near decommissioning activities (< 2 km) before and after decommissioning. When porpoises were present, foraging activity also decreased slightly next to the decommissioning activities (< 1 km) during decommissioning (Fig. 4B). There were no significant differences in porpoise foraging activity next to decommissioning activities (< 1 km) before and after decommissioning.

When considering only those data collected near (< 200 m) the Jacky Wellhead platform, the probability of harbour porpoise occurrence was significantly lower during the decommissioning period (0.74, 95 % CI: 0.59–0.86) compared to the occurrence before (0.95, 95 % CI: 0.90–0.98) and after (0.94, 95 % CI: 0.89–0.97) decommissioning (Fig. 5A). There were no differences in porpoise occurrence before and after decommissioning activities. When porpoises were present, there were no differences in foraging activity between periods (Fig. 5B).

In contrast, when considering those data collected near (< 200 m) Beatrice Bravo located at 4.5 km from Jacky Wellhead, there were no differences in porpoise occurrence during decommissioning activities (0.74, 95 % CI: 0.65–0.81) compared to either the occurrence before (0.84, 95 % CI: 0.76–0.90) or after (0.70, 95 % CI: 0.60–0.78) decommissioning. The probability of harbour porpoise occurrence was significantly lower after decommissioning period compared to the occurrence before (Tukey HSD p-value <0.05; Fig. 5A). When porpoises were present, there were no differences in foraging activity between periods (Fig. 5B). During decommissioning activities, there were no differences in foraging activity between data collected near Jacky Wellhead and data collected near Beatrice Bravo (Fig. 5B). However, before and after decommissioning, foraging activity was significantly higher near Jacky Wellhead compared to near Beatrice Bravo.

4. Discussion

This study characterised for the first time the noise produced by the decommissioning of a monopile O&G platform and described small-scale (< 2 km) but significant levels of harbour porpoise displacement linked to these activities.

The daily averaged sound pressure levels during the five-day decommissioning of an MMS were between 30 dB and 40 dB higher than the background levels prior to its decommissioning (Fig. 2A). Previous studies suggested that cutting activities would be the highest source of noise during the decommissioning of an O&G platform (INEOS UK SNS Ltd., 2018) and that cutting underwater structures may produce adverse noise impacts (Hall et al., 2022). However, here, within the decommissioning period, there was no clear change in the 30-min SPL during specific activities such as cutting at the measured location, 751 m from the MMS (Fig. 3A). Any noise produced during these specific decommissioning activities appears to have been masked by the dominant vessel noise produced by the three vessels (crane, safety, and support vessels) that remained on site through this 5-day

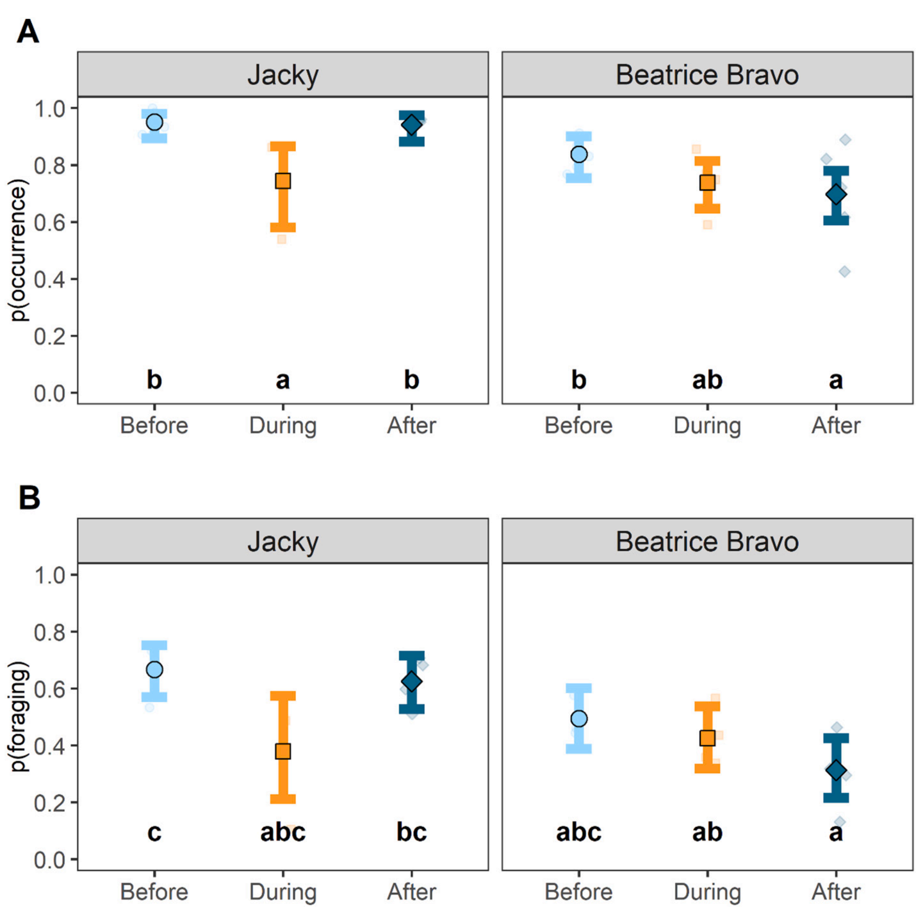

Fig. 5. Mean predicted probability of harbour porpoise occurrence (A) and foraging activity (B) near man-made marine structures (< 200 m) during each decommissioning period, including 95 % confidence intervals for the fixed effects (circle error bar: before; square error bar: during; diamond error bar: after). Unlike letters denote groups that differed statistically from each other in Tukey post-hoc test (e.g. a and b: *p*-value <0.05; a and ab: p-value >0.05).

decommissioning period. Similarly, no obvious differences in sound pressure spectral density spectrum during specific activities were observed at either location (184 or 751 m) when values were averaged at 15-min bins (Fig. 3B). Although the choice of 15-min period bins was motivated by a desire to isolate the sound signatures of individual sources, the process may have been imperfect and cross-contamination cannot be ruled out. Nevertheless, the findings of this study support the expectation in the Environmental Impact Assessment for this project that the primary source of noise generation was the vessel noise (Ithaca Energy (UK) Limited, 2018).

Using passive acoustic monitoring we detected significant but small levels of porpoise displacement linked to the decommissioning activities of an O&G platform. However, the scale of this effect was broadly similar to the observed responses of porpoises to large vessels in the same study area (Benhemma-Le Gall et al., 2021) and may not provide evidence for any additional effects of the decommissioning activity itself. Previous studies found that tagged harbour porpoises modify their movement and echolocation behaviour in response to certain vessels up to 7 km away (Wisniewska et al., 2018). It is possible that during this five-day decommissioning period, stronger displacement may have occurred in relation to particularly noisy activities, but the methods used here would have been unable to detect those finer scale effects. Instead, the overall response presented in Fig. 4 provides an average response over the entire five-day event. In future studies, fine-scale responses to these and similar activities could be explored using alternative methods, either by logging techniques applied to individual marine mammals (Wisniewska et al., 2018), or finer scale passive acoustic monitoring methods (Graham et al., 2023).

One surprising outcome of our analyses was that porpoise occurrence increased at the decommissioning site in the period immediately following the departure of the vessel involved in these activities (Fig. 5). Several potential explanations could account for this phenomenon. Firstly, the disturbance caused by decommissioning and the dislodgement of the platform fouling growth could have created a pulse of scavenger activity, potentially attracting other predators like porpoises. Alternatively, individual porpoises may be returning to areas where they had previously encountered successful foraging opportunities (Iorio-Merlo et al., 2022). Finally, since changes in porpoise behaviour can modify the acoustic detection of porpoises (Macaulay et al., 2023) we cannot rule out the possibility that fewer animals, albeit more vocal, were using the site after decommissioning. Our analyses showed that, at Jacky, there were no differences in foraging activity after decommissioning compared to before, which may indicate similar levels of foraging activity between those periods. Overall, the results of this analysis suggest that porpoises were attracted to and were foraging at the decommissioning site after the removal of the MMS. These findings have interesting implications for the time scales over which areas with artificial structures may continue to be attractive to mobile marine predators such as harbour porpoises. Unfortunately, for this study, passive acoustic monitoring equipment had to be removed relatively soon after the end of decommissioning and it was not possible to explore the duration of this post decommissioning phase. Nevertheless, these findings suggest that longer term studies of both prey and predator occurrence on sites which have recently been decommissioned would be a valuable addition for any future monitoring.

In the North Sea, there are a significant number of O&G platforms that have either reached or will reach the end of their productive life within the coming decades (Ahiaga-Dagbui et al., 2017). At the same time, the marine renewable industry has installed hundreds of wind turbines in the region (Martins et al., 2023). It is important to note that all these MMS will eventually require removal if the current regulations remain unchanged. This study specifically examined the underwater noise levels generated during the complete removal of a suction-piled, monopile O&G platform, and it is reasonable to expect similar noise levels during the decommissioning of MMS with a similar foundation system (Parente et al., 2006). Given that wind turbines occasionally employ suction-piled foundations (Shonberg et al., 2017; Dekker, 2018; Wang et al., 2018), a similar increase in noise levels could be anticipated during decommissioning of such wind turbines, but further work would be required to assess noise levels during removal of piled structures. In addition, it is important to highlight that this study focused on the removal of a single isolated MMS. Further investigation will be required to understand the cumulative effects of removing multiple MMS within a concentrated area, such as a windfarm development, over an extended period of time.

Our study suggests that the decommissioning of man-made marine structures may have small-scale (< 2 km) and short-term effects on harbour porpoises. By improving our understanding of the noise produced by decommissioning activities and the variation on marine mammal occurrence and behaviour, we have provided evidence for the consenting process of future decommissioning projects (Fortune and Paterson, 2020; Lemasson et al., 2023).

CRediT authorship contribution statement

Oihane Fernandez-Betelu: Writing – original draft, Visualization, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Isla M. Graham:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization. **Freya Malcher:** Writing – review & editing, Visualization, Formal analysis. **Emily Webster:** Writing – review & editing, Visualization, Formal analysis. **Sei-Him Cheong:** Writing – review & editing. **Lian Wang:** Writing – review & editing. **Virginia Iorio-Merlo:** Writing – review & editing, Visualization, Data curation. **Stephen Robinson:** Writing – review & editing. **Paul M. Thompson:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data statement

All datasets and R code used for the analyses are available on the Dryad Digital Repository https://doi.org/10.5061/dryad.xwdbrv1kh.

Acknowledgements

We are grateful to the UK Department for Business, Energy & Industrial Strategy (BEIS) Offshore Energy Strategic Environmental Assessment research programme for funding this project. We thank Bill Ruck and colleagues from Moray First Marine, the University of Aberdeen, and Marine Scotland Science for their aid in data collection, John Hartley for his support and constructive comments throughout the project and anonymous reviewers for comments that helped improve the manuscript. We are also grateful to Ithaca Energy (UK) Limited, Repsol Sinopec Resources UK Limited, and SSE Generation Limited for allowing access to the Jacky platform, Beatrice Bravo platform, and Beatrice wind demonstrator turbine sites.

Funding sources

This study was funded by the UK Department for Business, Energy & Industrial Strategy (BEIS) Offshore Energy Strategic Environmental Assessment research programme under contracts OESEA-20-125 and OESEA-21-133, using equipment previously purchased by UK Department of Energy and Climate Change, Scottish Government, Oil and Gas UK, COWRIE and Moray Offshore Renewables Ltd.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.116083.

References

Ahiaga-Dagbui, D.D., Love, P.E.D., Whyte, A., Boateng, P., 2017. Costing and technological challenges of offshore oil and gas decommissioning in the U.K. North Sea. J. Constr. Eng. Manag. 143, 05017008.

Bang, S., Preber, T., Cho, Y., Thomason, J., Karnoski, S.R., Taylor, R.J., 2000. Suction piles for mooring of mobile offshore bases. Mar. Struct. 13, 367–382.

Basan, F., Fischer, J.-G., Putland, R., Putland, R., Brinkkemper, J.A., de Jong, et al., 2024. The underwater soundscape of the North Sea. Mar. Pollut. Bull. 198, 115891.

Benhemma-Le Gall, A., Graham, I.M., Merchant, N.D., Thompson, P.M., 2021. Broad-scale responses of harbor porpoises to pile-driving and vessel activities during offshore windfarm construction. Front. Mar. Sci. 8, 735.

Brandt, M.J., Dragon, A.-C., Diederichs, A., Bellmann, M.A., Wahl, V., Piper, W., et al., 2018. Disturbance of harbour porpoises during construction of the first seven offshore wind farms in Germany. Mar. Ecol. Prog. Ser. 596, 213–232.

Brookes, K.L., Bailey, H., Thompson, P.M., 2013. Predictions from harbor porpoise habitat association models are confirmed by long-term passive acoustic monitoring. J. Acoust. Soc. Am. 134, 2523–2533.

Burdon, D., Barnard, S., Boyes, S.J., Elliott, M., 2018. Oil and gas infrastructure decommissioning in marine protected areas: system complexity, analysis and challenges. Mar. Pollut. Bull. 135, 739–758.

Capobianco, N., Basile, V., Loia, F., Vona, R., 2021. Toward a sustainable decommissioning of offshore platforms in the oil and gas industry: a PESTLE analysis. Sustainability 13.

Clausen, K.T., Wahlberg, M., Beedholm, K., Deruiter, S., Madsen, P.T., 2011. Click communication in harbour porpoises *Phocoena Phocoena*. Bioacoustics 20, 1–28.

Clausen, K.T., Tougaard, J., Carstensen, J., Delefosse, M., Teilmann, J., 2019. Noise affects porpoise click detections – the magnitude of the effect depends on logger type and detection filter settings. Bioacoustics 28, 443–458.

Clausen, K.T., Teilmann, J., Wisniewska, D.M., Balle, J.D., Delefosse, M., Beest, F.M., 2021. Echolocation activity of harbour porpoises, *Phocoena phocoena*, shows seasonal artificial reef attraction despite elevated noise levels close to oil and gas platforms. Ecological Solutions and Evidence 2, e12055.

Dähne, M., Gilles, A., Lucke, K., Peschko, V., Adler, S., Krügel, K., et al., 2013. Effects of pile-driving on harbour porpoises (*Phocoena phocoena*) at the first offshore wind farm in Germany. Environ. Res. Lett. 8, 025002.

Dekker, M., 2018. Achievement Under Pressure: Suction Pile Jackets for the Aberdeen Offshore Wind Farm.

Erbe, C., Dunlop, R., Dolman, S., 2018. Effects of noise on marine mammals. In: Slabbekoorn, H., Dooling, R.J., Popper, A.N., Fay, R.R. (Eds.), Effects of Anthropogenic Noise on Animals. Springer New York, New York, NY, pp. 277–309.

Fernandez-Betelu, O., Graham, I.M., Thompson, P.M., 2022. Reef effect of offshore structures on the occurrence and foraging activity of harbour porpoises. Frontiers in Marine. Science 9.

Fortune, I.S., Paterson, D.M., 2020. Ecological best practice in decommissioning: a review of scientific research. ICES J. Mar. Sci. 77, 1079–1091.

Fowler, A.M., Jørgensen, A.M., Coolen, J.W.P., Jones, D.O.B., Svendsen, J.C., Brabant, R., et al., 2020. The ecology of infrastructure decommissioning in the North Sea: what we need to know and how to achieve it. ICES J. Mar. Sci. 77, 1109–1126.

Graham, I.M., Merchant, N.D., Farcas, A., Barton, T.R., Cheney, B., Bono, S., et al., 2019. Harbour porpoise responses to pile-driving diminish over time. R. Soc. Open Sci. 6, 190335.

Graham, I.M., Gillespie, D., Gkikopoulou, K.C., Hastie, G.D., Thompson, P.M., 2023. Directional hydrophone clusters reveal evasive responses of small cetaceans to disturbance during construction at offshore windfarms. Biol. Lett. 19, 20220101.

Hall, R., Topham, E., João, E., 2022. Environmental Impact Assessment for the decommissioning of offshore wind farms. Renew. Sust. Energ. Rev. 165.

Hamzah, B.A., 2003. International rules on decommissioning of offshore installations: some observations. Mar. Policy 27, 339–348.

Hartig, F., 2017. DHARMa: Residual Diagnostics for Hierarchical (Multi-level/Mixed) Regression Models. R Package Version 0.3, p. 3.

Hayman, G., Robinson, S., Lepper, P., 2016. Calibration and characterization of autonomous recorders used in the measurement of underwater noise. In: The Effects of Noise on Aquatic Life II. Springer New York, pp. 441–445.

Hayman, G., Robinson, S.P., Pangerc, T., Ablitt, J., Theobald, P.D., 2017. Calibration of Marine Autonomous Acoustic Recorders. IEEE.

INEOS UK SNS Ltd, 2018. Windermere Decommissioning Project Comparative Assessment. Technical Report April. INEOS UK SNS Limited, UK.

Iorio-Merlo, V., Graham, I.M., Hewitt, R.C., Aarts, G., Pirotta, E., Hastie, G.D., et al., 2022. Prey encounters and spatial memory influence use of foraging patches in a marine central place forager. Proceedings of the Royal Society B-Biological Sciences 289, 20212261.

Ithaca Energy (UK) Limited, 2018. Jacky Decommissioning Environmental Impact Assessment. Prepared for Ithaca Energy (UK) Limited by Hartley Anderson Limited (p. 136).

Lemasson, A.J., Knights, A.M., Thompson, M., Lessin, G., Beaumont, N., Pascoe, C., et al., 2021. Evidence for the effects of decommissioning man-made structures on marine ecosystems globally: a systematic map protocol. Environmental Evidence 10, 4.

Lemasson, A.J., Somerfield, P.J., Schratzberger, M., Knights, A.M., 2023. Challenges of evidence-informed offshore decommissioning: an environmental perspective. Trends Ecol. Evol. 38 (8), 688–692.

Li, Y., Hu, Z., 2022. A review of multi-attributes decision-making models for offshore oil and gas facilities decommissioning. Journal of Ocean Engineering and Science 7, 58–74.

Macaulay, J.D.J., Rojano-Donate, L., Ladegaard, M., Tougaard, J., Teilmann, J., Marques, T.A., et al., 2023. Implications of porpoise echolocation and dive behaviour on passive acoustic monitoring. J. Acoust. Soc. Am. 154, 1982–1995.

Martins, M.C.I., Carter, M.I.D., Rouse, S., Russell, D.J.F., 2023. Offshore energy structures in the North Sea: past, present and future. Mar. Policy 152.

Murray, F., Needham, K., Gormley, K., Rouse, S., Coolen, J.W.P., Billett, D., et al., 2018. Data challenges and opportunities for environmental management of North Sea oil and gas decommissioning in an era of blue growth. Mar. Policy 97, 130–138.

Nelder, J.A., Wedderburn, R.W.M., 1972. Generalized linear models. Journal of the Royal Statistical Society: Series A (General) 135, 370–384.

OSPAR Commission Decision 98/3 on the disposal of disused offshore installations. In: OSPAR, OSPAR (Eds.), 1998. Meeting of the OSPAR Commission, London, UK.

Pangerc, T., Robinson, S., Theobald, P., Galley, L., 2016. Underwater Sound Measurement Data during Diamond Wire Cutting: First Description of Radiated Noise. Acoustical Society of America, p. 040012.

Parente, V., Ferreira, D., Moutinho dos Santos, E., Luczynski, E., 2006. Offshore decommissioning issues: deductibility and transferability. Energy Policy 34, 1992–2001.

Pirotta, E., Brookes, K.L., Graham, I.M., Thompson, P.M., 2014a. Variation in harbour porpoise activity in response to seismic survey noise. Biol. Lett. 10, 5. https://royalsocietypublishing.org/doi/full/10.1098/rsbl.2013.1090.

Pirotta, E., Thompson, P.M., Miller, P.I., Brookes, K.L., Cheney, B., Barton, T.R., et al., 2014b. Scale-dependent foraging ecology of a marine top predator modelled using passive acoustic data. Funct. Ecol. 28, 206–217.

R Core Team, 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Viena, Austria.

Reeve, L.L.N., 2019. Transboundary Pollution in the New Legally Binding Instrument under the U.N. Convention on the Law of the Sea: The Case for Anthropogenic Underwater Noise. IEEE.

Shonberg, A., Harte, M., Aghakouchak, A., Brown, C.S.D., Andrade, M.P. & Liingaard, M. A. (2017). Suction Bucket Jackets for Offshore Wind Turbines: Applications From In Situ Observations. pp. p65–77.

Smyth, K., Christie, N., Burdon, D., Atkins, J.P., Barnes, R., Elliott, M., 2015. Renewables-to-reefs? – decommissioning options for the offshore wind power industry. Mar. Pollut. Bull. 90, 247–258.

Sørensen, P.M., Wisniewska, D.M., Jensen, F.H., Johnson, M., Teilmann, J., Madsen, P.T., 2018. Click communication in wild harbour porpoises (*Phocoena phocoena*). Sci. Rep. 8, 9702.

Stedt, J., Wahlberg, M., Carlström, J., Nilsson, P.A., Amundin, M., Oskolkov, N., et al., 2023. Micro-scale spatial preference and temporal cyclicity linked to foraging in harbour porpoises. Mar. Ecol. Prog. Ser. 708, 143–161.

Sueur, J., Aubin, T., Simonis, C., 2008. Seewave, a free modular tool for sound analysis and synthesis. Bioacoustics 18, 213–226.

Tan, Y., Li, H.X., Cheng, J.C.P., Wang, J., Jiang, B., Song, Y., et al., 2021. Cost and environmental impact estimation methodology and potential impact factors in offshore oil and gas platform decommissioning: a review. Environ. Impact Assess. Rev. 87.

Thompson, P.M., Brookes, K.L., Graham, I.M., Barton, T.R., Needham, K., Bradbury, G., et al., 2013. Short-term disturbance by a commercial two-dimensional seismic survey does not lead to long-term displacement of harbour porpoises. Proc. R. Soc. B Biol. Sci. 280, 20132001.

Todd, V.L.G., Lazar, L., Williamson, L.D., Peters, I.T., Hoover, A.L., Cox, S.E., et al., 2020. Underwater visual records of marine megafauna around offshore anthropogenic structures. Frontiers in Marine. Science 7.

Topham, E., McMillan, D., 2017. Sustainable decommissioning of an offshore wind farm. Renew. Energy 102, 470–480.

Tukey, J.W., 1991. The philosophy of multiple comparisons. Stat. Sci. 100–116.

Wang, X., Zeng, X., Li, J., Yang, X., Wang, H., 2018. A review on recent advancements of substructures for offshore wind turbines. Energy Convers. Manag. 158, 103–119.

Williamson, L., Brookes, K.L., Scott, B.E., Graham, I.M., Thompson, P.M., 2017. Diurnal variation in harbour porpoise detection – potential implications for management. Mar. Ecol. Prog. Ser. 570, 223–232.

Wisniewska, D.M., Johnson, M., Teilmann, J., Siebert, U., Galatius, A., Dietz, R., et al., 2018. High rates of vessel noise disrupt foraging in wild harbour porpoises (*Phocoena phocoena*). Proc. R. Soc. B Biol. Sci. 285.

Wood, S.N., 2006. Low rank scale invariant tensor product smooths for Generalized Additive Mixed Models. Biometrics 62, 1025–1036.

Wood, S., 2015. Package 'mgcv'. R Package Version, 1, p. 729.