Moray Firth Marine Mammal Monitoring Programme *

Work Package 4 - Changes in the occurrence of harbour porpoises following the construction of Moray Firth offshore windfarms

Iorio-Merlo, V.[1], Fernandez-Betelu, O. [1], Benhemma-Le Gall, A. [1], Graham, I.M. [1,2] and Thompson, P.M. [1]

1. Lighthouse Field Station, School of Biological Sciences, University of Aberdeen, Cromarty, IV11 8YL

2. Current address: Cairngorms National Park Authority, Grantown on Spey PH26 3HG

25th March 2024

* This report includes element of work carried out under Task 4.2 of the PrePARED Project

PrePARED Report

Changes in the occurrence of harbour porpoises following the construction of Moray Firth offshore windfarms

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1. Lighthouse Field Station, School of Biological Sciences, University of Aberdeen, Cromarty, IV11 8YL

2. Current address: Cairngorms National Park Authority, Grantown on Spey PH26 3HG

Summary

- This report presents harbour porpoise post-construction monitoring data that were collected under the industry funded Moray Firth Marine Mammal Monitoring Programme. These data also underpin studies of reef effects being conducted through the OWEC funded PrePARED Project.

- Throughout August 2022, an array of 68 echolocation detectors (CPODs) recorded harbour porpoise occurrence and foraging activity across constructed windfarms at Beatrice and Moray East, and reference sites within Moray West where no structures are yet present.

- Our aims were: (1) to relate these data to pre-construction data collected >10 years earlier to assess whether there have been broad-scale changes in the occurrence of porpoises in relation to the operational windfarms; (2) to assess if there was evidence of finer-scale reef effects around jacket structures within constructed windfarms.

- Analyses of data from CPODs confirmed that porpoises were detected regularly, for between 6 and 19 hours a day, throughout the study area in August 2022.

- Comparison with pre-construction data from 2009-2011 suggested that, on average, occurrence was slightly lower (~17.7%) in constructed windfarms, but this was largely driven by high occurrence within Beatrice in two of three baseline

years. Comparison of pairs of CPODs at turbine structures and in the corridors between turbines found no evidence of finer-scale reef effects within the constructed windfarms.

- These results are discussed in relation to findings from other windfarms and artificial structures in the North Sea. Further analyses will now relate these data to information on spatio-temporal variation in prey being gathered through the PrePARED Project.

Recommended Citation

Iorio-Merlo, V., Fernandez-Betelu, O., Benhemma-Le Gall, A., Graham, I. M., Thompson, P.M. (2023). Task 4.2. Work Package 4 – Changes in the occurrence of harbour porpoises following the construction of Moray Firth offshore windfarms. PrePARED Report, No. 002. March 2024.

March 2024

1. Introduction

Shelf waters provide enormous potential to meet climate change targets through the development of large-scale offshore windfarms (Bugnot et al. 2021; Martinez et al. 2023). However, efforts to realize this potential must be balanced against the need to minimize impacts on the long-term viability of protected wildlife populations. Furthermore, the increasing need to consider compensatory measures when potential impacts cannot be mitigated also requires a better understanding of broader ecosystem effects of new windfarms. Assessments of these trade-offs are currently constrained due to a lack of information on whether renewable developments will have beneficial or detrimental effects on wildlife populations. The introduction of artificial structures in the marine environment generates *de facto* new artificial reefs which potentially have several benefits for the ecosystem (Degraer et al. 2020; Paxton et al. 2022; Petersen and Maim 2006). Artificial reefs have been found to increase flora and fauna diversity and the overall biotic complexity (Coates et al. 2014; Lefaible et al. 2018). They also aggregate prey, generating new foraging opportunities for the upper trophic levels (Dierschke et al. 2016; Fernandez-Betelu et al. 2022; Russell et al. 2014).

Harbour porpoises (*Phocoena phocoena*) are abundant and widely distributed across most, if not all, the North Sea and US waters being considered for offshore wind developments (Hammond et al. 2013; Roberts et al. 2016). Assessments of the species' responses to these developments have generally focused on disturbance during construction, particularly from impulsive pile driving (Brandt et al. 2011; Brandt et al. 2018; Carstensen et al. 2006; Dähne et al. 2013; Graham et al. 2019; Thompson et al. 2010; Tougaard et al. 2009). Less is known about whether there are longer term changes in the extent to which porpoises use operational windfarms, with some initial but contrasting results indicating some increase in occurrence compared to baseline data (Potlock et al. 2023; Scheidat et al. 2011) and one reporting a significant decline (Teilmann et al. 2002). Changes in the use of windfarm development areas could also be occurring at a finer scale, with re-distribution within the windfarms in response to a reef effect around individual turbines.

Two previous studies have demonstrated that harbour porpoises are attracted to single or sparse arrays of older structures which include more complex oil and gas platforms and jacket substructures from demonstration wind turbines (Clausen et al. 2011; Fernandez-Betelu et al. 2022). Both studies found that porpoise occurrence was higher within the vicinity of structures (800 m - Clausen et al. 2011; 200 m - Fernandez-Betelu et al. 2022). Furthermore, several other studies found that harbour porpoise foraging activity around structures increased at night (Brandt et al. 2014; Fernandez-Betelu et al. 2022; Todd et al. 2009; Todd et al. 2022). However, less is known about reef effects at the windfarm scale, where tens or hundreds of turbines may be located within much denser arrays.

Observations of harbour seals (*Phoca vitulina*) foraging around turbine structures suggest that some individuals respond directly to new foraging opportunities resulting from fine scale reef effects (Russell et al. 2014). However, the drivers of observed changes in porpoise density within operational windfarms are less clear. For example, Scheidat et al. (2011) observed an increase in use of a windfarm area during operation, however it was unclear whether this was due to an increase in prey availability through enhanced habitat and/or change in fishing intensity, a reduction in vessel disturbance from navigational restrictions or due to the overall increase in porpoise abundance across Dutch waters. Although porpoise responses to windfarm construction are relatively well studied, most research has occurred during early phases of the industry, when windfarms were being built in previously undeveloped areas. Efforts to meet climate change targets now mean that planned windfarm developments often form clusters in the vicinity of existing operational sites (Benhemma-Le Gall et al. 2021). Understanding how porpoises respond to change in habitat structure, prey availability and vessel disturbance within constructed windfarm sites is therefore critical both for assessing cumulative effects of new developments and optimizing management within these multi-use areas.

In this report, we present data collected within both pre- and post-construction phases of the Moray Firth developers' environmental monitoring programmes. These developer-funded data, collected during 2022, underpin ongoing work within Task 4.2 of the OWEC funded PrePARED project. This study builds upon earlier work that characterized responses of harbour porpoises to pile-driving and other construction activities at the Beatrice and Moray East Offshore Windfarms (Benhemma-Le Gall et al. 2021; Graham et al. 2023; Graham et al. 2019). Here, we use an array of echolocation click detectors to investigate the variation in porpoise occurrence and foraging activity across these two windfarms after two and four years of operation, and across the Moray West Windfarm reference site that has not yet been constructed. Our first objective was to relate these data to pre-construction data collected 10 years earlier to assess whether there have been broad-scale changes in the occurrence of porpoises in relation to the operational windfarms. Our second objective was to assess if there was evidence of finer-scale reef effects within constructed windfarms, which could result in high occurrence of porpoises around jacket structures compared to areas within the corridors between turbines.

2. Methods

2.1 Study site

The study was carried out in the North-East part of the Moray Firth (Scotland, UK). Data on porpoise occurrence within offshore windfarm sites were collected in 2022 over the Smith Bank where two offshore windfarms have been built (Figure 1). The first, Beatrice Offshore Windfarm was built between April 2017 and May 2019, and the site became fully operational a month later in June 2019. The second, Moray East Offshore Windfarm started construction in May 2019 and was completed in June 2021. Currently, there is a third windfarm consented in the same area, Moray West Offshore Windfarm, which has started construction in September 2023, and had no structures in the water at the time in which the study was carried out. Porpoise occurrence was compared with data collected over a baseline period at the same sites between 2009 and 2011, when no structures were present.

2.2 Acoustic deployments

Throughout August 2022, an array of 68 echolocation click detectors (V.0 and V.2 CPODS www.chelonia.co.uk) was deployed across the three offshore windfarm sites (Figure 1; Table S1). Within the Beatrice and Moray East sites, devices were moored as 28 pairs, with one device located within 60 m of the centre of a turbine foundation (hereafter called structure POD) and the second device at the mid-point to an adjacent turbine (hereafter called midpoint POD) with a distance varying between 510 m to 951 m (Table S1). Given the size of each structure, the structure PODs were typically within 50 m of the nearest part of the structure. For our first objective, these data were compared with those collected in August 2009, 2010 and 2011 during earlier studies within the same areas prior to windfarm construction (Brookes et al. 2013; Thompson et al. 2013; see Table 1 and Figure S1). In all periods, CPODs were moored 2-3 m above the seabed (for deployment details see Bailey et al. 2010). Devices were set to record continuously, but with a default set limit to the maximum number of clicks recorded in each minute (maximum clicks = 4096).

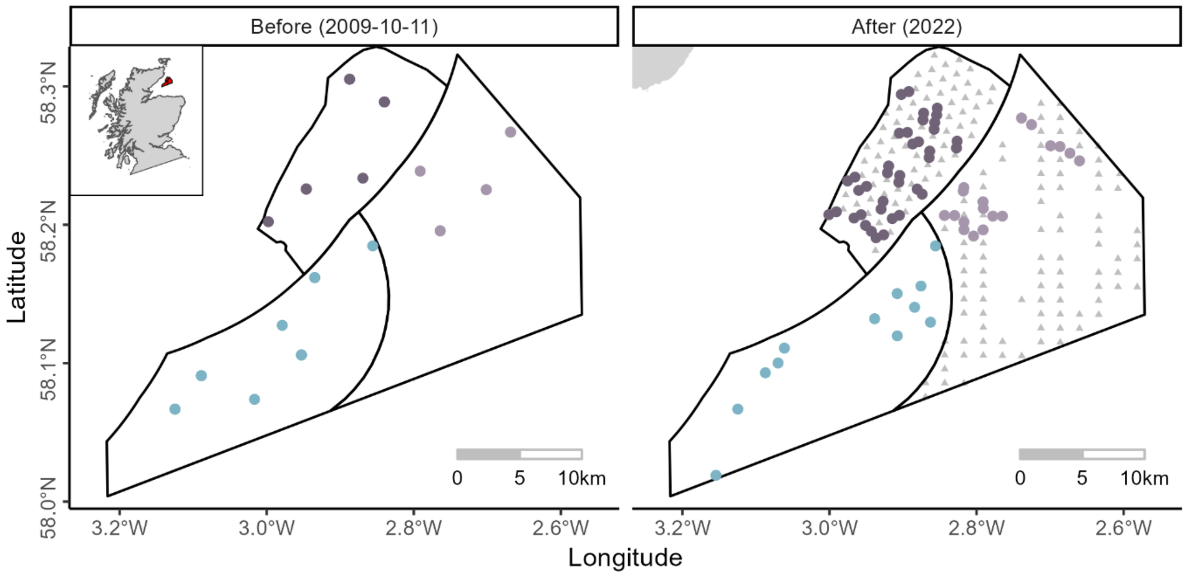

Figure 1. Map showing the location of the three windfarms boundaries (blacklines), the installed turbine locations after construction (grey triangles) and PAM sampling sites (circles colour coded by windfarm: ● Beatrice Offshore Windfarm; ● Moray East Offshore Windfarm; ● Moray West Offshore Windfarm).

2.3 Broad-scale responses of porpoises to operational windfarms

We used pre-construction (2009, 2010 and 2011) and post-construction (2022) data within a Before-After Control-Impact (BACI) design (Smith 2002) to explore whether the installation and operation of these offshore windfarms had either reduced or increased the occurrence and foraging activity of porpoises. The fully operational Beatrice and Moray East offshore windfarms were considered as Impact areas, while the Moray West offshore windfarm which had not been built yet was considered as the Reference area (Figure 1).

Table 1. Summary of data available (sites and days) across the three years in the *Before* and *After* construction periods across the three windfarms.

		Control Area		Impact Area			
		Moray West		Beatrice		Moray East	
		CPOD sites	CPOD data days	CPOD sites	CPOD data days	CPOD sites	CPOD data days
Before	2009	5	154	2	62	1	31
	2010	5	155	5	155	4	124
	2011	5	155	3	93	2	62
After	2022	12	364	38	1156	18	558

2.4 Fine-scale reef effects within windfarm sites

We investigated whether there were finer-scale reef effects within constructed windfarms by comparing porpoise detections at *Structure PODs* and *Midpoint PODs* (Figure 2, Table S1). To control for spatial variation in detection rates (see results), we investigated whether there were differences in detections within individual pairs of CPODs, assuming that habitat characteristics other than proximity to turbine structures were broadly similar within each pair. Similarly, we controlled for temporal variation at daily and hourly scales by comparing the number of detections within pairs of CPODs at different temporal scales.

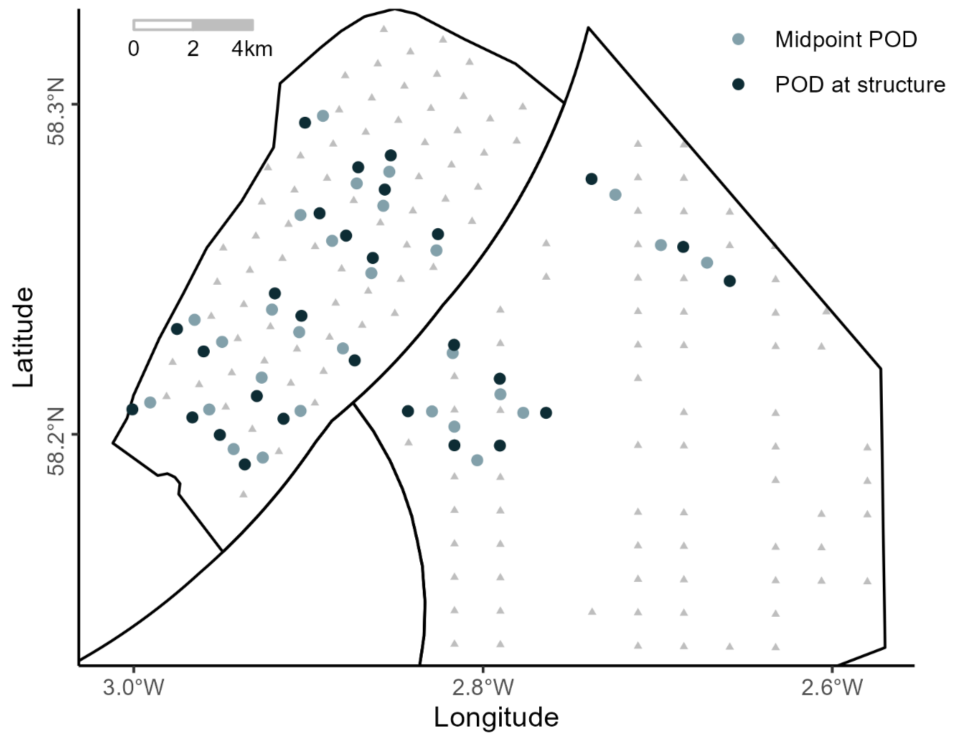

Figure 2. Map showing the location of the ● Midpoint (>500 m away from a turbine) and ● Structure (within 60 m of a turbine) CPOD array within Beatrice and Moray East Offshore Windfarms.

2.5 Data processing & analyses

Following recovery, CPOD data were downloaded and processed using the custom software (CPOD.exe v 2.044, www.chelonia.co.uk). As in earlier studies, all subsequent analyses were restricted to detections of porpoise echolocation clicks that were classified as "High" or "Moderate" quality by the software's "KERNO" classifier. To minimize any effect of masking by anthropogenic activities, we followed the approach described in Brandt et al. (2018) and discarded all hours where the maximum number of clicks had been reached in more than two minutes and when more than 100,000 clicks were detected in an hour. This resulted in the removal of 2.5% of the hours of the 2022 dataset (1,239 hours removed out of 49,863 hours) and 1.1% of the hours from the baseline dataset (284 hours removed out of 25,896 hours). Investigation of those hours excluded in the 2022 dataset revealed no clear spatial or temporal pattern that might result in this approach leading to any bias in the resulting analyses (Figure S2).

CPOD data were used first to assess variation in porpoise occurrence, with those periods containing at least one echolocation click being defined as detection positive hours (DPH) and detection positive minutes (DPM) (Brookes et al. 2013; Williamson et al. 2016). We then fitted a Gaussian mixture-model to log-transformed inter-click intervals (ICIs) to identify the presence of echolocation buzzes (i.e. fast-sequence of echolocation clicks) within each of these hours or minutes (Pirotta et al. 2014b). Porpoises may use echolocation buzzes for both foraging activity and social communication (Clausen et al. 2011; Sørensen et al. 2018). In line with previous work (Benhemma-Le Gall et al. 2021; Pirotta et al. 2014a; Williamson et al. 2017), we assume that the presence of buzzes within each detection positive hour or minute can be used as a proxy for foraging.

In the BACI analyses, we included the proportion of detection positive hours and echolocation buzz positive hours per day as response variables in separate models. We defined the proportion of detection positive hours per day as the ratio between the number of hours when porpoises were detected, and the total number of hours retained during that day. We defined proportion of echolocation buzz positive hours per day as the ratio between the number of hours in which at least one buzz was detected and the number of hours in which porpoises were detected in that day (Pirotta et al. 2014b). We included block (*Impact/Reference*) and period (*Before/After*) as explanatory variables in an interaction. We performed generalized linear mixed models (GLMM ; Bolker et al. 2009) with a binomial family distribution. The family link function was chosen between *probit* and *cloclog* based on the lowest Akaike Information Criterion (AIC ; Sakamoto et al. 1986). We included unique deployment identifier and Julian day within year as random effects to control for device-specific differences in detection and temporal autocorrelation respectively. Models were validated through visual inspection of the residuals and using the R package *DHARMa* (Hartig 2021). Following a significant outlier test, 21 data points (out of 3066) were removed from the echolocation buzz positive hours models, which significantly improved model fit.

3. Results

Porpoises were detected regularly throughout the study area in 2022. Typically, porpoises were detected between six and 19 hours per day, with some spatial variation in occurrence across the study site (Figure 3), and temporal variation in median detection rates throughout August (Figure 4).

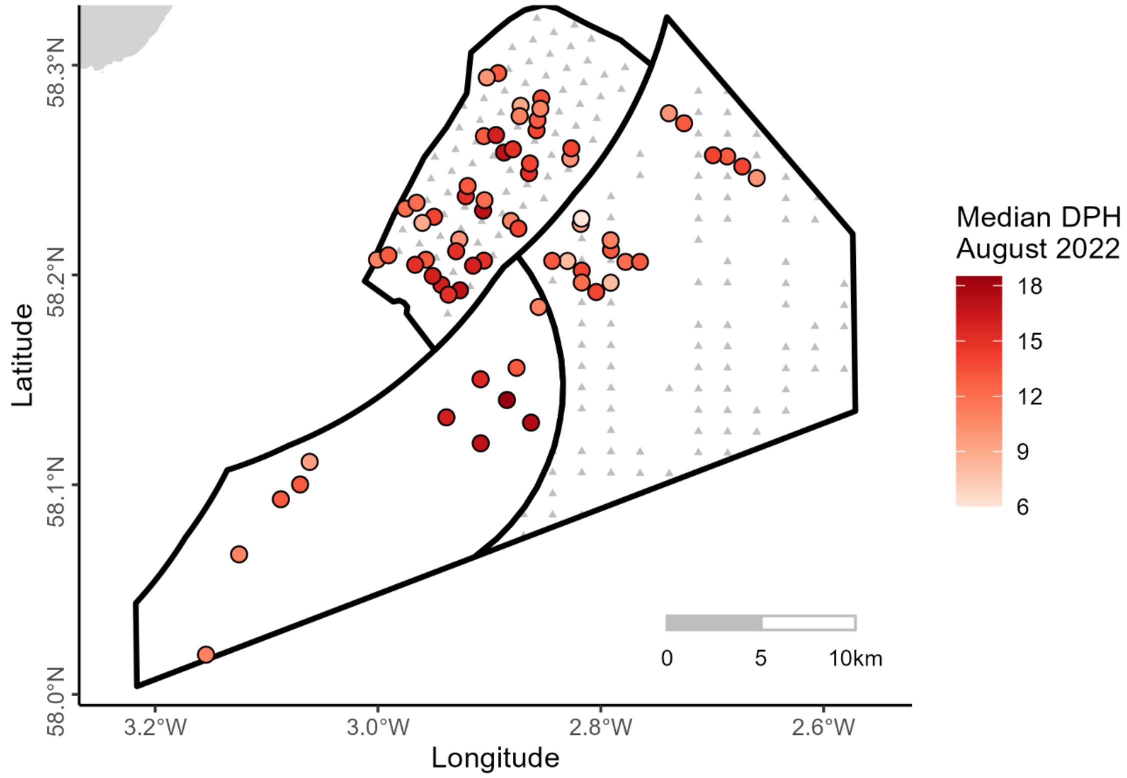

Figure 3. Map showing CPOD locations, within the three windfarms, colour coded by harbour porpoise median detection positive hours (DPH) during the month of August 2022.

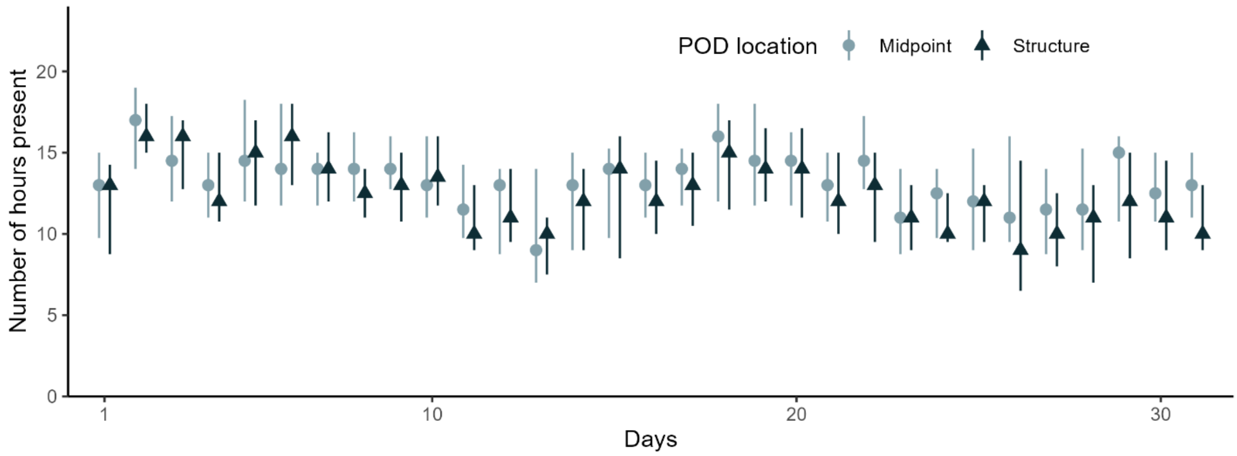

Figure 4. Variation in the number of hours with harbour porpoise detections throughout the month of August 2022 at the ● Midpoint and ▲ Structure CPODs deployed in Beatrice and Moray East Offshore Windfarms.

3.1 Broad-scale responses of porpoises to operational windfarms

The BACI comparison of the 2022 data with the pre-construction baseline showed that there was a significant decrease in the occurrence of porpoises in the constructed windfarm sites relative to the reference area (Figure 5A; GLMM: $\chi^2 = 4.9656$, df = 1, p-value = 0.026). However, further investigation suggests that this was largely driven by changes within Beatrice Offshore Windfarm (Figure S3), and particularly when comparing 2022 data with higher porpoise detection in 2009 and 2010 (Figure S4). In comparison, 2022 data were similar to the 2011 baseline data. Similarly, we did not find any significant difference in detections within Moray East Offshore Windfarm, though this may have been constrained by lower power given that the majority of sampling sites were within Beatrice (Table 1). Although porpoises spent less hours each day within the windfarm sites following construction, there was no evidence that feeding activity was more or less likely to be detected when they were present (Figure 5B; GLMM: $\chi^2 = 0.1824$, df = 1, p-value > 0.05).

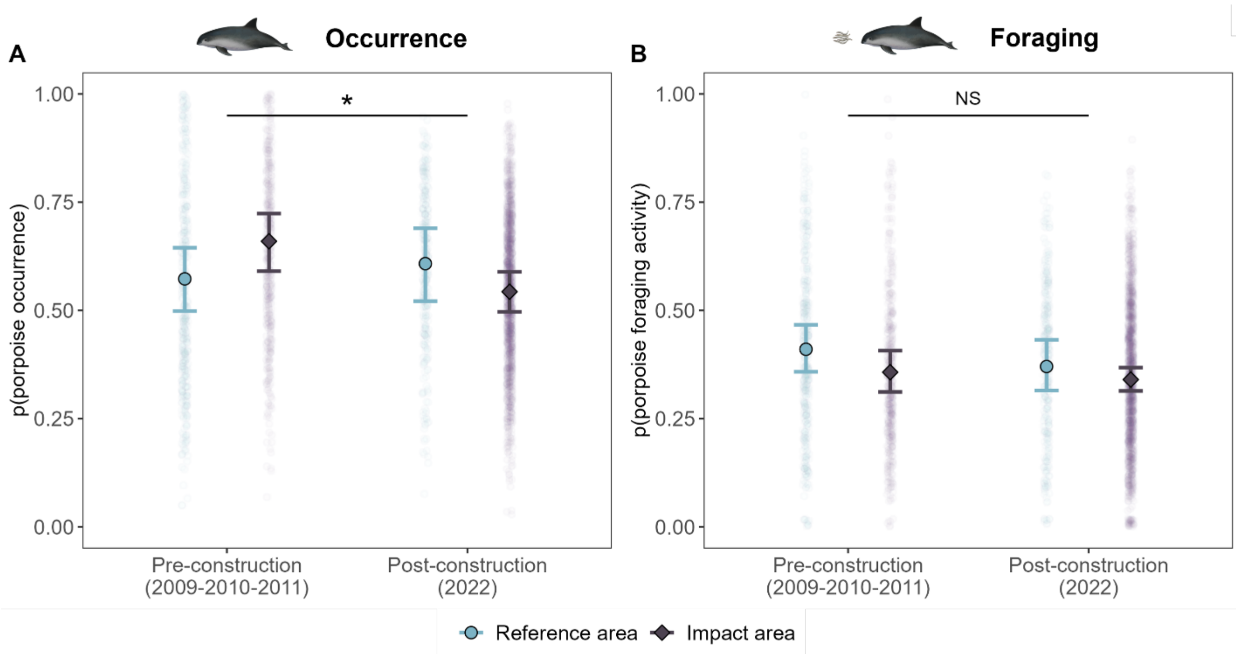

Figure 5.A) Probability of harbour porpoise occurrence per hour and B) probability of foraging activity within those hours in the ● *Control* (Moray West) or ◆ *Impact* (Beatrice and Moray East) site *Before* (Baseline) and *After* (2022) construction.

3.2 Fine-scale reef effects within windfarm sites

Contrary to expectations, the overall occurrence of porpoises was slightly higher (Figure 6A; *paired t-test:* $t = -6.15$, $p < 0.0001$) at sites away from the structures than near the structures (Figure 6B; *median* difference = -1). While there was no difference (Figure 6A; *paired t-test:* $t = -1.02$, $p = 0.31$) in the proportion of hours in which foraging was detected when porpoises were detected at sites near or away from structures (Figure 6B; *median difference* = 0).

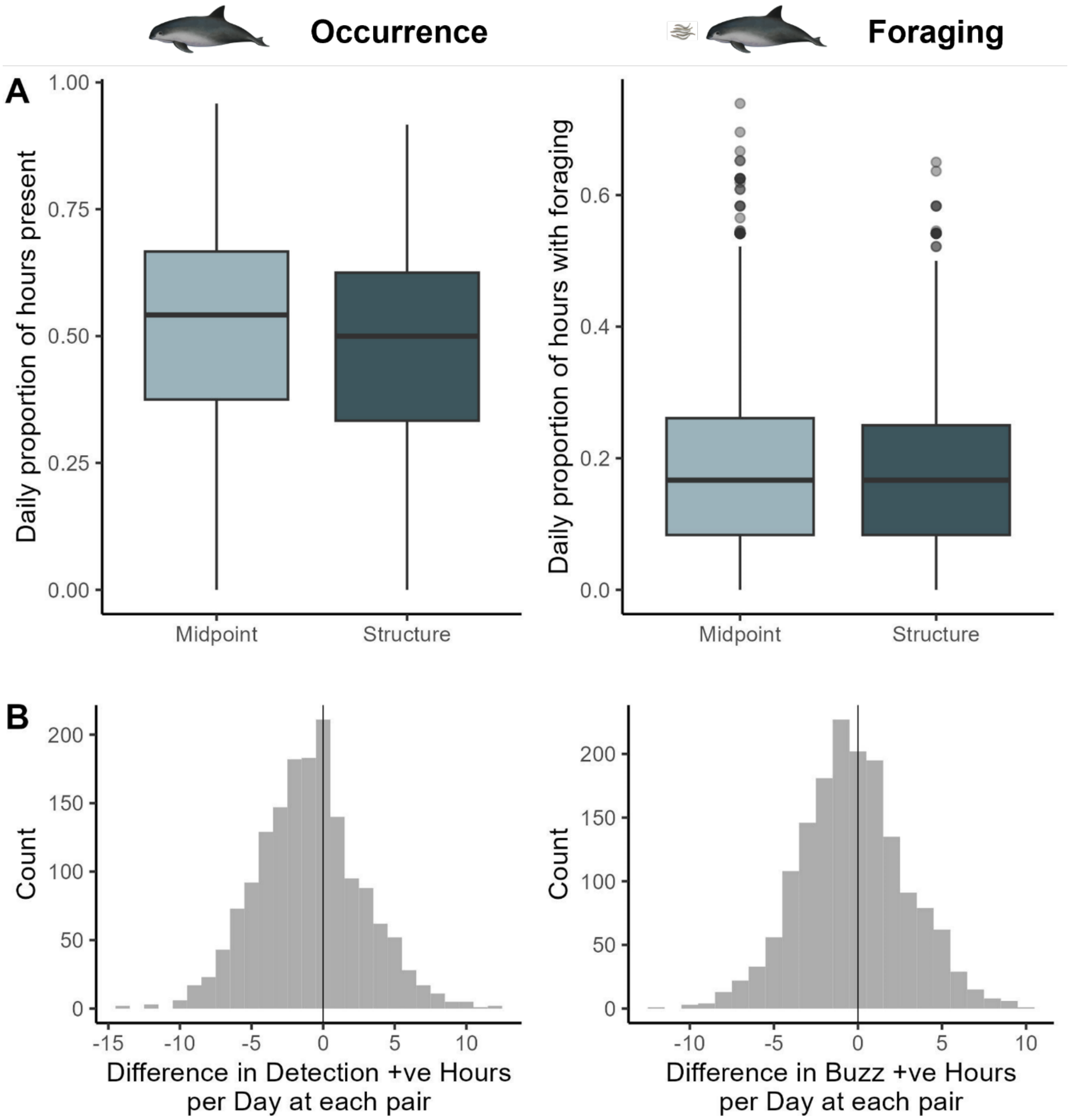

Figure 6. A) Daily proportion of hours in which harbour porpoises were present and daily proportion of those spent foraging at the *Midpoint* (>500 m from structure) and *Structure* CPODs (within 60 m). B) Variability in the difference of detections and buzz positive hours per day calculated as the hours at *Structure* minus the hours at *Midpoint* for each pair.

Finer scale differences within pairs at the minute level revealed a similar pattern with a significant difference (Figure 7A; *Wilcoxon rank test: p* < 0.0001) in the proportion of minutes detected in each hour. However, the median number of minutes that porpoises were detected in each hour in both groups was two, and this result therefore lacks biological significance (Figure 7B; *Structure median DPM* = 2; *Midpoint median DPM* = 2; *median difference* = 0). As seen at the hourly scale, there was no difference (Figure 7A; *Wilcoxon rank test: p* = 0.92) in the proportion of minutes with foraging behaviour (Figure 7B; *median difference* = 0).

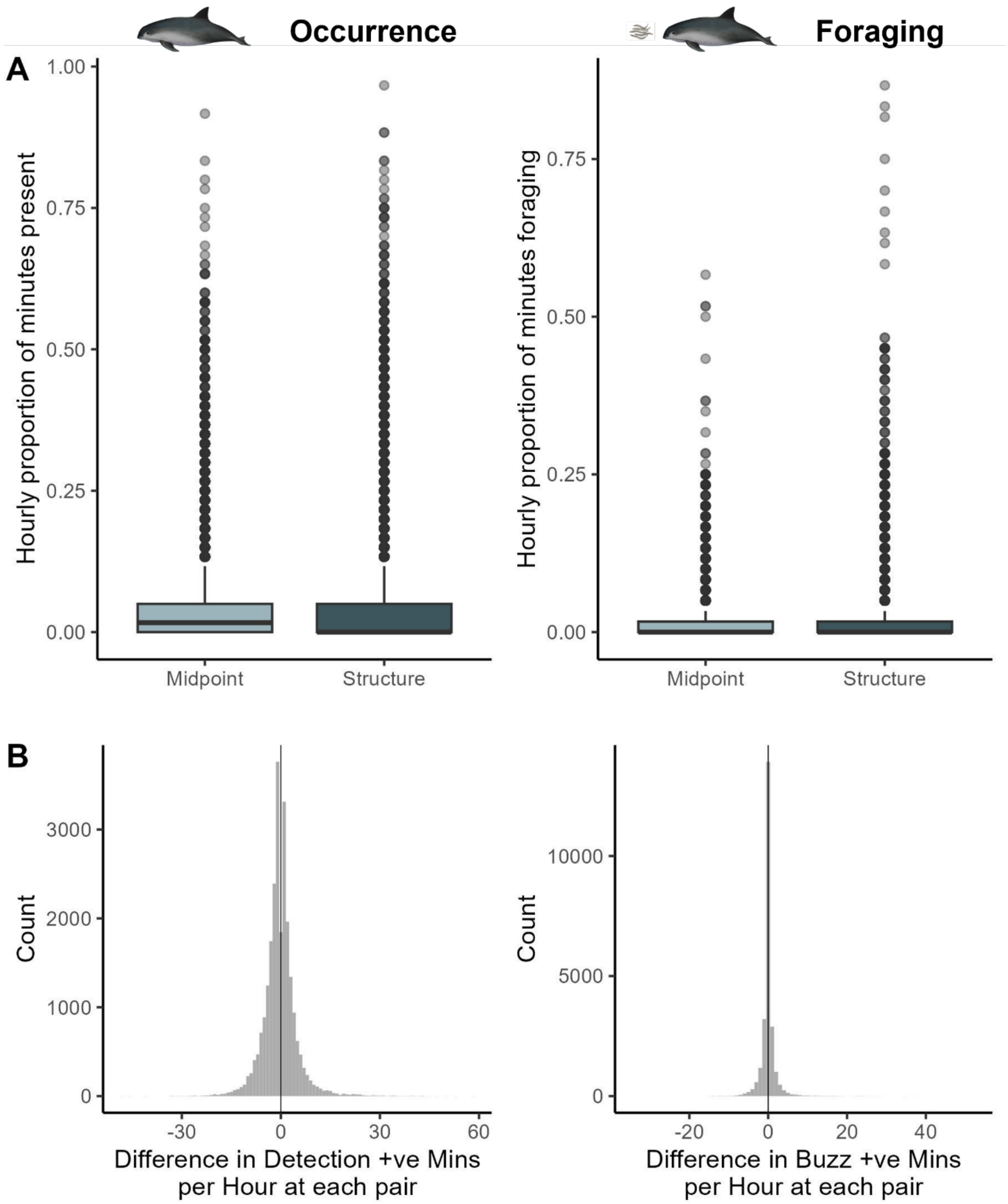

Figure 7. A) Hourly proportion of minutes in which harbour porpoises were present and hourly proportion of those spent foraging at the *Midpoint* (>500 m from structures) and *Structure* CPODs (within 60 m). B) Variability in the difference of detections and buzz positive minutes per hour calculated as the minutes at *Structure* minus the minutes at *Midpoint* for each pair.

4. Discussion

4.1 Broad-scale responses of porpoises to operational windfarms

Previous studies at these sites have shown that harbour porpoises were temporarily displaced by vessel and pile-driving activities during the construction of Beatrice and Moray East Offshore Windfarms (Benhemma-Le Gall et al. 2021; Graham et al. 2019). Nevertheless, the spatial scale and duration of this effect meant porpoises continued to be detected on these sites throughout the four years of construction activities, albeit at lower levels than in baseline periods. Here, the BACI analysis compared 2022 post-construction data from both these windfarms with data collected between 2009 and 2011, when no structures were in place. The results suggested that, when compared to a three-year baseline at reference sites, porpoise occurrence remained slightly lower at these windfarm sites after construction (Figure 5A). In contrast, the level of foraging activity appeared no different in those hours that porpoises were present (Figure 5B).

Whilst our findings suggest there was a decrease in porpoise detections within the windfarms compared to the reference site, this result was driven by high detections within one of the sites (Beatrice Offshore Windfarm), in two (2009 and 2010) of the three baseline years (Figure S4). These data highlight how uncertainties over drivers of spatio-temporal variation in occurrence within relatively short pre-construction baseline periods can constrain assessments of windfarm impacts. Furthermore, the low number of devices in some of our baseline years (Table 1) makes it difficult to determine to what extent this baseline variability was due to changes in sampling effort rather than inter-annual variability in animal occurrence. Nevertheless, whilst further investigation is required, these data do provide initial estimates of potential changes in the occurrence of porpoises within constructed windfarm sites; which could (with appropriate caveats) be used in future environmental assessments. On average, we found porpoise detections decreased by around 17.7% across the windfarm sites post-construction (Figure 5). Additional sampling across these sites in 2023 will provide opportunities to assess whether this remains consistent across post-construction years. Furthermore, other work on prey behaviour within the PrePARED project will extend previous habitat modelling (eg. Brookes et al. 2013; Williamson et al. 2017) to explore how observed variation in occurrence within (Figure 3) and between (Figure S4) sites may be related to spatial variation in prey fields.

Whilst passive acoustic monitoring using CPODs provides a cost-effective monitoring tool for studies such as this, it does have limitations which need to be considered when using these findings. For example, CPOD detections of echolocation clicks provide information on porpoise presence or absence in different time periods, but not on changes either in the number of individuals detected or turnover of individuals at sampling sites. Thus, observed decreases in occurrence could be due either to changes in abundance or to other behavioural changes. Work is currently underway to explore if passive acoustic monitoring data such as these can be combined with digital aerial surveys (DAS) to provide more robust estimates of density change. In future, this could allow more detailed assessments of responses to construction by combining these data with those from seabird DAS to assess changes in marine mammal densities. Furthermore, our findings are currently based on analyses of data from August, which had the best coverage within our dataset. This is the month in which porpoise occurrence typically peaks in this region (Graham et al. 2019). However, given evidence that harbour porpoise densities follow differing seasonal patterns in other parts of the North Sea (Gilles et al. 2016) and have seasonal changes in their diet (Santos and Pierce 2003), different responses could be observed in other seasons or other regions.

Several studies in the southern North Sea have used similar approaches to assess changes in porpoise occurrence within operating windfarms, potentially providing opportunities to assess the generality of observed responses (Potlock et al. 2023; Scheidat et al. 2011; Teilmann and Carstensen 2012; Tougaard et al. 2009). Elsewhere, some studies observed an increase in porpoise occurrence within operational windfarms (Potlock et al. 2023; Scheidat et al. 2011), while Teilmann and Carstensen (2012) found negative impacts of windfarm presence on harbour porpoise occurrence that persisted for 10-years post-construction. However, as seen within our datasets, there were differences in sampling design and uncertainty over other natural or anthropogenic drivers of variation in occurrence which constrain generalization across regions. Authors have suggested that turbine-related reef effects maybe have increased local prey densities, and thus attracted predators at some sites (Scheidat et al. 2011; Teilmann and Carstensen 2012). However, these studies also recognised that exclusion of fisheries and recreational vessels from these windfarm sites may also have led to an increase in harbour porpoise occurrence. In Scottish waters, fishing typically remains unrestricted within operational windfarms, and there is limited information on changes in fishing intensity following construction. Whilst recreational traffic may be limited in these sites, operation of the Moray Firth offshore windfarms has resulted in high levels of vessel activity (e.g. from Crew Transfer Vessels) which may result in higher levels of disturbance that could make these areas less attractive for porpoises. Future work within PrePARED will explore how these data can be used within the DEPONS model (Nabe-Nielsen et al. 2018) to incorporate the effects of vessel traffic when assessing population consequences of windfarm construction and operation on harbour porpoise populations.

4.2 Fine-scale reef effects within windfarm sites

In addition to the broad-scale comparison of occurrence across the windfarms, we hypothesized that there could be finer scale reef effects around individual turbine structures. To test this hypothesis, we used a paired design, with one CPOD within 60 m of a turbine (*Structure PODs*) and a second device between adjacent turbines (*Midpoint PODs*) with distances varying from 510 m to 946 m (Table S1). Contrary to the reef effect hypothesis (Fernandez-Betelu et al. 2022), we found higher detections at midpoint locations. However, although significant, data showed large variability and the median difference in detection was only 1 hour per day between the pair (Figure 6).

If this does represent a real lack of any reef effect, this is in contrast to recent evidence of significant increases in porpoise foraging behaviour around other structures in the Moray Firth (Fernandez-Betelu et al. 2022). There are several possible hypotheses to explain the discrepancy in these results. First, in the present study, the oldest structures were installed in the Beatrice Offshore Windfarm only 4 years earlier. In contrast, Fernandez-Betelu et al. (2022) investigated porpoises around oil and gas platforms and demonstrator wind turbines that have been in the water for over 10 years, and these older structures may sustain more complex ecosystems. For example, older oil and gas wellheads had the highest number of fish species, individuals and greater coverage of invertebrate habitat (McLean et al. 2018). Second, the complexity of structures may influence communities that establish on them (Krone et al. 2017; Lefaible et al. 2018; Love et al. 2019). Thus, the greater complexity of large oil and gas structures may have led to a more complex ecosystem. But this seems a less likely explanation given that some structures in Fernandez-Betelu et al. (2022) study (e.g. the Jacky Platform and the Beatrice Demonstrators) were similar or simpler in complexity to Beatrice and Moray East turbine foundations. However, differences in the use of scour protection or cable and pipe-line armouring could also influence complexity, but comparative data for the different structures of interest are not available. Finally, another key difference between the windfarm sites investigated here and isolated structures, is the occurrence of regular vessel activity around the wind turbines. During operation, maintenance vessels (e.g. crew-transfer vessels) routinely visit the windfarm sites and may hold station at individual turbines during maintenance work. These differences again highlight the need for future studies to incorporate information on vessel activity, given the potential for vessels to moderate any attraction to artificial reefs.

Currently, however, we suggest that these results remain inconclusive, and it is not possible to determine whether the expected relationship is absent or whether our data are confounded by sampling issues. For example, the lack of evidence for a reef effect may be due to the spatial scale we selected for our study design. If the reef effect was occurring within a more localized area surrounding structures, a bottom mounted CPOD, 60 m away from the centre of the structure, may be insufficiently close to detect a change. Porpoise echolocation clicks are also highly directional (Koblitz et al. 2012) and if the animals were foraging intensively around or within the structure they may not be detected 60 m away. Detectability may also be further reduced by fouling communities on the turbine substructures and the structures themselves. In practice, this may remain a significant constraint when relying on passive acoustics. Study of finer-scale movements of top predators around structures may therefore be restricted to those species which can be studied using biologgers, such as harbour seals (Russell et al. 2014).

Alternatively, reef effects could be occurring at much larger spatial scales which would mean that our design would not detect differences between pairs of CPODs. For example, Clausen et al. (2021) detected high porpoise foraging activity up to 800 m away from an oil and gas structure. If similar patterns were occurring around Moray Firth turbine foundations, this could explain why there was no significant difference between CPODs within 60 m and 500 m of a structure. In future, ongoing studies within the PrePARED project should provide more data on the distribution of prey within these windfarm sites, allowing us to explore other evidence of reef effects around turbines and appropriate scale for exploring predator responses to these changes in prey field.

5. Acknowledgements

We thank Barbara Cheney, Robert Bashford, Tim Barton, and other colleagues at the University of Aberdeen’s Lighthouse Field Station for support and assistance with data collection, Bill Ruck at Moray First Marine for deploying and recovering moorings and Bill Turrell for his valuable comments that improved the report.

These analyses were funded by OWEC and Crown Estate Scotland through the PrePARED Project. Field data were collected through the Moray Firth Marine Mammal Monitoring Programme, with funding from Beatrice Offshore Wind Ltd., Moray Offshore Wind Farm (East) Ltd. and Moray Offshore Wind Farm (West) Ltd, using equipment previously purchased by UK Department of Energy & Climate Change, Scottish Government, Oil and Gas UK, COWRIE and Moray Offshore Renewables Ltd.

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Supplementary Material

Table S1. Details of CPOD deployment locations and data start and end dates for the devices deployed in 2022. Distance to turbine indicate the distance to the closest turbine within either windfarms and the deployment group indicates whether the POD was a *Midpoint* (in between structures) or a *Structure* CPOD (deployed near a turbine).

LOCATION ID	POD #	LATITUDE	LONGITUE	DATA START DATE	DATA END DATE	DISTAN-CE TO TURBINE (M)	DEPLOYMENT GROUP
BEATRICE OFFSHORE WINDFARM							
303	617	58.29645	-2.89118	30/07/2022	26/09/2022	583	Midpoint
304	1618	58.29438	-2.90150	30/07/2022	26/09/2022	60	Structure
305	590	58.26917	-2.85657	30/07/2022	26/09/2022	585	Midpoint
306	583	58.27408	-2.85570	30/07/2022	26/09/2022	60	Structure
307	635	58.25562	-2.82607	30/07/2022	26/09/2022	584	Midpoint
308	554	58.26053	-2.82518	30/07/2022	26/09/2022	59	Structure
309	658	58.23778	-2.92063	29/07/2022	13/09/2022	584	Midpoint
310	645	58.24267	-2.91897	29/07/2022	27/09/2022	61	Structure
311	1028	58.23093	-2.90503	29/07/2022	13/09/2022	577	Midpoint
312	2948	58.23588	-2.90372	29/07/2022	26/09/2022	59	Structure
313	600	58.22598	-2.87995	29/07/2022	13/09/2022	585	Midpoint
314	629	58.22235	-2.87317	29/07/2022	26/09/2022	57	Structure
315	650	58.20753	-2.95673	29/07/2022	12/09/2022	564	Midpoint
316	634	58.20513	-2.96640	29/07/2022	12/09/2022	60	Structure
317	2946	58.19553	-2.94275	29/07/2022	12/09/2022	649	Midpoint
318	626	58.19982	-2.95065	29/07/2022	12/09/2022	60	Structure
319	618	58.19295	-2.92603	29/07/2022	12/09/2022	581	Midpoint
320	588	58.19088	-2.93635	29/07/2022	13/09/2022	60	Structure
321	584	58.24877	-2.86350	30/07/2022	26/09/2022	552	Midpoint
322	587	58.25337	-2.86267	30/07/2022	26/09/2022	59	Structure
323	1619	58.25858	-2.88602	30/07/2022	26/09/2022	563	Midpoint
324	2947	58.26015	-2.87800	30/07/2022	26/09/2022	61	Structure
325	783	58.26642	-2.90420	30/07/2022	27/09/2022	510	Midpoint
326	593	58.26692	-2.89322	30/07/2022	26/09/2022	60	Structure
327	641	58.20707	-2.90433	29/07/2022	13/09/2022	552	Midpoint
328	2949	58.20470	-2.91410	29/07/2022	12/09/2022	65	Structure
329	564	58.21718	-2.92660	29/07/2022	13/09/2022	568	Midpoint
330	568	58.21158	-2.92940	29/07/2022	12/09/2022	60	Structure
331	354	58.22800	-2.94930	29/07/2022	12/09/2022	541	Midpoint
332	649	58.22512	-2.95992	29/07/2022	12/09/2022	60	Structure
351	561	58.20757	-3.00085	29/07/2022	12/09/2022	62	Structure
352	2132	58.23192	-2.97522	29/07/2022	12/09/2022	61	Structure
353	637	58.28085	-2.87095	30/07/2022	26/09/2022	60	Structure
354	628	58.28443	-2.85220	30/07/2022	10/08/2022	60	Structure

364	662	58.20965	-2.99062	29/07/2022	12/09/2022	584	Midpoint
365	655	58.27595	-2.87182	30/07/2022	26/09/2022	584	Midpoint
366	558	58.27948	-2.85307	30/07/2022	26/09/2022	581	Midpoint
367	612	58.23470	-2.96512	29/07/2022	12/09/2022	574	Midpoint
MORAY EAST OFFSHORE WINDFARM							
333	602	58.27230	-2.72310	28/07/2022	15/11/2022	945	Midpoint
334	2943	58.27710	-2.73678	28/07/2022	04/11/2022	60	Structure
337	610	58.25158	-2.67058	28/07/2022	15/11/2022	946	Midpoint
338	565	58.25640	-2.68423	28/07/2022	04/11/2022	61	Structure
339	603	58.20683	-2.82887	28/07/2022	15/11/2022	760	Midpoint
340	2951	58.20692	-2.84267	28/07/2022	04/11/2022	61	Structure
341	357	58.20220	-2.81605	28/07/2022	25/10/2022	562	Midpoint
342	2134	58.19655	-2.81605	28/07/2022	04/11/2022	62	Structure
343	598	58.19200	-2.80300	28/07/2022	15/11/2022	951	Midpoint
345	633	58.22450	-2.81690	28/07/2022	15/11/2022	567	Midpoint
346	642	58.22698	-2.81610	28/07/2022	04/11/2022	61	Structure
347	2944	58.21197	-2.78957	28/07/2022	15/11/2022	547	Midpoint
348	592	58.21668	-2.78990	28/07/2022	04/11/2022	59	Structure
349	903	58.20633	-2.77650	28/07/2022	15/11/2022	776	Midpoint
350	2945	58.20630	-2.76340	28/07/2022	04/11/2022	62	Structure
368	2952	58.19642	-2.78995	28/07/2022	04/11/2022	57	Structure
369	652	58.24600	-2.65760	28/07/2022	04/11/2022	62	Structure
MORAY WEST OFFSHORE WINDFARM							
48	1620	58.06697	-3.12500	01/05/2022	26/09/2022		
52	1024	58.18333	-2.85000	01/05/2022	26/09/2022		
159	599	58.15595	-2.87500	01/05/2022	26/09/2022		
280	1621	58.01915	-3.15447	01/05/2022	26/09/2022		
355	646	58.09332	-3.08743	29/07/2022	12/09/2022		
356	640	58.10038	-3.07013	29/07/2022	12/09/2022		
357	648	58.11115	-3.06155	29/07/2022	12/09/2022		
358	1094	58.15052	-2.90750	30/07/2022	12/09/2022		
359	51	58.14062	-2.88377	30/07/2022	12/09/2022		
360	48	58.12982	-2.86210	30/07/2022	12/09/2022		
361	659	58.13238	-2.93837	30/07/2022	12/09/2022		
362	489	58.12000	-2.90747	30/07/2022	12/09/2022		
363	1144	58.11050	-2.88380	30/07/2022	POD failed		

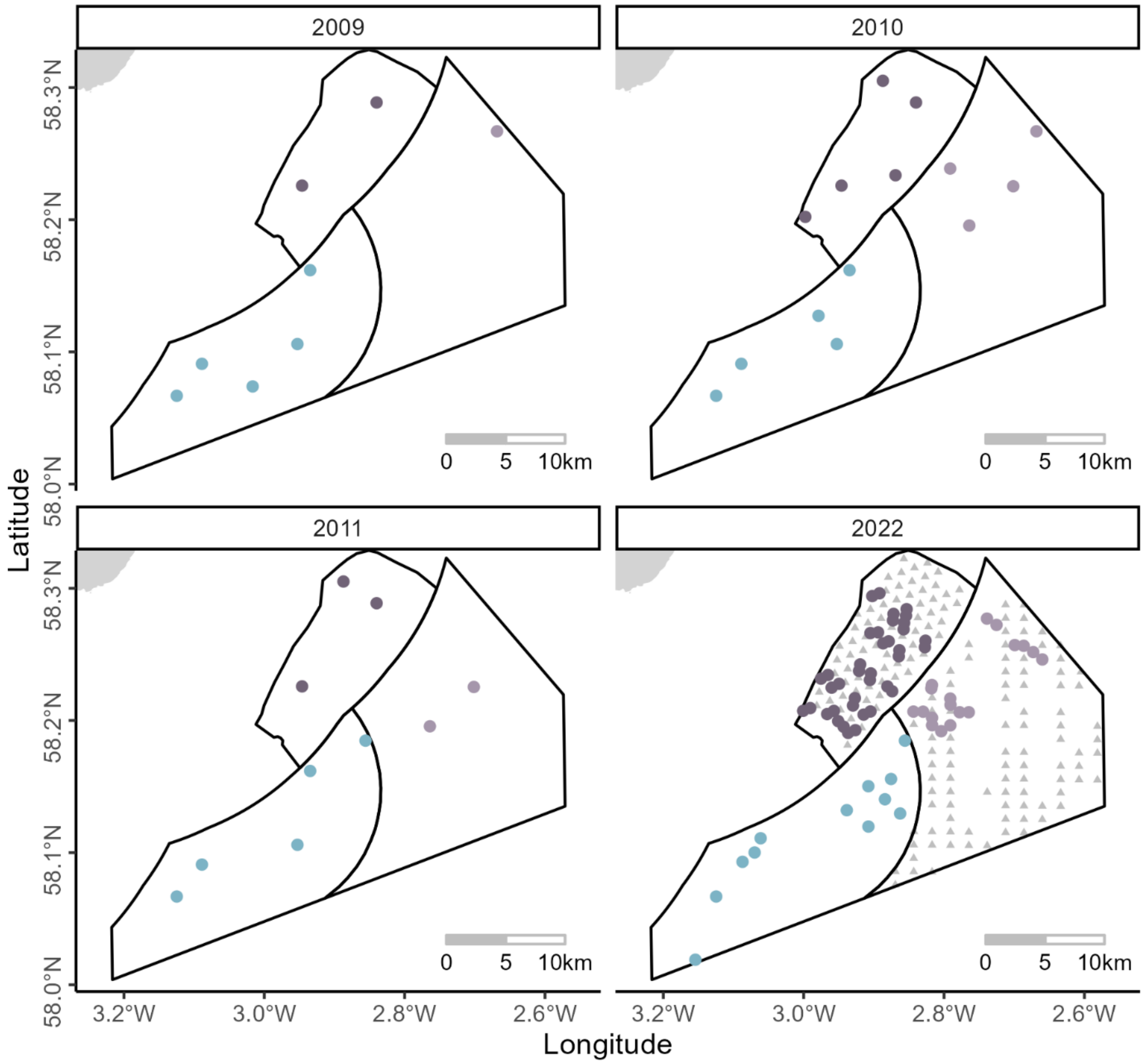

Figure S1. Map showing the location of the three windfarms boundaries (blacklines), the installed turbine locations in the after period (grey triangles) and PAM sampling sites by year of deployment (circles colour coded by windfarm: ● Beatrice Offshore Windfarm; ● Moray East Offshore Windfarm; ● Moray West Offshore Windfarm).

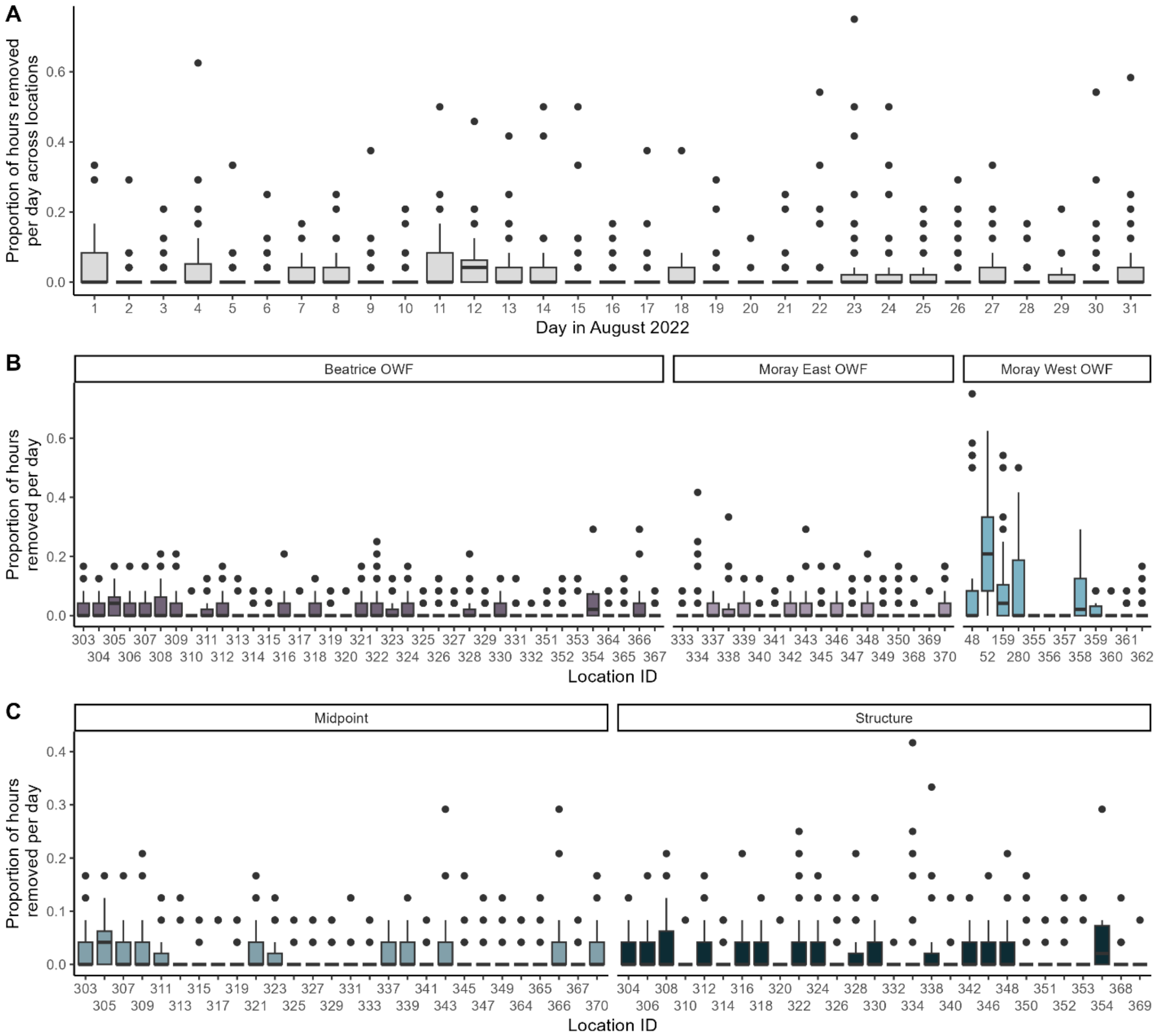

Figure S2. Variation in the proportion of hours removed: A) across the deployment sites in the three windfarms throughout the month, B) at each location within the three windfarms, C) at each location deployed near a structure ("Structure") or in between structures ("Midpoint").

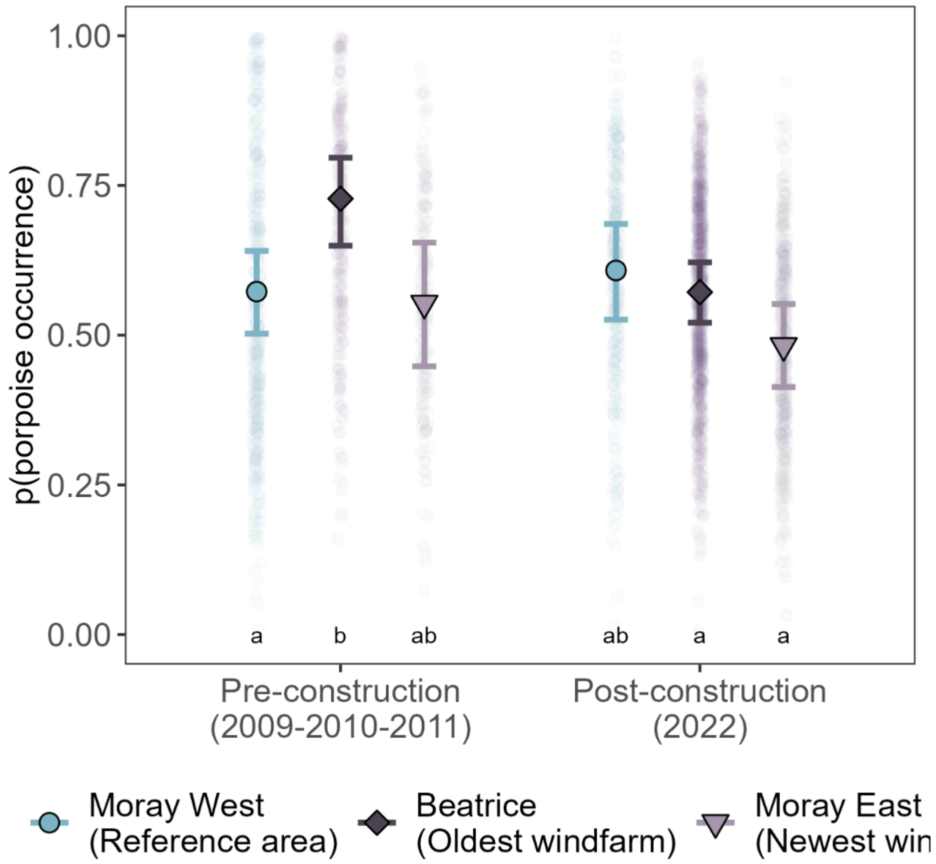

Figure S3. Probability of harbour porpoise occurrence per hour in ● Moray West, ◆ Beatrice and ▼ Moray East Offshore Windfarms during the pre- (Baseline) and post- (2022) construction periods. Unlike letters denote groups that differed statistically from each other in Tukey post-hoc test.

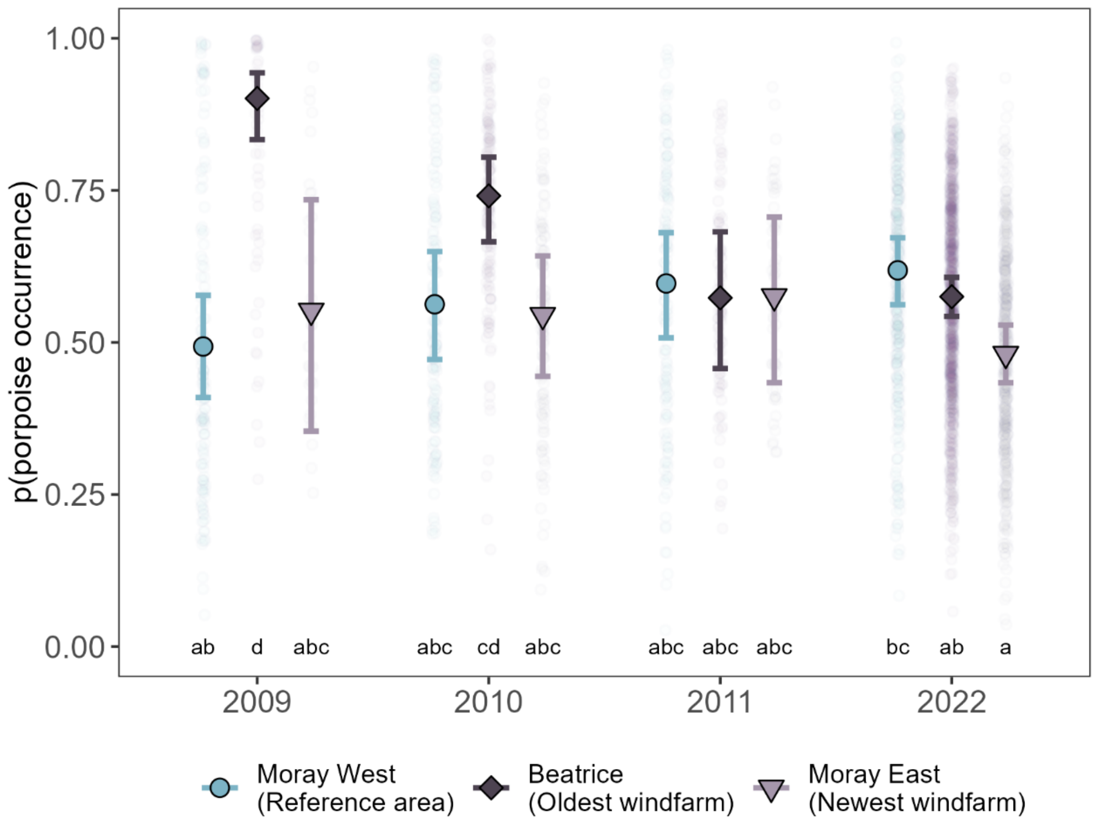

Figure S4. Probability of harbour porpoise occurrence per hour in ● Moray West, ◆ Beatrice and ▼ Moray East Offshore Windfarms in each year included in the study. Unlike letters denote groups that differed statistically from each other in Tukey post-hoc test.