Far-Field Effects of Impulsive Noise on Coastal Bottlenose Dolphins

Oihane Fernandez-Betelu*, Isla M. Graham, Kate L. Brookes†, Barbara J. Cheney, Tim R. Barton and Paul M. Thompson

Lighthouse Field Station, School of Biological Sciences, University of Aberdeen, Aberdeen, United Kingdom

Increasing levels of anthropogenic underwater noise have caused concern over their potential impacts on marine life. Offshore renewable energy developments and seismic exploration can produce impulsive noise which is especially hazardous for marine mammals because it can induce auditory damage at shorter distances and behavioral disturbance at longer distances. However, far-field effects of impulsive noise remain poorly understood, causing a high level of uncertainty when predicting the impacts of offshore energy developments on marine mammal populations. Here we used a 10-year dataset on the occurrence of coastal bottlenose dolphins over the period 2009–2019 to investigate far-field effects of impulsive noise from offshore activities undertaken in three different years. Activities included a 2D seismic survey and the pile installation at two offshore wind farms, 20–75 km from coastal waters known to be frequented by dolphins. We collected passive acoustic data in key coastal areas and used a Before-After Control-Impact design to investigate variation in dolphin detections in areas exposed to different levels of impulsive noise from these offshore activities. We compared dolphin detections at two temporal scales, comparing years and days with and without impulsive noise. Passive acoustic data confirmed that dolphins continued to use the impact area throughout each offshore activity period, but also provided evidence of short-term behavioral responses in this area. Unexpectedly, and only at the smallest temporal scale, a consistent increase in dolphin detections was observed at the impact sites during activities generating impulsive noise. We suggest that this increase in dolphin detections could be explained by changes in vocalization behavior. Marine mammal protection policies focus on the near-field effects of impulsive noise; however, our results emphasize the importance of investigating the far-field effects of anthropogenic disturbances to better understand the impacts of human activities on marine mammal populations.

Keywords: anthropogenic noise, BACI, renewable energy, seismic exploration, acoustic disturbance, offshore wind farm, passive acoustic monitoring, marine mammal

INTRODUCTION

Ambient noise in the marine environment has increased since the 1950s due to the rise of human activities at sea (Frisk, 2012). In response to the heightened concerns about the potential impacts of noise on marine life, many countries have reached international agreements to monitor underwater noise levels (Van der Graaf et al., 2012; OSPAR, 2017; Reeve, 2019). In Europe, the Marine Strategy

Framework Directive (MSFD) requires Member States to avoid sound sources that are likely to cause significant impact in the marine environment (Tasker et al., 2010). The MSFD sets out a series of indicators to assess the environmental status of an area, which for underwater noise is the proportion and spatial distribution of days on which sound sources exceed levels likely to entail significant impact.

Human activities such as pile-driving, seismic surveys and sonars produce some of the most powerful sounds underwater (Gordon et al., 2003). These impulsive sounds are defined as acute, broadband, transient signals with a rapid onset and a rapid decay (<1 s) and are considered particularly hazardous to marine mammals (Southall et al., 2007). However, during the propagation, the acoustic characteristics of sound change at rates that vary according to the specific environmental conditions. The greatest change in the acoustic characteristics of impulsive sounds occurs within ∼ 10 km from the source (Hastie et al., 2019) and, therefore, the hazardous characteristics of these sounds will vary with distance (Southall et al., 2007). Impulsive sounds have the potential to impact cetaceans through direct injury at shorter distances (here near-field) and through behavioral disturbance at longer distances (here far-field; Erbe et al., 2018). Measures to mitigate near-field effects from injury are widely adopted (Bröker et al., 2015; Verfuss et al., 2016). However, potential far-field behavioral effects and the longer-term consequences of any short-term disturbance remain challenging to assess (Pirotta et al., 2018). To date, most of the studies on the effect of impulsive noise on wild marine mammals have focused on harbor porpoises (*Phocoena phocoena*) and seals (*Phoca vitulina*) (e.g., Russell et al., 2016; Brandt et al., 2018; Graham et al., 2019). Other species, such as bottlenose dolphins (*Tursiops truncatus*), may react differently to this disturbance but information on this is sparse (David, 2006; Finneran et al., 2015; Graham et al., 2017). Due to the lack of empirical data, estimates of potential behavioral effects required for the regulation of marine energy developments have a high level of uncertainty for these animals (Merchant, 2019).

This uncertainty can be especially challenging where offshore energy developments are being considered within or near to areas used by protected cetacean populations. Over the last decade, three major energy developments have been undertaken in NE Scotland, near a Special Area of Conservation (SAC) that was established in the Moray Firth to protect bottlenose dolphins. These included a 2D seismic survey for oil and gas exploration in 2011, and the installation of foundation piles for two offshore wind farms in 2017 (Beatrice Offshore Wind Farm) and 2019 (Moray East Offshore Wind Farm), all of which are known to result in high levels of impulsive underwater noise (Madsen et al., 2006; Thomsen et al., 2011). The Habitats Directive (92/43/EEC) requires regulators to ensure that the Favorable Conservation Status of the SAC is maintained. Therefore, higher levels of assessment and protection were required prior to all three of these projects. The Appropriate Assessments undertaken by the regulator, concluded that there were no likely long-term impacts on the protected bottlenose dolphin population and permissions were granted (Berr, 2007; MS-LOT, 2014; MS-LOT and Marine Scotland Science, 2014). However, significant objections were raised during some of these processes, arguing that dolphins could be displaced from the southern coast of the Moray Firth, an important area for this population (Cheney et al., 2013).
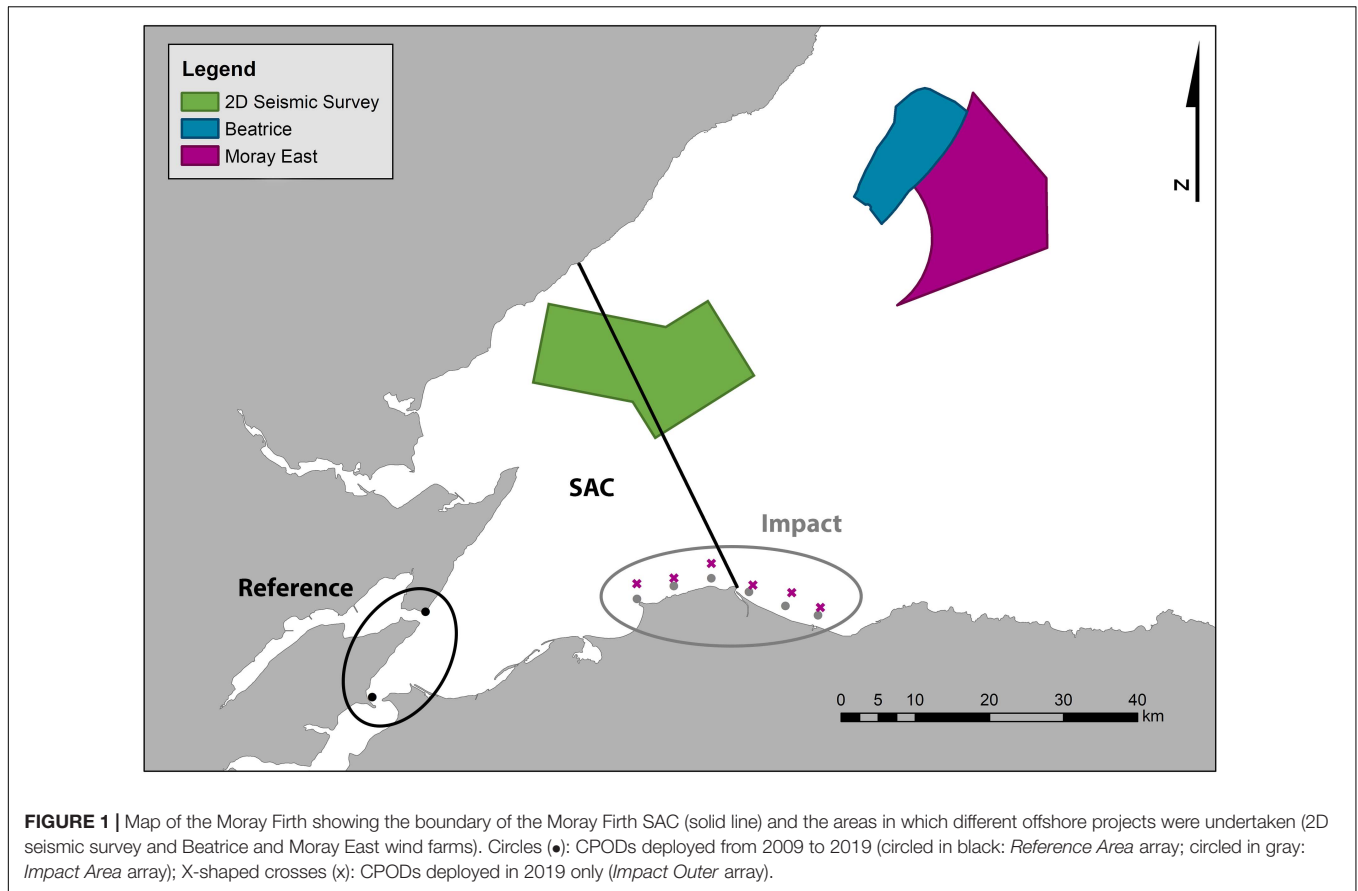
Given the sensitivities surrounding this issue and the level of uncertainty in the predictions, we used passive acoustic monitoring (PAM) to investigate whether far-field effects of impulsive noise from these offshore activities resulted in displacement of dolphins from coastal waters in the southern Moray Firth. To do so, echolocation data loggers (CPODs) were deployed to study variation in dolphin detections in areas exposed to different levels of impulsive noise. First, year-to-year variability in dolphin occurrence was investigated in each of those areas. Second, Before-After Control-Impact analyses (BACI; Underwood, 1992; Smith, 2002) were performed at two temporal scales to assess potential differences in detections within these areas. At the medium temporal scale, the BACI analysis compared years in which impulsive noise from offshore activities was present or absent. At the small temporal scale, finer-scale patterns within years with offshore activity were explored by comparing days in which impulsive noise was present or absent. Lastly, during the construction of Moray East wind farm, a more extensive PAM array was deployed in the coastal area nearest this development to investigate whether dolphins were displaced away from it and toward the coast during piling days.

MATERIALS AND METHODS

Study Area and Moray Firth Projects

The study was carried out in the Moray Firth, a large triangular embayment of the North Sea that covers approximately 5,230 km^2. The seabed gradually slopes from the coast to depths of up to 200 m and, in the center, there is a shallow sand bank of 40–50 m depth called the Smith Bank (Eleftheriou et al., 2004). The Firth is frequented by a range of cetacean species (Thompson et al., 2015; Robinson et al., 2017; Risch et al., 2019) that includes animals from a protected population of bottlenose dolphins that uses the Moray Firth SAC (**Figure 1**). The distribution of this population is primarily coastal (Thompson et al., 2015) and, although individuals show interannual variability in their range (Pirotta et al., 2015b), the population shows high site fidelity at a broader scale (Cheney et al., 2014). The area most intensively used by these dolphins is the inner Moray Firth, in the south-western part of the Firth, which is considered to be their core area of distribution (Cheney et al., 2013). However, a large proportion of the population uses other areas further south along the east coast of Scotland, such as St Andrews Bay and the Tay Estuary (Arso Civil et al., 2019). The southern coast of the Moray Firth is also intensively used by these dolphins and acts as a corridor between the SAC in the Moray Firth and the other key areas around the east coast (Culloch and Robinson, 2008; Cheney et al., 2013; Arso Civil et al., 2019).

In 2011, between the 2nd and the 11th of September, 2D seismic surveys were undertaken within the central Moray Firth, at minimum distances of 18 and 42 km from the southern coast and inner Moray Firth, respectively (**Figure 1** and **Table 1**). They were conducted with a 470 cubic inch airgun array and a 5–6 s

FIGURE 1 | Map of the Moray Firth showing the boundary of the Moray Firth SAC (solid line) and the areas in which different offshore projects were undertaken (2D seismic survey and Beatrice and Moray East wind farms). Circles (●): CPODs deployed from 2009 to 2019 (circled in black: *Reference Area* array; circled in gray: *Impact Area* array); X-shaped crosses (x): CPODs deployed in 2019 only (*Impact Outer* array).

shot interval (see Thompson et al., 2013 for survey details and modeled predictions of received noise levels). Between the 2nd April and the 2nd December 2017, the 344 pile foundations for the Beatrice wind farm were installed on the Smith Bank at least 53 km from the southern coast and 80 km from the inner Moray Firth. Each pile was hammered into the seabed using impulsive pile driving techniques with a maximum hammer energy of 2299 kJ (see Graham et al., 2019 for modeled predictions of received noise levels). On the 30th May 2019, construction started at the Moray East wind farm next to Beatrice; 264 pile foundations were installed between May and December 2019 (see MORL, 2016 for modeled predictions of received noise levels). Piles were installed using similar impulsive pile driving techniques and a maximum

hammer energy of 2071 kJ (see **Supplementary Tables 1, 2** for detailed piling timelines from Beatrice and Moray East).

Passive Acoustic Monitoring

Echolocation detectors (CPODs, Chelonia Ltd.) were used to collect information on temporal patterns of occurrence in areas known to be frequented by bottlenose dolphins (Cheney et al., 2014). CPODs were deployed between 2009 and 2019 following previously described techniques (Bailey et al., 2010a; Thompson et al., 2013; Graham et al., 2019). Two CPODs were deployed at sites within the inner Moray Firth where the impact was expected to be lowest; hereafter the *Reference Area* (**Figure 1**; Fernandez-Betelu et al., 2019). These reference sites were located at minimum distances of 42, 80, and 78 km from the seismic survey, Beatrice and Moray East wind farm developments, respectively. Six CPODs were deployed along the southern Moray Firth coast, the part of the dolphin population's coastal range that was closest to all three offshore activities, where the impact was expected to be highest, hereafter the *Impact Area* (Thompson et al., 2010). These impact sites were located at minimum distances of 18, 53, and 45 km from the seismic survey, Beatrice and Moray East wind farm developments, respectively. In 2019, during the construction of Moray East wind farm, six extra CPODs were deployed in the *Impact Area* at greater distances from the coast (from 3 to 4 km), hereafter *Impact Outer* area. With this array we aimed to investigate whether dolphins from

TABLE 1 | Summary table with distance to the offshore project and maximum predicted received noise levels expressed as unweighted single-pulse sound exposure levels (SEL: dB re 1 $\mu Pa^2 s$ (Thompson et al., 2013; MORL, 2016; Graham et al., 2019).

		Reference area	Impact area
2D seismic	Minimum distance (km)	42	18
	Max Received noise levels (SEL)	132	139
Beatrice	Minimum distance (km)	80	53
	Max Received noise levels (SEL)	100	128
Moray east	Minimum distance (km)	78	45
	Max Received noise levels (SEL)	93	141

further out at sea were displaced toward the coast in the southern Moray Firth by impulsive noise. Although data were collected year round at some locations, data from November to April were excluded from all the analyses due to the low occurrence of dolphins during those months along the southern Moray Firth coast (Fernandez-Betelu et al., 2019).

CPOD data were downloaded and trainfiltered using the manufacturer's software[1] to identify which echolocation clicks were produced by dolphins. As recommended by the manufacturer, only click trains classified as high and moderate quality were used in this study. Since previous photo-ID, line transects and aerial surveys confirmed that the presence of other species of dolphins is rare in the studied sites (Thompson et al., 2015), all detected echolocation clicks were assumed to be produced by bottlenose dolphins. Detection Positive Hours per day (DPH) was the metric derived from the click train detections that we chose as the proxy for dolphin occurrence. DPH describes the number of hours in each day in which a dolphin click train was detected on each CPOD and is a robust proxy for studying odontocete occurrence (Brookes et al., 2013; Williamson et al., 2016). We used the statistical program R v. 3.5.1 (R Core Team, 2018) in all subsequent analyses.

Inter-Annual Variability in Dolphin Occurrence

Inter-annual variability in the occurrence of dolphins in the *Reference* and *Impact Areas* was characterized from a sub-set of comparable data from 4 long-term CPODs, two in each of the areas, that provided complete datasets for August and September from 2009 to 2019 (see timeline with CPOD deployments in **Supplementary Figure 1**). We calculated the DPH per day for these months and assessed the year-to-year variability in dolphin occurrence within these areas. Comparisons between years were made using non-parametric Kruskal-Wallis tests because data were not normally distributed.

Far-Field Effects on Bottlenose Dolphin Occurrence in Relation to Seismic and Wind Farm Projects: Medium and Small Temporal Scales

We performed BACI analyses (Underwood, 1992; Smith, 2002) to investigate whether there was a change in dolphin detections in the *Impact Area* relative to the more distant *Reference Area* during each offshore activity. In the BACI analyses we performed generalized linear mixed models (GLMM) with a Poisson family distribution and square root link function (Bolker et al., 2009). We used dolphin DPH as the response variable and included area (*Reference Area/Impact Area*) and period (*Baseline period/Activity period*) as fixed effects in interaction. At the medium temporal scale, the *Activity period* comprised years when offshore activities were undertaken and the *Baseline period* years without these offshore activities. At the small temporal scale, the *Activity period* included days in which impulsive noise was generated and the *Baseline period*, days in which impulsive noise

[1]www.chelonia.co.uk

was not generated (**Table 2**). We included CPOD location and day within a year as random intercepts to remove patterns in the residuals and improve the fit of GLMM models at both temporal scales.

Far-Field Effect on Bottlenose Dolphin Occurrence in Relation to Moray East Wind Farm: Displacement From the Southern Moray Firth at a Fine Spatial Scale

During foundation installation at Moray East wind farm we investigated the occurrence of dolphins in the *Impact Area* at a fine spatial scale and assessed whether dolphins were displaced toward the coast during piling days. To do so, we assessed differences in dolphin DPH between the CPODs closer to the shore (*Impact Inner* array) and the CPODs further from the coast (*Impact Outer* array) in the impact area (**Figure 1**). We used GLMM and introduced array (*Impact Inner/Impact Outer*) and period (*Piling/Non-piling days*) as explanatory variables in interaction. CPOD location and day within a year were included as random intercepts.

RESULTS

CPODs were successfully deployed from 2009 to 2019 and provided more than 10,000 days of CPOD data. Gaps in the dataset occurred due to a combination of device failure and logistical constraints. Data from 2012 were removed from these analyses because only one CPOD was recovered that year from the *Impact Area* (**Supplementary Figure 1**).

TABLE 2 | Data used in the BACI analyses for the medium and small temporal scales.

			Baseline period	Activity period
Medium temporal scale	2D seismic	Dates	01–14 Sep	02–11 Sep
		Years	2009, 2010, 2013, 2014	2011
		Tot. ndays	60	10
	Beatrice	Dates	May–Sep	May–Sep
		Years	2014, 2015, 2016, 2018	2017
		Tot. ndays	611	153
	Moray East	Dates	May–Sep	May–Sep
		Years	2014, 2015, 2016, 2018	2019
		Tot. ndays	611	153
Small temporal scale	2D seismic	Dates	23 Aug–01 Sep, 12–21 Sep	02–11 Sep
		Years	2011	2011
		Tot. ndays	20	10 (16.4%)
	Beatrice	Dates	Non-piling days May–Sep	Piling days May–Sep
		Years	2017	2017
		Tot. ndays	68	85 (52.4%)
	Moray East	Dates	Non-piling days May–Sep	Piling days May–Sep
		Years	2019	2019
		Tot. ndays	101	52 (24.6%)

Table includes the total number of days in each of the periods (Baseline period/Activity period) and the percentage of days with impulsive noise in August and September in brackets.
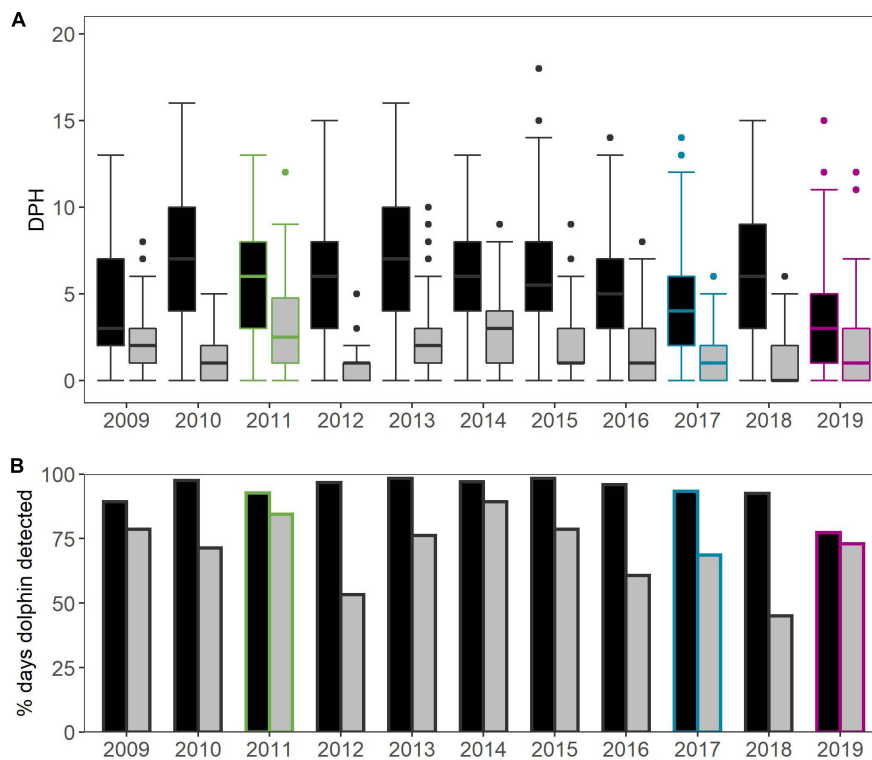
FIGURE 2 | Inter-annual variation in **(A)** dolphin Detection Positive Hours per day and **(B)** percentage of days that dolphins were detected in *Reference Area* (black) and *Impact Area* (gray). Data from August-September 2009 to 2019 from the 4 long-term CPODs. Colored borders indicate years when offshore activities took place (2011: 2D seismic survey; 2017: Beatrice wind farm construction; and 2019: Moray East wind farm construction).

Inter-Annual Variability in Dolphin Occurrence

The seismic survey, Beatrice and Moray East wind farm construction resulted in impulsive noise being produced within the Moray Firth on 16.4, 52.4, and 24.6% of days in August and September 2011, 2017, and 2019, respectively (**Table 2**).
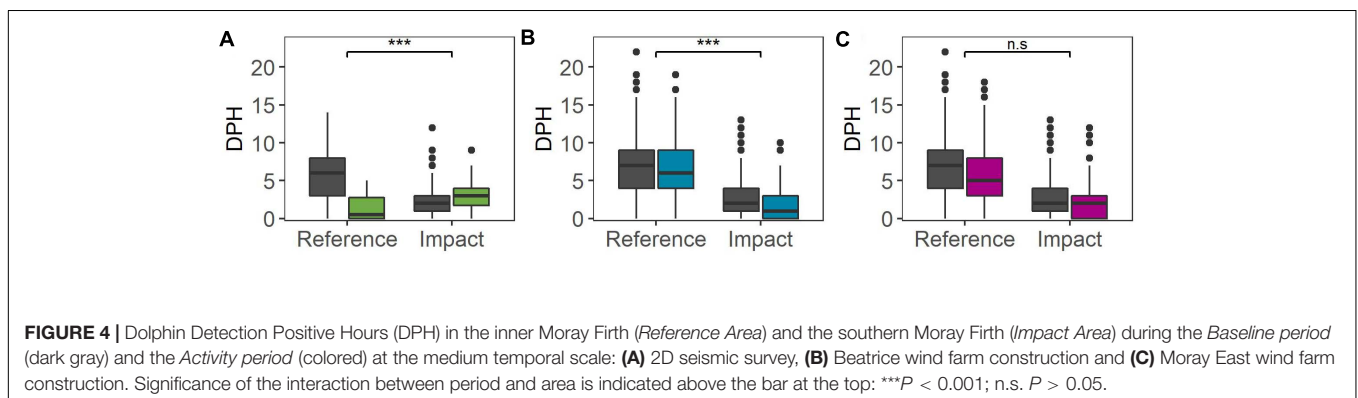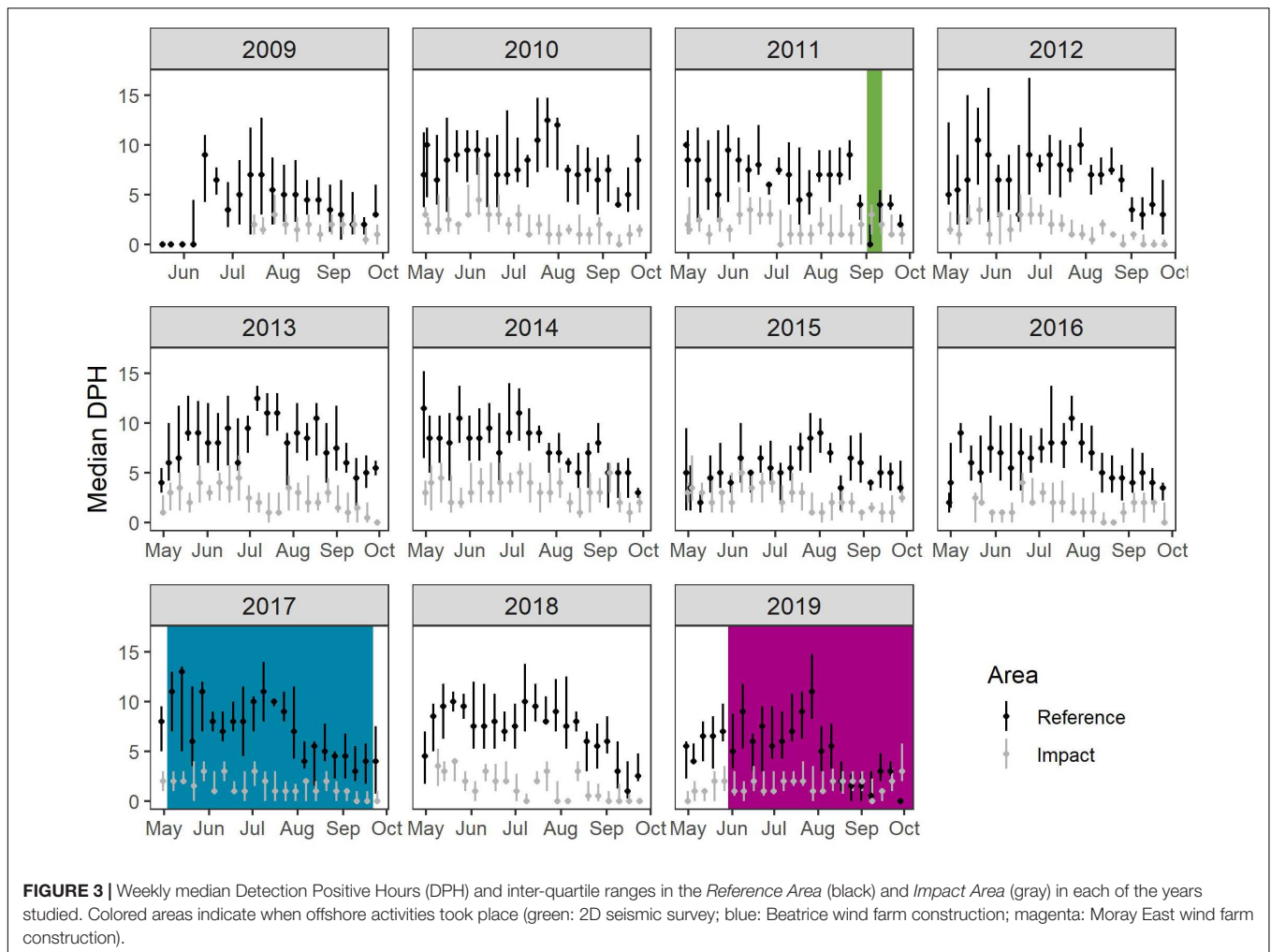
For the comparable subset of data from August-September, there were significant inter-annual differences in the daily occurrence of dolphins (DPH) in both areas (**Figure 2A**). The median DPH ranged between 3 and 7 h in the *Reference Area* ($X^2 = 102.26$, df = 10, $p < 0.0001$) and between 0 and 3 h in the *Impact Area* ($X^2 = 139.4$, df = 10, p-value < 0.0001) (**Figure 3** and details in **Supplementary Table 3**). Dolphin detections were higher in the *Reference Area* than in the *Impact Area* during all years: dolphins were detected on 77–98% of the days in the *Reference Area*, compared to 45–89% of the days in the *Impact Area* (**Figure 2B**).

Far-Field Effects on Bottlenose Dolphin Occurrence in Relation to Seismic and Wind Farm Projects: Medium and Small Temporal Scales

At the medium temporal scale, the BACI analysis did not identify any consistent relationship between observed inter-annual variability and the occurrence of impulsive noise from these offshore activities (**Figure 4** and **Table 3**). There were significant impacts of both the seismic survey and Beatrice wind farm construction, but the effects were in opposite directions. For the seismic survey in 2011, dolphin detections in the *Impact Area* increased by 50% (to a median of 3 h per day) compared to baseline years but reduced by 100% (to a median of 0.5 h per day) in the *Reference Area* (GLMM: $X^2 = 32.975$, df = 1, $p < 0.001$). In contrast, during the Beatrice wind farm piling campaign in 2017, compared to baseline years, dolphin detections decreased by 50% in the *Impact Area* (to a median of 1 h per day) and decreased by 14% (to a median of 6 h per day) in the *Reference Area* (GLMM: $X^2 = 39.342$, df = 1, $p < 0.001$). Finally, when impact piling was conducted at Moray East wind farm in 2019, no significant difference in dolphin detections between areas was found compared to baseline years (GLMM: $X^2 = 0.9451$, df = 1, $p > 0.05$; **Figure 4** and **Table 3**).

At the small temporal scale, the BACI analysis identified a significant impact of all three offshore activities, with an increase in dolphin detections in the impact area during those days on which impulsive noise was generated (**Figure 5** and **Table 3**). For the seismic survey, an increase in dolphin detections of 200% (to a median of 3 h per day) was obtained in the *Impact Area* whereas a reduction of 90% (to a median of 0.5 h per day) was detected in the *Reference Area* (GLMM: $X^2 = 38.861$, df = 1, $p < 0.001$).

FIGURE 3 | Weekly median Detection Positive Hours (DPH) and inter-quartile ranges in the *Reference Area* (black) and *Impact Area* (gray) in each of the years studied. Colored areas indicate when offshore activities took place (green: 2D seismic survey; blue: Beatrice wind farm construction; magenta: Moray East wind farm construction).

FIGURE 4 | Dolphin Detection Positive Hours (DPH) in the inner Moray Firth (*Reference Area*) and the southern Moray Firth (*Impact Area*) during the *Baseline period* (dark gray) and the *Activity period* (colored) at the medium temporal scale: **(A)** 2D seismic survey, **(B)** Beatrice wind farm construction and **(C)** Moray East wind farm construction. Significance of the interaction between period and area is indicated above the bar at the top: ***$P < 0.001$; n.s. $P > 0.05$.

During pile-driving at Beatrice wind farm, an increase in dolphin detections of 100% was found in the *Impact Area* (to a median of 2 h per day) whereas there was no change in the *Reference Area* (GLMM: $X^2 = 5.198$, df = 1, $p < 0.05$). For the Moray East wind farm development, dolphin detections increased by 100% (to a median of 2 h per day) in the *Impact Area* and increased by 20% (to a median of 6 h per day) in the *Reference Area* (GLMM: $X^2 = 4.807$, df = 1, $p < 0.05$; **Figure 5** and **Table 3**).

Far-Field Effect on Bottlenose Dolphin Occurrence in Relation to Moray East Wind Farm: Displacement From the Southern Moray Firth at a Fine Spatial Scale

There was a significant increase in dolphin detections during piling days in both *Impact Inner* and *Impact*

TABLE 3 | Results of the Poisson generalized linear mixed models used to investigate the effect of impulsive noise from offshore activities on the acoustic detection of dolphins at sites in the inner Moray Firth (*Reference Area*) and the southern Moray Firth (*Impact Area*) at the medium and small temporal scales and in the *Impact Inner* and *Impact Outer* arrays at the fine spatial scale.

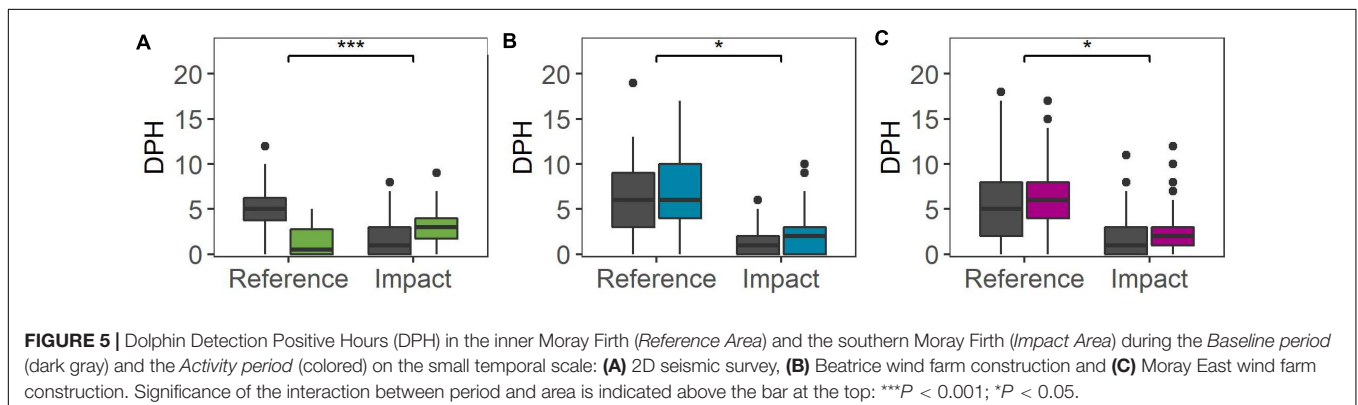|			Estimate	Std. error	Df	*P*-Value
Medium temporal scale	2D seismic survey	*Intercept*	0.777	0.089	1	< 0.001
		Period	0.240	0.154	1	0.119
		Area	0.910	0.137	1	< 0.001
		Period:Area	−1.617	0.286	1	< 0.001
	Beatrice	*Intercept*	0.786	0.066	1	< 0.001
		Period	−0.338	0.046	1	< 0.001
		Area	1.078	0.127	1	< 0.001
		Period:Area	0.270	0.041	1	< 0.001
	Moray East	*Intercept*	0.786	0.069	1	< 0.001
		Period	−0.205	0.046	1	< 0.001
		Area	1.085	0.132	1	< 0.001
		Period:Area	0.039	0.040	1	0.331
Small temporal scale	2D seismic survey	*Intercept*	0.502	0.163	1	0.002
		Period	0.478	0.170	1	0.005
		Area	1.147	0.350	1	0.001
		Period:Area	−0.186	0.298	1	< 0.001
	Beatrice	*Intercept*	0.274	0.093	1	0.003
		Period	0.286	0.089	1	0.001
		Area	1.428	0.141	1	< 0.001
		Period:Area	−0.174	0.077	1	0.023
	Moray East	*Intercept*	0.385	0.121	1	< 0.001
		Period	0.327	0.086	1	< 0.001
		Area	1.209	0.208	1	< 0.001
		Period:Area	−0.162	0.074	1	0.028
Fine spatial scale	Moray East	*Intercept*	0.471	0.397	1	0.235
		Period	0.245	0.082	1	0.003
		Area	−2.211	0.603	1	< 0.001
		Period:Area	0.153	0.980	1	0.121

Outer arrays compared to non-piling days (GLMM: X^2 = 8.932, df = 1, *p* = 0.003; **Figure 6**). Dolphin detections were significantly higher at the *Impact Inner* array than at the *Impact Outer* array (GLMM: X^2 = 14.659, df = 1, *p* < 0.001). The interaction between array and period was not significant (GLMM: X^2 = 2.406, df = 1, *p* > 0.05; **Table 3**).
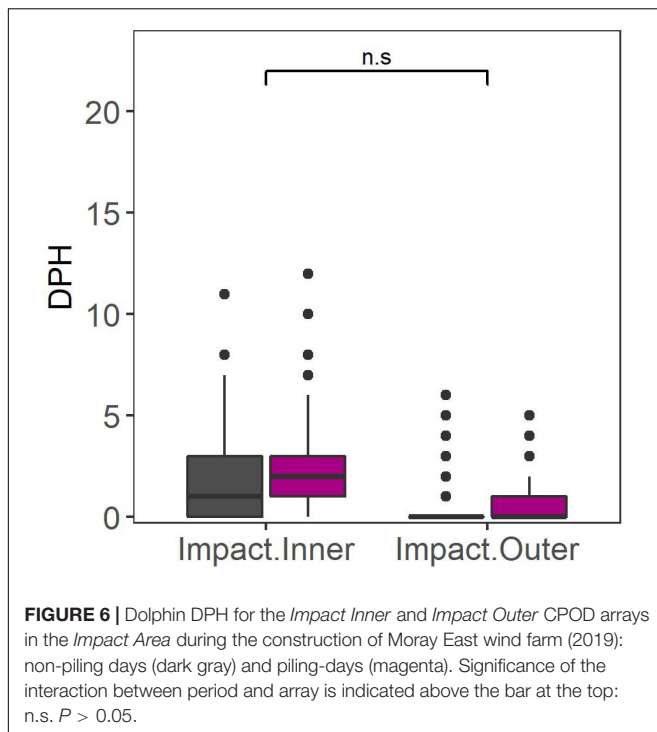
DISCUSSION

The analysis of 10 years of PAM data highlighted that dolphins used Moray Firth inshore areas regularly, albeit the extent of use varied from year to year without any consistent relationship to the impulsive noise generated by offshore activities. Nevertheless, at a fine temporal scale within offshore activity years, there was a significant change in dolphin occurrence depending upon the presence or absence of impulsive noise on different days.

The results of this study suggest that the impulsive noise generated by offshore activities did not cause any dolphin displacement from the southern coast of the Moray Firth. The southern coast is the closest area to the offshore activities within this bottlenose dolphin population's range (Arso Civil et al., 2019): the seismic survey took place 20–30 km away, and piling at Beatrice 50–70 km and Moray East 40–70 km, from the southern coast. Predicted maximum received noise levels were 139 dB and 128 dB re 1 μPa^2s during the seismic survey and during piling at Beatrice wind farm, respectively (unweighted single pulse SEL; Thompson et al., 2013; Graham et al., 2019) and 141 dB re μPa^2s in the worst-case scenario for Moray East wind farm (MORL, 2016). Our analyses showed that dolphins continued using the southern coast of the Moray Firth during the seismic survey and impact pile-driving. These results are in line with recent studies that found that displacement of marine mammals from impulsive noise sources only occurs at shorter distances. For instance, displacement of harbor porpoises and baleen whales, which are more sensitive to noise (Southall et al., 2019b), has been reported up to 20 km away from impulsive noise sources (Dähne et al., 2013; Dunlop et al., 2018; Graham et al., 2019; Southall et al., 2019a; Sarnocińska et al., 2020). There are no similar studies for bottlenose dolphins but, since they are less sensitive than baleen whales and harbor porpoises to noise, shorter ranges of displacement would be expected.

Contrary to expectations, the BACI analysis at the smaller temporal scale, showed an increase in dolphin detections on the southern Moray Firth coast on days with impulsive noise. Furthermore, this increase was consistent between all three offshore projects. The short-term increase in dolphin detections observed only at the smallest temporal scale is in line with

FIGURE 5 | Dolphin Detection Positive Hours (DPH) in the inner Moray Firth (*Reference Area*) and the southern Moray Firth (*Impact Area*) during the *Baseline period* (dark gray) and the *Activity period* (colored) on the small temporal scale: **(A)** 2D seismic survey, **(B)** Beatrice wind farm construction and **(C)** Moray East wind farm construction. Significance of the interaction between period and area is indicated above the bar at the top: ***P < 0.001; *P < 0.05.

FIGURE 6 | Dolphin DPH for the *Impact Inner* and *Impact Outer* CPOD arrays in the *Impact Area* during the construction of Moray East wind farm (2019): non-piling days (dark gray) and piling-days (magenta). Significance of the interaction between period and array is indicated above the bar at the top: n.s. *P* > 0.05.

previous studies that found that behavioral alterations due to noise exposure last less than a day (Thompson et al., 2013; Van Beest et al., 2018). Our findings are consistent with those of Bailey et al. (2010b) who, based on criteria in Southall et al. (2007) suggested that dolphins in this study area might exhibit modifications in behavior at around 50 km away from a piling vessel. Acute noises can modify marine mammal group size and group behavior (Visser et al., 2016; Curé et al., 2021), which in turn can cause changes in vocalizations (Henderson et al., 2012). Therefore, one possible explanation for the observed increase in dolphin detections is that noise modified bottlenose dolphin group sizes or group behavior. Although whistle vocalization rates have been linked to group sizes (Quick and Janik, 2008), echolocation click rates cannot be directly linked to the size of bottlenose dolphin groups (Nuuttila et al., 2013). Since our study was based on echolocation data loggers, we cannot test whether the increase in noise levels modified dolphin group sizes. Moreover, since CPOD detections and the number of individuals are not directly linked (Nuuttila et al., 2013), it does not follow that the increase in detections observed here is indicative of changes in group size. Changes in marine mammal vocalizations due to distant (>20 km) anthropogenic noise sources have been observed previously (Risch et al., 2012; Blackwell et al., 2013; Shannon et al., 2016). Therefore, another explanation of the increase in detections is that dolphins might have changed their vocalization rate (Blackwell et al., 2015) or the amplitude of their calls (Holt et al., 2009; Parks et al., 2011) in response to the impulsive noise generated by the offshore activities. In an experiment with captive bottlenose dolphins, the playback of pile driving noise resulted in an increase in the number

of clicks produced by these animals (Branstetter et al., 2018). Caution is required when extrapolating information from trained to wild animals, but an increase in the click rate could explain the observed increase in detections by our CPODs during the impulsive noise events. Results obtained from the fine scale spatial analysis during the construction of Moray East wind farm also support this hypothesis. No displacement from the outer toward the inner array was observed during piling days, while a subtle but consistent increase in dolphin detections was observed on both arrays. Research is needed to further investigate potential changes in the acoustic characteristics of bottlenose dolphin clicks during far-field impulsive noise events. Passive acoustic devices that collect information on marine mammal click characteristics could be deployed during future offshore developments to explore in more detail whether these activities can be linked to differences in dolphin click rates or click amplitude.

At the medium temporal scale, comparing dolphin occurrence to baseline years, the results were not consistent between offshore activities. During the seismic survey, an increase in dolphin detections was observed on the southern coast. During the construction of Beatrice wind farm, a decrease was detected in the same area and during the construction of Moray East wind farm, no significant difference was detected. In line with previous studies, dolphin detections overall were higher in the *Reference Area* of the inner Moray Firth, compared with the *Impact Inner* area on the southern coast, but the extent of use varied between years and through the season (Thompson et al., 2015; Fernandez-Betelu et al., 2019). The difference in detections at the medium temporal scale therefore seems likely to be related to the natural inter-annual variation in occurrence that was also reflected in our analyses here (**Figure 2**). Although potentially modified by anthropogenic factors, bottlenose dolphin occurrence is largely influenced by a range of natural drivers, such as prey abundance and oceanographic processes (Heithaus and Dill, 2002; Benjamins et al., 2015). Our results suggest that the effect of far-field noise is less important than these other natural drivers in affecting the occurrence of dolphins in this study area.

We used a BACI design to investigate the effect of impulsive noise on the coastal occurrence of dolphins. This methodology is based on the comparison of data from two similar areas (Impact and Control) in situations where only one of them is affected by a disturbance. However, finding control sites with similar ecological characteristics to impact sites, while being distant enough to be unaffected by the disturbance, is not always feasible (Underwood, 1992, 1994). The sites defined here as reference sites were chosen because they were located at greater distances from the developments but were still within the bottlenose dolphin population's range. However, a complete lack of disturbance cannot be assured there, hence the term *Reference* instead of *Control Area*. For instance, during the construction of Moray East wind farm an increase in detections was observed at both *Reference* and *Impact Areas* during piling days, potentially indicating that noise levels might also have affected dolphins at reference sites. Nevertheless, these 10 years of passive acoustic

monitoring data provided a robust dataset to investigate the effects of three offshore projects, while overcoming some of the limitations of the BACI design. The consistent results at the smallest temporal scale strengthened our hypothesis that a change in vocal behavior may have caused the observed increase in dolphin detections. While the contrasting results at the medium temporal scale from multiple offshore activities prevented us from suggesting misleading effects that might have been inferred from work conducted only during a single project. Overall, our analyses showed that long-term datasets such as this provide opportunities to detect relatively subtle differences in bottlenose dolphin behavior linked to the far-field impulsive noise generated by offshore activities.

Management Implications

Limited data on localized cetacean populations can constrain environmental assessments for new developments, particularly where these occur in or near protected areas. In the Moray Firth, concerns over the potential impacts of offshore developments on the protected population of bottlenose dolphins required additional research and survey effort in the area to inform licensing decisions.

The findings of this study support the Appropriate Assessments' conclusions that these offshore activities would not have a major impact on the bottlenose dolphin population using the SAC (Berr, 2007; MS-LOT, 2014; MS-LOT and Marine Scotland Science, 2014). Our results also concur with recent photo-ID studies of this dolphin population that showed increasing trends in both population size (Cheney et al., 2014) and vital rates (Cheney et al., 2019), supporting the lack of any large-scale impacts on the population. Our analysis showed that dolphins continued using the area of their range where the impact was expected to be highest when these projects took place. The monitoring of the far-field responses of dolphins provided evidence of potential short-term changes in vocalizations as reported for other marine mammal species (Gomez et al., 2016). Developers are required to perform marine mammal monitoring for several years to create a sufficient baseline and assess potential impacts (Diederichs et al., 2008). However, in places with high inter-annual variability in the presence of marine mammals, analyses using data from other years as a baseline may produce misleading results.

Marine mammal protection policies are focused on minimizing the near-field acute effects of impulsive noise (Bröker et al., 2015; Verfuss et al., 2016). While the risk of death or injury is limited to the first hundreds of meters from the sound source (Southall et al., 2019b), behavioral responses, such as changes in vocalizations, can occur at greater distances (hundreds of km) potentially affecting a greater number of animals (Risch et al., 2012). Here, we suggested that distant impulsive noise sources may have caused modifications of bottlenose dolphin vocalizations. Further research is now required to test this hypothesis and describe the extent of any change in more detail, given that moderate modifications of vocal behavior have the potential to affect foraging and individual vital rates (Southall

et al., 2007). The challenge in future research will be linking modifications of vocal behavior to changes in energetic costs (Booth, 2020; Pirotta et al., 2021) and, ultimately, population level consequences (Pirotta et al., 2015a; Reed et al., 2020).

DATA AVAILABILITY STATEMENT

All data are available from the Dryad Digital Repository. All datasets and R code used for the analyses are available at: https://doi.org/10.5061/dryad.6hdr7sr17.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because this was a non-invasive, acoustic observational study of bottlenose dolphin responses to offshore seismic surveys and pile-driving. The authors had no control or influence over the duration or scheduling of offshore activities. No animals were captured or tagged during this study and no research or animal ethical assessments were required. Bottlenose dolphin responses to impulsive noise were determined using remote passive acoustic devices on seabed moorings licensed for scientific use by Marine Scotland, and consented by the Crown Estate. Moorings were deployed and recovered using vessels with appropriate certification, accreditation and endorsements.

AUTHOR CONTRIBUTIONS

OFB, IG, and PT designed the study based on data collection that had been led by IG, KB, and PT. TB managed data collection. IG and BC processed the raw data. All analyses were designed and conducted by OFB and supervised by IG. OFB led the writing of the manuscript. All authors reviewed and contributed critically to the drafts.

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