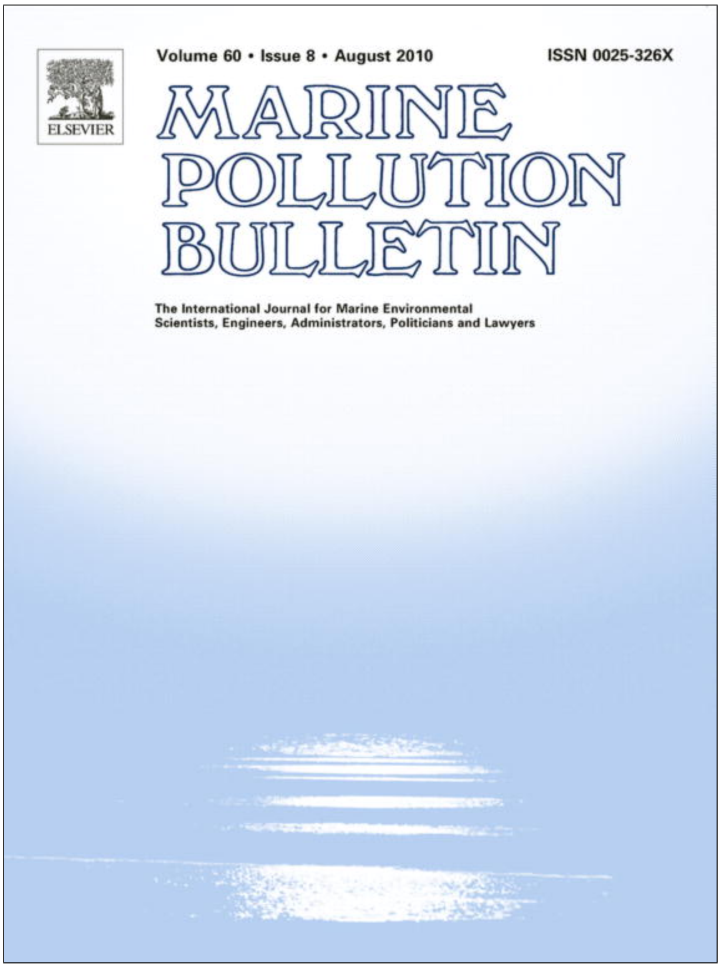
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Assessing the responses of coastal cetaceans to the construction of offshore wind turbines

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ABSTRACT

The expansion of offshore renewables has raised concerns over potential disturbance to coastal cetaceans. In this study, we used passive acoustic monitoring to assess whether cetaceans responded to pile-driving noise during the installation of two 5 MW offshore wind turbines off NE Scotland in 2006. Monitoring was carried out at both the turbine site and a control site in 2005, 2006 and 2007. Harbour porpoises occurred regularly around the turbine site in all years, but there was some evidence that porpoises did respond to disturbance from installation activities. We use these findings to highlight how uncertainty over cetacean distribution and the scale of disturbance effects constrains opportunities for B-A-C-I studies. We explore alternative approaches to assessing the impact of offshore wind farm upon cetaceans, and make recommendations for the research and monitoring that will be required to underpin future developments.

1. Introduction

The expansion of offshore renewables has raised a wide range of environmental concerns, that include potential impacts upon coastal cetacean populations (Gill, 2005; Madsen et al., 2006). Assessments of these impacts require better information on the occurrence of different species around development sites, and on the likely response of these animals to the anthropogenic noise that they produce (Richardson et al., 1995; Southall et al., 2007). Currently, however, there are limited fine-scale data on cetacean distribution patterns in many coastal areas, and even less is known about the extent to which these species may respond to development activity. This seriously constrains our understanding of whether the future expansion of marine renewables poses a significant threat to cetaceans.

Cetaceans may be affected by development of marine renewables in two main ways. First, noise from the construction, operation or decommissioning of structures such as wind turbines may disturb or injure these animals (Madsen et al., 2006). At close range, loud noises, for example from pile driving, could physically injure animals or cause temporary damage to hearing thresholds (David, 2006). Lower levels of noise could disturb foraging or social behaviour, and may lead to animals avoiding preferred habitat if the disturbance was long-term. Secondly, the physical structures themselves could alter the animals' habitat, potentially leading to either habitat loss or the creation of new habitats in which these structures could act as artificial reefs (Wilhelmsson et al., 2006). Effects of this kind are most likely to act indirectly, through changes in prey populations and consequently may prove particularly difficult to detect.

Recent environmental assessments for offshore wind farms have generally identified pile driving as the activity having the greatest potential impact upon local cetacean populations (Carstensen et al., 2006; Diederichs et al., 2008). Typically these assessments predict source levels for pile-driving noise based upon the size of the piles (Nedwell et al., 2005), and use generic models to estimate transmission loss at different distances from source (Richardson et al., 1995). In theory, zones of potential impact can then be estimated using data on the received sound levels likely to cause different types of damage or responses. In practice, these estimates are constrained by the limited data available on physiological and behavioural responses of cetaceans to different noise levels (Southall et al., 2007).

Empirical assessments of the subsequent impact of these activities on cetacean abundance or behaviour have proved difficult to conduct. Much of our understanding of cetacean densities in these coastal areas is based upon large-scale visual surveys that have been carried out either by plane or boat (Evans and Hammond, 2004). However, high levels of sampling variability mean that methods for assessing abundance from visual surveys have low power to detect change (Taylor et al., 2007). Furthermore, these animals are inherently difficult to study because they spend so little time at surface. This makes it unlikely that groups of cetaceans

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can be observed directly during potential impact events. Even when groups can be observed, it is difficult to interpret behavioural changes from surface observations and quantify changes in behaviour or movements. In some cases, these problems can be overcome by instrumentation of individuals with activity recorders or telemetry devices and remotely monitoring changes in behaviour in response to known events (Johnson and Tyack, 2003). However, the use of such devices is most likely to be practical for large cetaceans and pinnipeds, and remains less suitable for small cetaceans.

Recently, passive acoustic monitoring studies have provided more detailed data on cetacean distribution and information on temporal trends in the occurrence of cetaceans in particular areas (Clark and Clapham, 2004; Gillespie et al. 2005; Verfuss et al., 2007). Passive acoustic monitoring has also provided an important tool when mitigating the impact of particular activities upon cetaceans, as this can provide a more reliable way of detecting the presence of animals in an area (DiSciara and Gordon, 1997; Potter et al. 2007). Potentially damaging activities, such as pile driving, can then be avoided if cetaceans are nearby. The development of automated devices that can remotely record cetacean echolocation clicks has proved particularly important for supporting many assessments of the impact of marine renewables on coastal cetacean populations. These Timed POrpoise Detectors (T-PODS) were originally designed to study harbour porpoises (Thomsen et al., 2005), but can be programmed to detect echolocation clicks from a range of other species (Philpott et al., 2007). Devices can be left recording for periods of 10–20 weeks depending upon battery configuration. For harbour porpoises, it has been estimated that animals can be detected within a distance of approximately 200 m around the T-POD (Tougaard et al., 2006), whereas field studies indicate that bottlenose dolphins can be detected at distances up to 1200 m (Philpott et al., 2007).

T-PODs therefore offer great potential as a tool for assessing responses of cetaceans to disturbances such as those occurring during wind farm construction. For example, Carstensen et al. (2006) showed that porpoise activity decreased in response to ramming and vibration of steel sheet piles during the construction of the Nysted wind farm in Denmark. Recent guidelines on methodologies for assessing whether wind farms influence marine mammal distribution also recommend using TPODs for baseline monitoring and for carrying out impact studies (Diederichs et al., 2008), where a B-A-C-I design (see Underwood, 1994) can be used to compare the occurrence of animals in impact and control areas, before, during and after the presence of a disturbance.

In this study, we explore the potential for using T-PODS to assess the impact of offshore developments on echolocating cetaceans through monitoring studies that were carried out during the Beatrice Demonstrator Project in NE Scotland. This project involved the installation of two demonstration wind turbines in 2006, where there were particular concerns about the potential impact upon a protected population of bottlenose dolphins. In particular, we use this case study to highlight how uncertainties over baseline distributions, the scale of impact and the presence of other unknown anthropogenic stressors can limit the potential for using a B-A-C-I approach in these situations. Our findings are then used to explore alternative approaches to assessing the impact of future developments on local cetacean populations, and make recommendations for future research and monitoring.

2. Methods

2.1. Study area and case study details

The study was carried out as part of the Beatrice Demonstrator Project, when two 5 MW wind turbines were installed by Talisman Energy (UK) Ltd. (Talisman) and Scottish and Southern Energy. This work formed part of the EU Framework VI funded DOWNVInD project that aimed to assess the potential for deep-water offshore wind farms.

The turbine sites were 25 km from the nearest coastline (58° 06′ N, 03° 04′ W), in water 42 m deep (Fig. 1). Importantly, the Moray Firth contains a Special Area of Conservation (SAC) that was designated to protect bottlenose dolphins (*Tursiops truncatus*) through the EU Habitats Directive (Thompson et al., 2000). Although the outer boundary of the SAC was 25 km from the turbine site, the potential both for underwater noise to travel long distances, and for dolphins to travel outside the SAC boundary, meant that the potential impacts of the development on this protected population was a key concern for the developer and environmental stakeholders (Talisman, 2005). Other cetaceans such as harbour porpoises (*Phocoena phocoena*) and minke whales (*Balaenoptera acutorostrata*) were known to occur in the outer Moray Firth area, but at the beginning of the project there were limited data on the density or seasonal occurrence of any cetaceans in the waters around the turbine site.

Key concerns for these cetacean populations centred upon the installation of the turbine sub-structures, each of which was attached to the seabed by installing four (44 m × 1.8 m) tubular piles. Based upon measurements of other piling events, and equations in Nedwell et al. (2005), it was predicted that the installation of these 1.8 m piles would result in sound source levels of 225 dB re 1 Pa at 1 m. The project's environmental assessment used available data on marine mammal hearing thresholds and likely background noise to estimate the distance at which these sounds would be audible to different species. Similarly, available data on the noise thresholds likely to elicit avoidance behaviour suggested that bottlenose dolphins and harbour porpoises would respond at distances of 2 and 9.3 km, respectively (Talisman, 2005). However, more recent assessments of the impacts of underwater noise on cetaceans (Southall et al., 2007) have since been used to revise these estimates, and it is possible that behavioural disturbance could occur at distances of 43 and 70 km for bottlenose dolphins and harbour porpoises, respectively (Bailey et al., 2010a).

Because the duration of piling was relatively short, the regulators' main concern focused on potential near-field impacts on cetaceans from potential injury (Talisman, 2005). Consequently, an environmental protection plan was developed by Talisman to ensure that marine mammals were not within 1 km of the operation. This was achieved using trained marine mammal observers (MMOs) using both visual and passive acoustic detection to monitor cetacean activity. This mitigation was augmented by adopting a "soft start" whereby the force of piling was gradually increased to alert animals in the vicinity to the commencement of the operations (Bailey et al., 2010a).

The installation of the wind turbines involved two main phases. First, each sub-structure was transported to the site and the jacket was secured to the seabed by four piles. Second the nacelle, hub and blades were fitted to each tower on land, and then transported out to sea and attached to the sub-structure. The jackets were installed in July and August 2006, and the first wind turbine (WT-A) was installed on 21st August. Poor weather prevented the installation of the second wind turbine (WT-B) in late August 2006 and this was finally installed on 6th July 2007. These engineering constraints meant that pile-driving activity was clustered (Table 1). Each pile took 2–3 h to install, but the piling barge could work on only two of the piles from a single location. During the piling of each jacket, there was therefore a gap of <1 to 12 h while the barge re-positioned. Because the barge also had to return inshore to collect the second jacket, and required a suitable weather window for all these activities, there was a longer gap of 13 days between piling the two jackets.

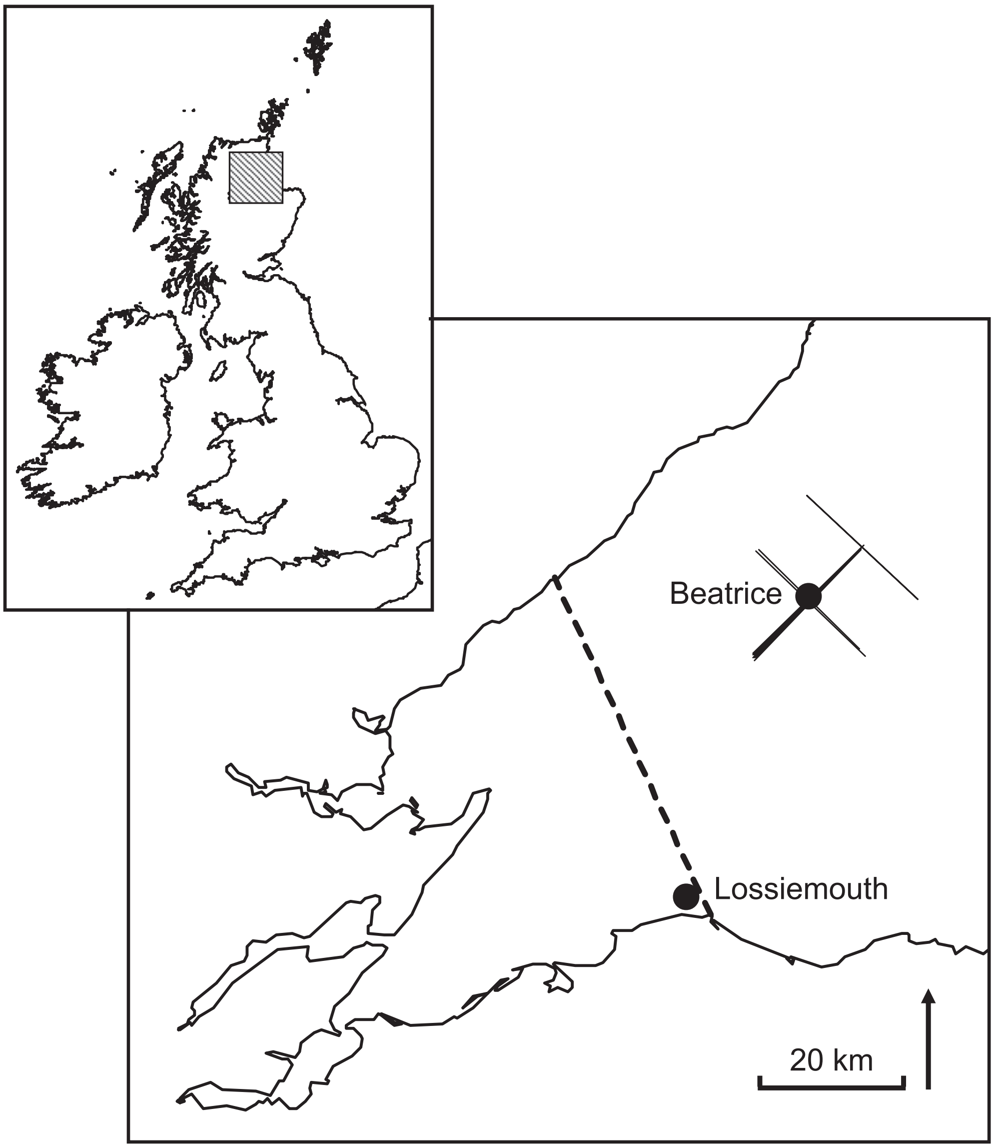

Fig. 1. A map of the study area showing the location of the T-PODs moored at the Beatrice impact site and the Lossiemouth control site. The tracks from the 18 boat-based visual surveys are shown as solid lines. The outer boundary of the Moray Firth SAC is shown as a dashed line.

2.2. Acoustic monitoring techniques

The occurrence of dolphins and porpoises were recorded using T-PODS that were deployed at an impact site near the two turbine sites at Beatrice, and at a second site at Lossiemouth, 40 km to the south (Fig. 1). Our aim was to use this second location as a control site, but in practice the identification of suitable control sites was constrained by limited availability of information on the distribution of different cetacean species across this large study area, and uncertainties over the scale of the potential impact (see Sections 3 and 4).

T-POD deployments were targeted to cover the summer months between May and October, to include periods before, during and after the planned installation of the turbine sub-structure in July and August 2006. Attempts were also made to collect comparable data from the summers of 2005 and 2007. Bailey et al. (2010b) provide full details of the methods used to set up, deploy and analyse T-PODs, and of their validation at an inshore site at which concurrent visual observations could be made. In brief, T-PODs were deployed at the impact and control site from August 2005–November 2007 and May 2005–December 2007, respectively. Each T-POD repeatedly scanned through six user defined frequency channels, with the alternate channels set up to detect the presence of echolocation clicks from dolphins (target frequency of 50 kHz) and porpoises (target frequency of 130 kHz). Echolocation click

Table 1
Times during which pile-driving operations occurred during the installation of the four piles required for Beatrice Windturbine A (WT A) and Beatrice Windturbine B (WT B).

Turbine	Pile	Date	Start	End	Duration
WT A	A1	22/7/06	07:51	10:48	2 h 51 m
	A2	21/7/06	08:52	11:04	2 h 42 m
	B1	21/7/06	18:24	20:47	2 h 22 m
	B2	20/7/06	17:36	21:33	2 h 34 m
WTB	A1	5/8/06	18:51	21:11	2 h 20 m
	A2	4/8/06	19:04	21:04	1 h 59 m
	B1	5/8/06	15:28	18:21	2 h 52 m
	B2	4/8/06	15:51	18:29	2 h 34 m

trains were then identified using the manufacturer's software, and data extracted on the presence or absence of dolphins and porpoises in each minute. Field studies in the inner Moray Firth indicate that all dolphin groups remaining within 1–3 km of a T-POD for more than 30 min were detected by the T-POD at some point during that period (Bailey et al., 2010a). These validation studies had also previously shown that false porpoise detections sometimes occurred within a series of dolphin detections, even when dolphins were confirmed to be the only cetacean present in the area. To avoid this problem, we only considered porpoise detections as positive if they occurred during a minute in which no dolphin clicks were detected.

T-POD data were subsequently used to determine those hours in which dolphins and porpoises had been detected at each site. Differences in the number of days on which cetaceans were detected or absent in different areas and time periods were compared using Chi-squared tests. We also assessed temporal changes in the use of these areas by calculating the number of hours in each day that animals were detected. These data were not normally distributed and comparisons between periods were made using non-parametric Kruskal–Wallis tests.

Low detections of dolphins around the impact site meant that assessment of the impacts of the turbine installation focused upon the porpoises that were more abundant in this area. Furthermore, low detection rates of both porpoises and dolphins at Lossiemouth limited the extent to which this could be used a control site (see Section 3). To overcome this, we used two alternative approaches to compare detections of porpoises in relation to the installation of the turbine sub-structures in 2006. First, we used data collected at the same site in the following year as an alternative control when comparing the number of hours in each day that porpoises were detected in periods before, during and after the turbine installation. Second, following Carstensen et al. (2006) we measured the observed waiting times from a potential disturbance such as pile driving until the next acoustic detection on the T-PODS. If we let t_p be the time at which piling occurred, and t_{detect} be the time to the time at which a dolphin or porpoise was first detected after t_p, waiting time is then defined as Δt_p: the time elapsed between t_p and t_{detect}. Given that Δt_p is an interval between two point processes, we can expect it to be exponentially distributed. If the piling had no effect on the time elapsed until the next detection, then t_p should be no different to any other time before t_{detect}, hence it should not influence when t_{detect} occurred. Therefore Δt_p should not significantly differ from any Δt_{p_rand}, the time elapsed between a randomly selected time point (t_{p_rand}) and t_{detect}. We therefore drew 1000 t_{p_rand}, during the period June–October 2006, and compared the observed Δt_p to the distribution of Δt_{p_rand} to infer whether t_p differs from t_{p_rand}.

2.3. Visual observations

In addition to the remote acoustic monitoring data, visual identifications of cetaceans present in the impact area were available from the MMOs employed through the mitigation programme. When not engaged in this work, the stand-by vessel was used to carry out visual surveys along 20 km transect lines through the impact area. The primary transect line ran from SW–NE, and two secondary lines were perpendicular to this (Fig. 1). Surveys were made between 7th July and 6th August, on days with sea state less than Beaufort 4, at a speed of between 5.5 and 8 knots. Observations were made by two trained MMOs from the bow of the vessel, at a height of 5.5–6.5 m above sea level. During transects, both observers scanned the sea with the naked eye and 8 × 42 binoculars were used to confirm visual cues and identify species. When sightings of marine mammals were made, the time and the vessel position were recorded with a hand-held GPS, and the perpendicular distance from the vessel to the animals was recorded along with information on species and group size.

3. Results

3.1. Acoustic monitoring

T-PODs were successfully deployed at the Beatrice and Lossiemouth sites for periods of up to 20 weeks, with sequential deployments providing full coverage of the summer months in 2006 and partial coverage for 2005 and 2007 (Table 2). In 2007, some gaps in the dataset occurred due to a combination of battery failure and poor weather conditions delaying the recovery of devices. Nevertheless, data were available for at least 80% of days during the 1st May–31st October 2007 study period. Data were also available for the late summer of 2005. However, the position of the Beatrice T-POD mooring had to be moved in the spring of 2006 because of the engineering works. Thus, in 2005, the T-PODS were located directly between the turbine sites, whereas data from 2006 and 2007 were collected from a site 1.5 km to the SW of this (Table 2).

There were significant site-differences in the relative occurrence of porpoise and dolphin detections in all three summers (Table 3). In the Beatrice impact area, harbour porpoises were detected on 89–95% of days during the May–October study period, compared to 37–56% of days at the Lossiemouth control site (2005: $X^2 = 26$, 1 df, $p < 0.001$; 2006: $X^2 = 81$, 1 df, $p < 0.001$; 2007: $X^2 = 117$, 1 df, $p < 0.001$). Dolphins were less frequently detected at the Beatrice impact site, on only 6–9% of days, but were detected on 49–63% of days at Lossiemouth (2005: $X^2 = 69$, 1 df, $p < 0.001$; 2006: $X^2 = 99$, 1 df, $p < 0.001$; 2007: $X^2 = 61$, 1 df, $p < 0.001$).

A sub-set of comparable data from late summer (14th August–31st October) were available from all three years of the study, and these were used to compare inter-annual differences in detection rates at each of the two sites. At the Beatrice impact site, dolphin detections were low in all years and there was no significant be-

Table 2
Locations of the T-POD mooring sites at which acoustic monitoring for cetaceans was carried out, with details of the periods from which recordings were successfully made.

Site	Year	Recording Period	Lat	Long
Beatrice	2005	12 August–31 October	58.0985 N	−3.0762 E
	2006	1 May–31 October	58.0890 N	−3.0952 E
	2007	6 June–31 October	58.0890 N	−3.0952 E
Lossiemouth	2005	21 May–3 October	57.7339 N	−3.3331 E
		20 October–31 October	57.7339 N	−3.3331 E
	2006	1 May–31 October	57.7339 N	−3.3331 E
	2007	9 May–31 October	57.7339 N	−3.3331 E

Table 3
Summary data from all acoustic monitoring carried out during the summers of 2005, 2006 and 2007. Detections are presented as the number and percentage of days on which dolphin and porpoise echolocation clicks were detected at each of the two study sites. N = the number of days on which T-POD data were available from the period 1st May to 31st October (see Table 2 for periods in which T-PODs were deployed).

Site	Year	N	Dolphin detections		Porpoise detections	
			No. days	% days	No. days	% days
Beatrice	2005	80	5	6.3	71	88.8
	2006	184	16	8.7	175	95.1
	2007	147	11	7.5	140	95.2
Lossiemouth	2005	156	98	62.8	87	55.8
	2006	184	104	56.5	100	54.3
	2007	176	86	48.9	65	36.9

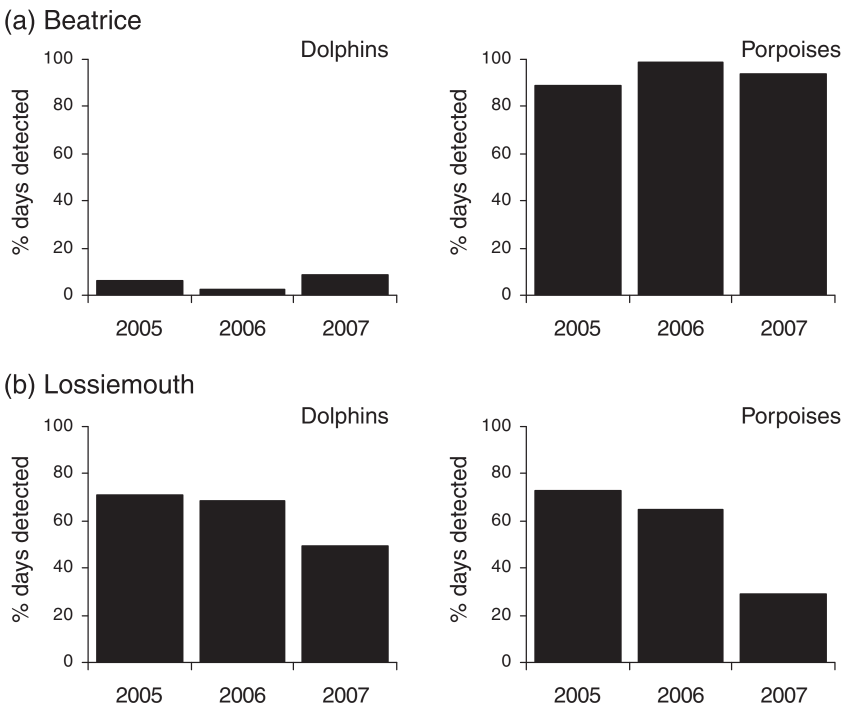

Fig. 2. Between-site and between-year differences in the percentage of days that dolphin and porpoise echolocation clicks were detected on T-POD moored at the Beatrice and Lossiemouth study sites. Data are from 14th August to 31st October, when comparable data were available from 2005, 2006 and 2007. At Beatrice, inter-annual differences in the number of days that animals were detected or absent were insignificant for dolphins ($X^2 = 2.29$, 2 df, $p = 0.24$) but significant for porpoises ($X^2 = 6.8$, 2 df, $p < 0.05$). At Lossiemouth, differences were significant for both dolphins ($X^2 = 8.8$, 2 df, $p < 0.05$) and porpoises ($X^2 = 31.9$, 2 df, $p < 0.001$).

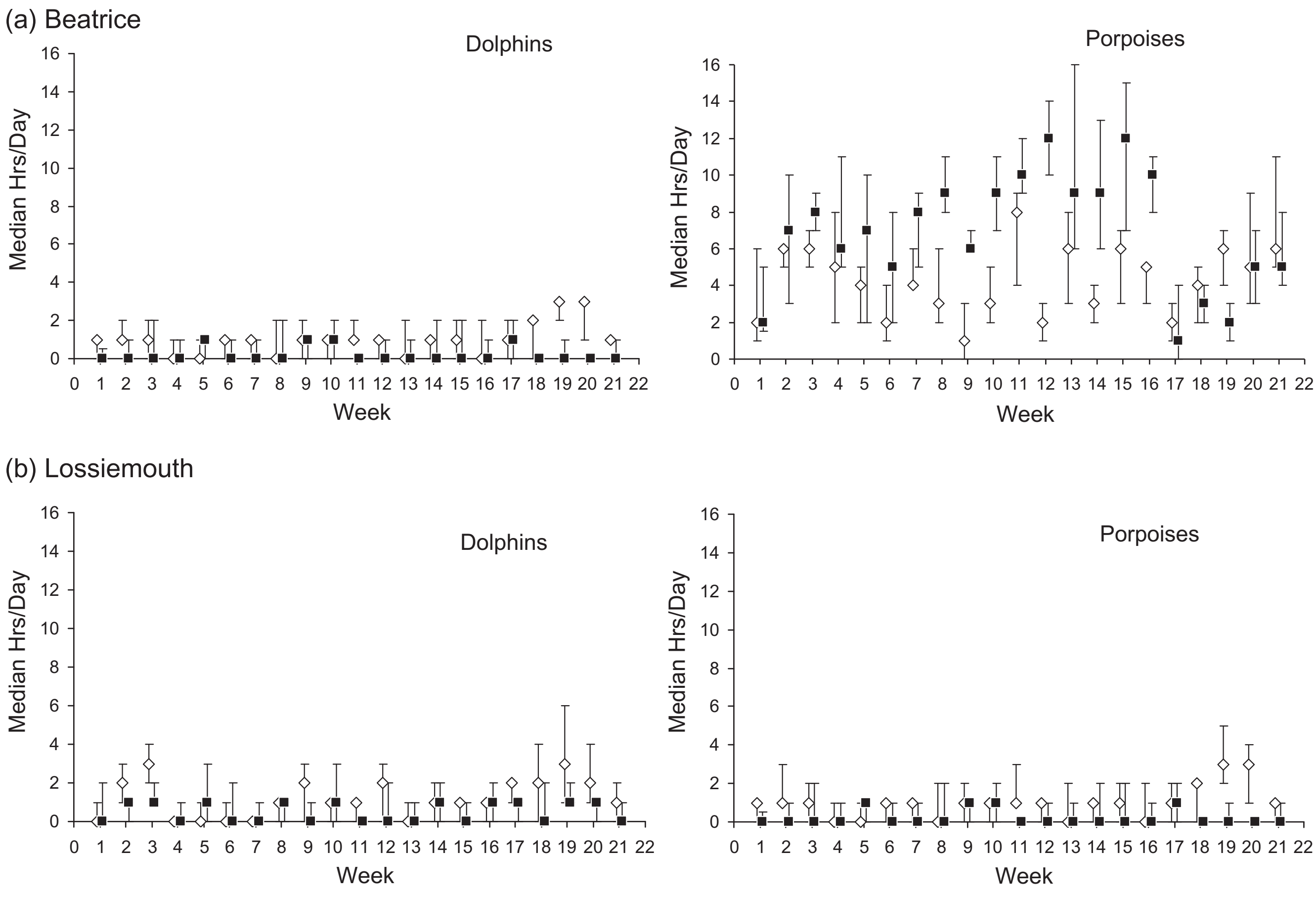

Fig. 3. Weekly variation in the number of hours in which dolphins and porpoises were detected on T-PODS (a) at Beatrice and (b) at Lossiemouth in 2006 (open diamonds) and 2007 (solid squares). Data are weekly medians (±IQ range) from June to October, where week 1 equals 4th to 11th June.

tween-year difference in the number of days they were detected. In contrast, porpoise detections were high in all years, and the difference between years was significant; primarily as a result of slightly higher detection rates in 2006 (Fig. 2). At the Lossiemouth control site, detection rates for dolphins and porpoises were more similar, and there was significant inter-annual variation in the number of days that both dolphins and porpoises were detected; primarily resulting from lower detections of both species in 2007 (Fig. 2).

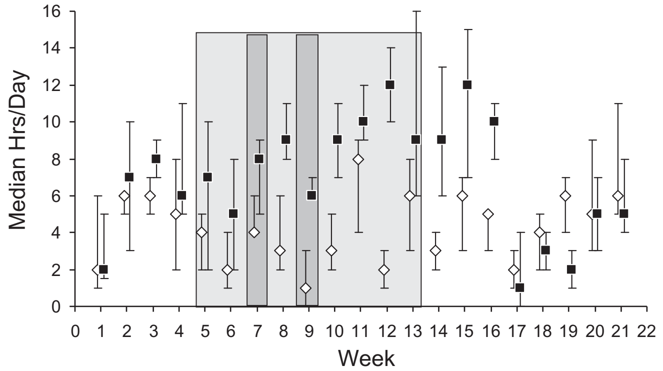

Fig. 4. Weekly variation in the number of hours that porpoises were detected on the Beatrice T-POD in 2006 (open diamonds) and 2007 (solid squares). Data are weekly medians (±IQ range) where week 1 equals 4th to11th June. The lightly shaded box between weeks 5 and 13 represents the main period during which the wind turbine site was being prepared and the turbine sub-structures installed. The darker shaded boxes in weeks 7 and 9 represent periods when pile driving was carried out.

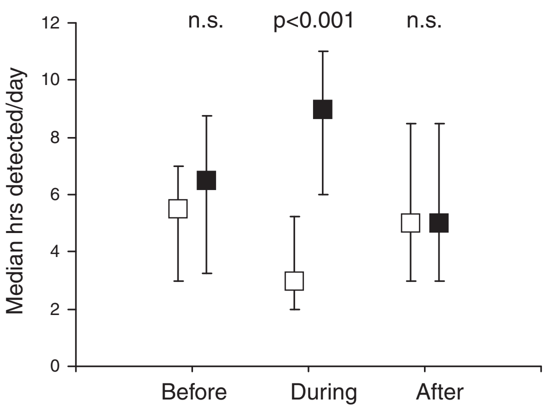

Fig. 5. Changes in the median (±IQ range) number of hours that porpoises were detected at Beatrice in periods before (June), during (July and August) and after (September–October) the installation of the wind turbines. Open squares = 2006, Solid squares = 2007.

3.2. Changes in cetacean detections in relation to wind turbine installation

Although both porpoise and dolphin echolocation clicks were detected at Lossiemouth on many days (Fig. 2), the median number of hours that they were detected on each of those days was generally low (Fig. 3). Similarly, at Beatrice dolphins were typically detected in only 1–2 h of those few days that they were present in the area (Fig. 3).

These low detection rates of dolphins at Beatrice, and both dolphin and porpoises at Lossiemouth, resulted in limited power in these data sets to detect, or control for, any impacts of pile driving or related activities during the turbine sub-structure installation. The only dataset where there was sufficient variability to explore these potential impacts was the dataset for porpoises at Beatrice. Fig. 4 presents weekly medians for the number of hours in which porpoises were detected in 2006 and 2007 in relation to the timing of the wind turbine installation work in 2006. Inspection of these data suggests that the occurrence of porpoises was similar in the two years at the beginning and end of the summer, but that porpoises were generally detected for longer each day during 2007. Fig. 5 summarises these data further, and presents the medians and inter-quartile ranges for the number of hours that porpoises were detected each day in (a) June (b) July and August, and (c) September and October of 2006 and 2007. In July and August 2006, the period in which the main installation work was carried out, porpoises were detected for significantly fewer hours per day when compared with a similar period in 2007 (Kruskal–Wallis Test: $H = 45.06$, 1 df, $p < 0.001$). In contrast, differences were insignificant for June ($H = 1.22$, 1 df, $p = 0.27$) and for September and October ($H = 1.73$, 1 df, $p = 0.19$).

Comparison of observed and random waiting times showed that the waiting time until the next porpoise detection was within the typical distribution for the piling of the first sub-structure, but an extreme outlier for the second sub-structure (Fig. 6a). No porpoises were detected on the 4th and 5th of August during the piling of the second sub-structure, and they were detected in only a single hour over the next two days. In the whole of the summer of 2006, there was only one other period (4th and 6th June) when porpoises were not detected, and later investigation revealed that this coincided with a period when a dive support vessel with thrusters and dy-

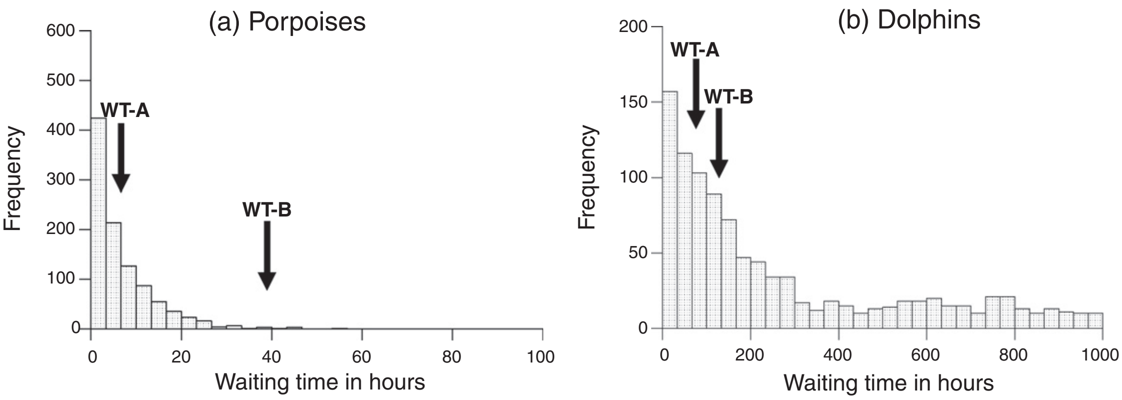

Fig. 6. Distributions of waiting times from 1000 random points until the next detection of (a) porpoises and (b) dolphins. Data are based on the T-POD records from Beatrice for the period June–October 2006. Also shown on each graph are the observed waiting time until the next detection after the start of the piling operation for Windturbine A (WT-A) Windturbine B (WT-B).

Table 4
Summary of the visual sightings made within 1.5 km of the track line during the 18 boat-based surveys along the routes shown in Fig. 1. Sightings rates are presented separately for surveys made under different sea states.

Sea state	Number of surveys	Survey time (h)	Porpoises encounters		Minke whale encounters		Common dolphin encounters	
			N	Rate/h	*N*	Rate/h	*N*	Rate/h
⩽1	5	8.44	9	1.07	2	0.24	1	0.12
2	5	8.57	2	0.23	1	0.12	0	0.00
3	8	11.77	4	0.34	0	0.00	0	0.00
All	18	28.76	15	0.52	3	0.10	1	0.03

namic positioning was working around the nearby Beatrice A oil platform. Waiting times until the next dolphin detection were similar to the random distribution for both piling events (Fig. 6b).

3.4. Visual monitoring

Eighteen transect surveys were carried out on 11 different days between 12th July and 6th August 2006. A further four transects were carried out in sea state >3, but no sightings were obtained and these surveys were not used to estimate sightings rates. Overall there were 32 cetacean sightings during just under 30 h of survey effort. Most were of single harbour porpoises (mean group size = 1.5) and minke whales (mean group size = 1.07). There were also sightings of two larger groups of common dolphins; one of 8–10 animals and one of >20. No bottlenose dolphins were observed in the Beatrice impact area during the visual survey period. Porpoises were generally observed within 1.5 km of the track line, although a group of at least five was seen at a distance of 3.5 km. Minke whales and common dolphins were both observed at up to 4 km from the track line. A summary of sightings rates for those observations made within 1.5 km of the track line is presented in Table 4. The sample sizes were too small and sea states too variable to carry out a formal comparison of sightings rates before and after the piling operations.

4. Discussion

These results highlight both the potential benefits and limitations of using T-PODs for assessing responses of cetaceans to the construction of wind turbines or other marine structures. Acoustic detection techniques proved effective for monitoring variations in the occurrence of dolphins and porpoises in time and space, for example highlighting differences in their relative distribution at coastal and offshore sites, and background year-to-year differences in detections at the control site (Fig. 2). At the same time, concurrent visual surveys revealed that dolphin detections in offshore areas appeared more likely to result from the presence of common dolphins (Table 4) rather than the bottlenose dolphins that had been the focus of conservation concern. Previous use of T-PODs in environmental assessments such as this have tended to focus on impacts in areas used predominantly by harbour porpoises (Carstensen et al., 2006; Diederichs et al., 2008), and their potential may be more limited in areas with more diverse cetacean communities. In future, however, new generation digital versions of the TPOD, the CPOD, should improve opportunities for discriminating between different species (see http://www.chelonia.co.uk/). Nevertheless, even where species can be discriminated effectively, T-POD data can only be used to determine the presence or absence of echolocation click trains in different time periods. Changes in detection rates such as those seen through the summer of 2006 (Figs. 2–5) may result from differences in the number of animals within the sample area, or from changes in the echolocation behaviour of animals within the sample area. Thus, whilst data from TPODs may provide evidence of response to a disturbance, it is not possible to determine whether that response was a change in echolocation behaviour or movement away from a disturbance (Carstensen et al., 2006). Finally, TPOD detections do not provide information on the number of animals in the sample area. Consequently, if animals respond to disturbances by moving away, TPODs might detect a major change that led to desertion of an area, but may not necessarily detect changes in density.

Given these caveats, our data show that harbour porpoises occurred regularly in the Beatrice study area, and they continued to use this area during the summer of 2006 when the wind turbines were being installed. However, there is also evidence that porpoises may have responded to the disturbance from the turbine installation work. First, whilst the analysis of waiting times until a porpoise detection suggested no strong response to the first piling event, the waiting time following the second piling event was at the extreme tail of the distribution (Fig. 6). This period of 2–3 days during which detections were absent or very low was similar in magnitude to the observed responses to pile driving at the Nysted Wind Farm in the Baltic Sea (Carstensen et al., 2006). The differences that we observed between the two piling events may simply have resulted from other chance factors. However, studies of a wide range of species have shown that responses to human disturbance can vary markedly depending upon the behavioural context in which they occur, and the animals may genuinely have responded differently to these two events for unknown biological reasons. The second line of evidence for a disturbance response comes from the comparison of Beatrice porpoise data from 2006 and 2007. Porpoises were detected on most days in both years, but the number of hours that they were detected in each day during July and August was significantly lower in 2006 (Fig. 4), when the core engineering work was carried out. In contrast, there was no significant between-year difference in the number of hours that porpoises were detected in June, September and October, which represented periods before and after the turbine installation (Fig. 5). These data highlight that, at least close to the turbine sites, chronic disturbance sources such as shipping associated with the installation may have been as important as the shorter-term disturbance from piling. However, noise levels from piling probably propagated much further than those from these other activities (Bailey et al., 2010a), and further work is required to assess how responses to these activities might vary at different distances from source.

These data provide evidence of potential effects that deserve further investigation, and consideration in future environmental assessments. However, several factors limited the power of this study to draw firm conclusions about potential impacts of the pile driving on porpoises and dolphins. The low numbers of dolphins recorded in the Beatrice impact area prevented an assessment of responses by these species, and conclusions about the potential impact upon porpoises are constrained by a lack of replication. Our dependence upon just one sampling site in the impact area was partly a resource issue, resulting from the logistic challenges of working over 25 km offshore. Nevertheless, limited background data on the distribution of cetaceans across the wider study area was a more fundamental constraint on the study design. Without information on the frequency of occurrence of animals in potential impact and control sites it will rarely be possible to identify appropriate locations for sampling sites, or determine the number of replicates required to provide adequate power to detect responses. Guidelines typically require environmental assessments for marine renewable projects to collect one or two years' baseline data prior to a new development (Diederichs et al., 2008). Such data may be sufficient to inform an assessment of the potential impacts of the project. However, as we found here, such data are unlikely to have been collected at appropriate temporal and spatial scales for more robust assessments of whether impacts did occur. Ideally, at least one of those year's baseline data is required to inform the design of a robust impact study. For example, had 2005 data from more offshore areas been available to inform the design of an impact study for bottlenose dolphins, it would have been clear that dolphins were recorded so rarely at Beatrice that the potential impact site would have been better located in those coastal areas exposed to the highest levels of pile-driving noise (see also Bailey et al., 2010a). These problems arose despite there being considerable previous research on the ecology of local cetacean populations. Adequate assessment of the impact of new marine developments in areas where fewer baseline data are available on cetaceans will be even more challenging.

A recent methodological review recommends the use of acoustic monitoring within a B-A-C-I study to assess responses of marine mammals to wind farm construction and operation (Diederichs et al., 2008). However, where impacts have the potential to operate at such large spatial scales, it remains extremely challenging to design robust B-A-C-I studies; even where good quality baseline data on cetacean distribution exist. First, where impact and control sites need to be many tens of kilometres apart, it can be difficult to identify sites that have similar ecological characteristics (Hewitt et al., 2001). This is clearly illustrated by the difference in the relative distribution of porpoises and dolphins at our two study sites (Fig. 2). Second, as our results indicate, the pile-driving noise upon which this study originally focussed is just one of many sources of anthropogenic noise that these animals experience. Quite apart from other activities associated with the turbine installation, we later discovered that both hydro-graphic and seismic survey work had been carried out in the Moray Firth during the summer of 2006. Clearly, this compromises attempts to compare the occurrence of cetaceans in such areas before and after pile driving or other noise-related potential impacts. Indeed, in the case of our results (e.g. Fig. 5), our lack of information on source levels and locations of other potential noise sources within the Moray Firth mean that we cannot exclude these as a possible cause of the lower levels of porpoise detections observed in July and August 2006 (Fig. 5). Ideally, future work of this kind should involve parallel deployments of remote data loggers that can make long-term recordings of broad-band noise (e.g. Lammers et al. 2008), thereby allowing post hoc identification of suitable control periods. Finally, limited understanding of the spatial scale at which the impacts of wind-turbine construction may operate also constrain a traditional B-A-C-I study. For example, Carstensen et al.'s (2006) study of the responses of porpoises to pile driving at Nysted offshore wind farm found evidence of some impacts at the control sites that they had located >15 km from the source. Given the wide uncertainty over the received sound levels at which cetaceans may response to anthropogenic noise (Southall et al. 2007), we suggest that future studies would benefit from using a gradient sampling design (Ellis and Schneider, 1997) rather than a B-A-C-I design. Quite apart from this design being likely to produce a more robust study, the results are also of greater use in environmental assessment and mitigation as they then provide insights into the likely spatial scale of potential impacts.

5. Conclusions and recommendations

Overall, results from our acoustic monitoring of cetaceans suggest that there were no dramatic long-term changes in the use of the area around the turbines, but that there may have been a short-term response by porpoises occurring within 1–2 km of the site. These acoustic monitoring data also support the conclusions from more opportunistic sightings (Reid et al., 2003) and less frequent visual surveys (Bailey and Thompson, 2009; Hastie et al., 2003), suggesting that the bottlenose dolphins using the Moray Firth SAC rarely frequent more offshore waters. Dolphins were detected on the Beatrice T-PODS on <10% of days (Fig. 2), and visual surveys by the MMOs indicate that dolphin detections in this area are more likely to represent common dolphins than bottlenose dolphins. Together, these findings suggest that this population of bottlenose dolphins was at low risk from the more significant near-field effects of pile driving, which could include direct injury or permanent threshold shifts (David, 2006; Southall et al., 2007). However, measurements of pile-driving source levels and sound propagation indicate that dolphins could exhibit behavioural responses at distances of up to 40 km (Bailey et al., 2010a). This could potentially impact areas along the southern coast of the Moray Firth which are known to be used regularly by this protected population (Culloch and Robinson, 2008). The limited spatial coverage and power of this study means that we cannot exclude the possibility that pile-driving activity caused some behavioural disruption to bottlenose dolphins and other cetaceans such as the minke whales that also regularly use the Moray Firth at this time (Tetley et al., 2008).

The UK Government currently plans to deliver a further 25 GW of power from offshore wind farms to meet the EU renewables target to source 20% of Europe's energy by 2020 (BERR, 2008). This third round of offshore developments will require a step-change in the scale of offshore wind farms, and a move into offshore areas where there is even more uncertainty about cetacean distribution patterns. Any potential disturbance to cetaceans from the pile driving required to install the two 5 MB wind turbines in this study would have been experienced over only a few days (Table 1). In contrast, the pile-driving activity required to install the 1–2 GW wind farms anticipated under Round 3 developments could extend over several years. This clearly demands a much higher level of understanding of likely impacts and effective mitigation measures. Based on the lessons learned in this study, we offer the following recommendations for the research programme that is required to support future developments.

1. Acoustic monitoring techniques provide excellent opportunities for collecting data on the occurrence of odontocete cetaceans over long temporal scales, but should be integrated with other survey techniques that can be used to provide data on species composition, and to explore the underlying basis of any changes in acoustic detections.
2. Baseline data on the occurrence of cetaceans in all potential development areas are urgently required to facilitate the design of monitoring programmes and impact assessments.
3. Assessments of the impact of wind farm construction should consider using gradient sampling designs rather than the more commonly used B-A-C-I designs. This avoids having to predetermine the location of impact and control sites at the large, and uncertain, spatial scales at which noise sources such as pile driving may impact cetaceans.
4. Assessments of cetacean distribution and behaviour should be underpinned by acoustic monitoring that permits measurements of received levels of noise from both the wind farm construction and other anthropogenic sources, thereby allowing the post hoc identification of appropriate control periods.
5. Studies of the impacts of wind farm construction should be designed to assess the relative importance of different construction activities (e.g. pile driving vs cable-laying).
6. The extent of behavioural disruption from pile driving remains uncertain. Nevertheless, given the scale of future offshore developments, there is an urgent need to develop engineering solutions to reduce the propagation of pile-driving noise at deep water sites, or develop alternative construction techniques that generate less intensive noise.

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References

Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G., Thompson, P.M., 2010. Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential impact on marine mammals. Marine Pollution Bulletin. doi:10.1016/j.marpolbul.2010.01.003.

Bailey, H., Clay, G., Coates, E.A., Lusseau, D., Senior, B., Thompson, P.M., 2010b. Using T-PODS to assess variations in the occurrence of coastal bottlenose dolphins and harbour porpoises. Aquatic Conservation: Marine and Freshwater Ecosystems 20, 150–158.

Bailey, H., Thompson, P.M., 2009. Using marine mammal habitat modelling to identify priority conservation zones within a marine protected area. Marine Ecology – Progress Series 378, 279–287.

BERR, 2008. UK Renewable Energy Strategy Consultation. HM Government.

Carstensen, J., Henriksen, O.D., Teilmann, J., 2006. Impacts of offshore wind farm construction on harbour porpoises: acoustic monitoring of echolocation activity using porpoise detectors (T-PODs). Marine Ecology – Progress Series 321, 295–308.

Clark, C.W., Clapham, P.J., 2004. Acoustic monitoring on a humpback whale (*Megaptera novaeangliae*) feeding ground shows continual singing into late spring. Proceedings of the Royal Society of London Series B – Biological Sciences 271, 1051–1057.

Culloch, R.M., Robinson, K.P., 2008. Bottlenose dolphins using coastal regions adjacent to a Special Area of Conservation in north-east Scotland. Journal of the Marine Biological Association of the United Kingdom 88, 1237–1243.

David, J.A., 2006. Likely sensitivity of bottlenose dolphins to pile-driving noise. Water and Environment Journal 20, 48–54.

Diederichs, A., Nehis, G., Dahne, M., Adler, S., Koschinski, S., Verfuss, U.K., 2008. Methodologies for Measuring and Assessing Potential Changes in Marine Mammal Behaviour, Abudnance or Distribution from Construction, Operation and Decommissioning of Offshore Windfarms. BioConsult SH report to COWRIE Ltd.

DiSciara, G.N., Gordon, J., 1997. Bioacoustics: a tool for the conservation of cetaceans in the Mediterranean Sea. Marine and Freshwater Behaviour and Physiology 30, 125–146.

Ellis, J.I., Schneider, D.C., 1997. Evaluation of a gradient sampling design for environmental impact assessment. Environmental Monitoring and Assessment 48, 157–172.

Evans, P.G.H., Hammond, P.S., 2004. Monitoring cetaceans in European waters. Mammal Review 34, 131–156.

Gill, A.B., 2005. Offshore renewable energy: ecological implications of generating electricity in the coastal zone. Journal of Applied Ecology 42, 605–615.

Gillespie, D., Berggren, P., Brown, S., Kuklik, I., Lacey, C., Lewis, T., Matthews, J., McLanaghan, R., Moscrop, A., Tregenza, N., 2005. Relative abundance of harbour porpoises (*Phocoena phocoena*) from acoustic and visual surveys of the Baltic Sea and adjacent waters during 2001 and 2002. Journal of Cetacean Research and Management 7, 51–57.

Hastie, G.D., Barton, T.R., Grellier, K., Hammond, P.S., Swift, R.J., Thompson, P.M., Wilson, B., 2003. Distribution of small cetaceans within a candidate special area of conservation; implications for management. Journal of Cetacean Research and Management 5, 261–266.

Hewitt, J.E., Thrush, S.E., Cummings, V.J., 2001. Assessing environmental impacts: effects of spatial and temporal variability at likely impact scales. Ecological Applications 11, 1502–1516.

Johnson, M.P., Tyack, P.L., 2003. A digital acoustic recording tag for measuring the response of wild marine mammals to sound. IEEE Journal of Oceanic Engineering 28, 3–12.

Lammers, M.O., Brainard, R.E., Au, W.W.L., Mooney, T.A., Wong, K.B., 2008. An ecological and acoustic recorder (EAER) for long-term monitoring of biological and anthropogenic sounds on coral reefs and other marine habitats. Journal of Acoustical Society of America 123, 1720–1728.

Madsen, P.T., Wahlberg, M., Tougaard, J., Lucke, K., Tyack, P., 2006. Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs. Marine Ecology – Progress Series 309, 279–295.

Nedwell, J.R., Workman, R., Parvin, S.J., 2005. The Assessment of Likely Levels of Piling Noise at Greater Gabbard and Its Comparison with Background Noise, Including Piling Noise Measurements Made at Kentish Flats, Rep. No. 633R0115. Subacoustech, Southampton.

Philpott, E., Englund, A., Ingram, S., Rogan, E., 2007. Using T-PODs to investigate the echolocation of coastal bottlenose dolphins. Journal of the Marine Biological Association of the United Kingdom 87, 11–17.

Potter, J.R., Thillet, M., Douglas, C., Chitre, M.A., Doborzynski, Z., Seekings, P.J., 2007. Visual and passive acoustic marine mammal observations and high-frequency seismic source characteristics recorded during a seismic survey. IEEE Journal of Oceanic Engineering 32, 469–483.

Reid, J.B., Evans, P.G.H., Northridge, S.P., 2003. Atlas of cetacean distribution in north-west European waters JNCC, Peterborough.

Richardson, W.J., Greene, J.C.R., Malme, C.I., Thomson, D.H., 1995. Marine Mammals and Noise. Academic Press, San Diego.

Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene, J.C.R., Kastak, D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, J.A., Tyack, P.L., 2007. Marine mammal noise exposure criteria: initial scientific recommendation. Aquatic Mammals 33, 411–521.

Talisman, 2005. Beatrice Wind Farm Demonstrator Project Environmental Assessment, Rep. No. D/2875/2005. Talisman Energy (UK) Limited, Aberdeen.

Taylor, B.L., Martinez, M., Gerrodette, T., Barlow, J., Hrovat, Y.N., 2007. Lessons from monitoring trends in abundance of marine mammals. Marine Mammal Science 23, 157–175.

Tetley, M.J., Mitchelson-Jacob, E.G., Robinson, K.P., 2008. The summer distribution of coastal minke whales (*Balaenoptera acutorostrata*) in the southern outer Moray Firth, NE Scotland, in relation to co-occurring mesoscale oceanographic features. Remote Sensing of Environment 112, 3449–3454.

Thompson, P.M., Wilson, B., Grellier, K., Hammond, P.S., 2000. Combining power analysis and population viability analysis to compare traditional and precautionary approaches to conservation of coastal cetaceans. Conservation Biology 14, 1253–1263.

Thomsen, F., van Elk, N., Brock, V., Piper, W., 2005. On the performance of automated porpoise-click-detectors in experiments with captive harbor porpoises (*Phocoena phocoena*) (L). Journal of the Acoustical Society of America 118, 37–40.

Tougaard, J., Poulsen, L., Amundin, M., Larsen, F., Rye, J., Teilman, J., 2006. Detection function of T-PODS and estimation of porpoise densities. In: Leeney, R., Treganza, N. (Eds.), Proceedings of the Workshop on Static Acoustic Monitoring of Cetaceans, vol. Special Issue No. 46. European Cetacean Society.

Underwood, A.J., 1994. On beyond baci – sampling designs that might reliably detect environmental disturbances. Ecological Applications 4, 3–15.

Verfuss, U.K., Honnef, C.G., Meding, A., Dahne, M., Mundry, R., Benke, H., 2007. Geographical and seasonal variation of harbour porpoise (*Phocoena phocoena*) presence in the German Baltic Sea revealed by passive acoustic monitoring. Journal of the Marine Biological Association of the United Kingdom 87, 165–176.

Wilhelmsson, D., Malm, T., Ohman, M.C., 2006. The influence of offshore windpower on demersal fish. ICES Journal of Marine Science 63, 775–784.