ASSESSING THE POTENTIAL IMPACT OF OIL AND GAS EXPLORATION OPERATIONS ON CETACEANS IN THE MORAY FIRTH

Paul Thompson, Kate Brookes, Line Cordes, Tim Barton,

Barbara Cheney & Isla Graham

University of Aberdeen, Institute of Biological & Environmental Sciences,

Lighthouse Field Station, Cromarty, Ross-shire IV11 8YJ.

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EXECUTIVE SUMMARY

Uncertainty over the distribution of cetaceans and their responses to underwater noise has led to concerns over the potential impact of oil and gas exploration in some UK waters, particularly in the vicinity of the Moray Firth Special Area of Conservation (SAC). In May 2009, the Department of Energy & Climate Change (DECC), with co-funding from the Scottish Government, Collaborative Offshore Wind Research Into the Environment (COWRIE) and Oil & Gas UK, contracted the University of Aberdeen to study the potential impact of oil and gas operations on cetaceans in the Moray Firth.

The project aimed, first, to provide baseline data on the occurrence of cetaceans in the Moray Firth's offshore waters, requiring a review of existing data and additional data collection using passive acoustics and visual surveys. Secondly, the study aimed to understand the impacts of commercial seismic surveys undertaken in 2011 on the distribution and behavioural responses of cetaceans. This final project report presents the major findings from these studies as five independent chapters, each covering different aspects of the project. The key findings from each of these chapters are summarised below.

1. *Integrating passive acoustic and visual data to model spatial patterns of occurrence in coastal dolphins*

The EU Habitats Directive requires an understanding of the extent to which animals from Special Areas of Conservation (SAC) use adjacent waters, where previous survey effort is often sparse. This chapter demonstrates how static passive acoustic monitoring using C-PODs could extend existing survey effort, using echolocation click detections to quantify levels of occurrence of coastal dolphins. However, this did not provide information on species identity. Information on the spatial occurrence of bottlenose dolphins in waters in and adjacent to the Moray Firth SAC was therefore obtained by integrating the C-POD data with presence-only data from visual surveys. C-POD data were used to model the occurrence of dolphins in relation to habitat type and predict the distribution of dolphins across a 4x4 km grid of the Moray Firth. Available visual survey data were then used to model the likely species identity of dolphins sighted in each grid cell in relation to local habitat. By

multiplying these probabilities, it was possible to provide advice on spatial variation in the probability of encountering bottlenose dolphins from the protected population at a regional scale.

2. *Predictions from harbour porpoise habitat association models are confirmed by long-term passive acoustic monitoring*

This chapter integrated different data sources to compare approaches to modelling the regional distribution of harbour porpoises. A habitat association model for harbour porpoises was created using data from five visual surveys of the Moray Firth. Its predictions were then tested over broader temporal scales using C-POD data collected in the summers of 2009 and 2010. Predictions of the relative abundance of harbour porpoises were obtained for each 4x4 km grid cell, and compared with the median number of hours per day that porpoises were acoustically detected in those cells. There was a significant correlation between predicted relative abundance and acoustic estimates of occurrence. The integration of these different types of data added value to the interpretation of results from each, and indicated that the patterns in relative abundance recorded during snapshot visual surveys are robust over longer time scales.

3. *Characteristics of underwater noise from a 2-D seismic survey; comparison with noise propagation models used for marine mammal impact assessments.*

Assessments of the potential impacts of anthropogenic noise on marine mammals require information on the characteristics and propagation of different noise sources. This chapter characterised the noise from air guns used in the 2-D seismic survey within the Moray Firth in 2011. We also measured received levels of noise at different distances from the seismic survey vessel, and compared these with predictions from acoustic propagation models used in environmental assessments. Measurements were made at 19 sites at distances of 1.6 – 61.8 km from the vessel and analysed using a broad suite of metrics used in bio-acoustic studies. Estimated peak to peak source levels were 242 - 253 dB re 1 µPa. Recordings at four sites (1.6 -14.2 km from source) were suitable for analyses of frequency spectra between 50 Hz and 96 kHz. These data confirmed that most energy occurred below 400 Hz, but that the signal contained high frequency components that would be detected by small cetaceans. Measured values showed a reasonable fit with two propagation models used within environmental assessments for the 2-D seismic survey. We also tabulate summary data for each site, and provide measurements from each pulse in an electronic appendix, so that these data can be used to evaluate the performance of other propagation models.

4. Short-term disturbance by a seismic survey does not lead to long-term displacement of harbour porpoises

Assessments of offshore energy developments in the Moray Firth and in many other parts of the world are constrained because it is not known whether fine-scale behavioral responses to noise lead to broader-scale displacement. In this chapter, we used data form the array of C-PODs, in combination with digital aerial surveys, to study changes in the occurrence of harbour porpoises during the 2011 seismic survey in the Moray Firth. Both acoustic and visual data provided evidence of fine-scale behavioral responses to seismic survey noise within 5-10 km, at received peak-to-peak sound pressure levels of 165-172 dB re 1 µPa and sound exposure levels of 145-151 dB re. 1µPa^2 s. However, animals were typically detected again at affected sites within a few hours, and the level of response declined through the 10 day survey. Overall, there was a significant decrease in acoustic detections over the survey period in the impact area compared to our control area. However, this effect was small in relation to natural variation, and porpoises were still detected in the impact area for a median of 10 hours per day throughout the seismic survey period. These results demonstrated that the seismic survey noise did not lead to broader-scale displacement into sub-optimal or higher-risk habitats. These findings suggest that future impact assessments should focus on sub-lethal effects resulting from changes in foraging performance of animals within affected sites.

5. Abundance and occurrence patterns of bottlenose dolphins in relation to a 2-D seismic survey in the Moray Firth

Concern over seismic survey activity in the Moray Firth has centred on the potential impacts of air-gun noise on the area’s protected bottlenose dolphin population. This last chapter used this case study to illustrate the challenges of consenting and conducting seismic surveys within or near sensitive habitats. Background is provided both on the history of seismic exploration and oil production in the area and on the development of the Moray Firth Special Area of Conservation (SAC) for bottlenose dolphins. We outline the requirement for additional survey and monitoring to better define bottlenose dolphin distribution and the need for an Appropriate Assessment (AA) that identified no likely long-term impacts of the seismic survey. Photo-identification estimates of the number of dolphins using the SAC were similar throughout the period 2009-2012. However, passive acoustic studies did provide some evidence of short-term behavioural responses in the part of their range closest to the seismic survey. These data indicated that the occurrence of dolphins at PAM sites on the southern Moray Firth coast increased during the 10 day seismic survey, most likely as a result of animals being displaced inshore, away from the survey vessel.

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1. Background

There is uncertainty over the distribution of cetaceans in offshore waters, and the extent to which these animals may be disturbed by offshore oil and gas exploration operations, particularly seismic surveys. This has led to concerns over the potential impact of further oil and gas exploration in some areas of UK waters, particularly in the vicinity of the Moray Firth Special Area of Conservation (SAC).

In May 2009, the Department of Energy & Climate Change (DECC), with co-funding from the Scottish Government, COWRIE and Oil & Gas UK, contracted the University of Aberdeen to carry out a three year study to assess the potential impact of oil and gas operations on cetaceans in the Moray Firth. The project has two broad aims. First, to provide baseline data on the occurrence of cetaceans in the Moray Firth's offshore waters. Second, to understand the impacts of any seismic exploration undertaken during the course of the study on the distribution and behaviour of cetaceans using the area.

In the first phase of the study, available data from existing cetacean surveys in the Moray Firth were drawn from a variety of peer-reviewed journals, the grey literature and unpublished sources. These data represented observations made over a period of almost 30 years, from 1980 to 2008, but coverage of the outer Moray Firth was extremely patchy in both space and time. Summaries of the results from each data source are presented in Thompson et al. (2010), including maps that show where each survey had been conducted, the sightings of all dolphins (including bottlenose dolphins, white-beaked dolphins, common dolphins, Risso's dolphins and unidentified groups) and sightings of harbour porpoises and minke whales.

Despite variations in the coverage of those different surveys, generalisations could be made about distribution patterns of the key cetacean species occurring in the Moray Firth. First, harbour porpoises were the most commonly encountered species in almost all studies, being seen throughout inshore and offshore waters. Second, almost all bottlenose dolphin sightings were within 15 km of the coast in the inner part of the Moray Firth SAC, or along the southern Moray Firth coast. There were a few records of bottlenose dolphins in the outer Moray Firth, but most sightings of dolphins in offshore waters were of common dolphins or white beaked dolphins. Third, minke whales appeared to be the second most commonly sighted species in offshore waters after harbour porpoises, although there was some evidence that this may have been a relatively recent situation, as comparatively few minke whale sightings existed in earlier data sets.

These analyses of existing data sources were supplemented by a programme of visual and acoustic surveys in the summer of 2009. These studies aimed to assess the relative abundance and distribution of bottlenose dolphins and other cetaceans using the central area of the Moray Firth adjacent to the Special Area of Conservation. In addition, they aimed to collect data along transects that represented a gradient of exposure to potential seismic survey noise, thereby providing baseline for subsequent studies of cetacean behavioural responses to noise if the proposed surveys went ahead. Passive acoustic monitoring techniques were selected as the primary tool for collecting data on spatial and temporal changes in the occurrence of dolphins and porpoises in this area. C-PODs were deployed at 64 sites across the Moray Firth from mid-July to late October 2009. These studies were complemented by 16 days of boat-based visual line-transect surveys in the outer Moray Firth, using pairs of observers to record sightings of all cetaceans along two different survey routes (Thompson et al. 2010). Ongoing photo-identification studies of bottlenose dolphins within the Moray Firth SAC were also extended to estimate the number of individual dolphins using both the inner Moray Firth and the southern shore of the Moray Firth, and to determine how individuals partitioned their time between these two areas.

These surveys provided important new data on the patterns of occurrence of dolphins and porpoises in the Outer Moray Firth. Both dolphins and porpoises were detected at least once on all PODs, but the number of days on which detections were made varied considerably. In the inner Moray Firth and along the coastal survey area, dolphins were typically detected at 52-64% of sites for 2–3 hours per day. In contrast, in the central part of the Moray Firth, dolphins were typically detected at only 11% of sites for around 1 hour per day, and dolphin detections were most common in the extreme NE of the area. It was not possible to use C-POD detections to discriminate between different dolphin species, but visual sightings of different dolphin species suggested that most detections within both the inner Moray Firth and along the southern coast were of bottlenose dolphins. In contrast, those in the central Moray Firth, particularly in the NE of the study area, were likely to represent other species. As suggested from previous visual surveys, porpoises were detected much more commonly throughout the whole study area, with the highest level of detections in the outer Moray Firth where they were typically detected at 97.5% of sites for over 6 hours per day (Thompson et al. 2010).

Together, these studies from the first phase of the project indicated that bottlenose dolphins were unlikely to occur in the central Moray Firth, where seismic surveys were planned. However, harbour porpoises regularly occurred in these offshore areas, providing excellent potential for assessing any responses of these small cetaceans to seismic survey noise.

In the second phase of the project, studies were therefore designed to assess the responses of harbour porpoises to seismic surveys that two companies, PA Resources and Caithness Oil, were intending to conduct during 2010. Building on baseline passive acoustic studies in 2009, a broad-scale array of C-PODs was deployed in July 2010, and a programme of aerial surveys conducted through August and September 2010 (Thompson et al. 2011). The planned seismic programme did not go ahead during 2010, but these data confirmed patterns seen in 2009 and provided additional evidence that dolphins detected in offshore areas were most likely to be white-beaked, common or Risso's dolphins.

Following the delay in the seismic surveys, DECC and the Scottish Government provided additional funding so that the planned research could be repeated in 2011. In this final project report, we present the major findings from these studies in the following five chapters, each covering different aspects of the project. The first two chapters integrate data collected in this study with other available data sources to model the distribution of bottlenose dolphins and harbour porpoises across the Moray Firth. The third chapter characterises the noise levels resulting from the seismic survey, and compares received levels with those predicted by the propagation models used in environmental assessments. Finally, the last two chapters assess the responses of harbour porpoises and bottlenose dolphins to the 2011 seismic survey. In the case of harbour porpoises, responses were expected because this species occurred in high numbers over the seismic survey area, and the study aimed to assess the spatial and temporal scale of this response. In the case of bottlenose dolphins, far field responses by this species were not anticipated, but monitoring was conducted within the SAC and in core areas closest to the seismic survey area to confirm these predictions.

Integrating passive acoustic and visual data to model spatial patterns of occurrence in coastal dolphins

Paul M. Thompson[1], Kate L. Brookes[1,2] & Line S. Cordes[1,3]

[1] Lighthouse Field Station, Institute of Biological & Environmental Sciences, University of Aberdeen, Cromarty, IV11 8YL, UK.

[2] Current address: Marine Scotland Science, 375 Victoria Road, Aberdeen, AB11 9DB, UK.

[3] Current address: Colorado State University, Department of Fish, Wildlife and Conservation Biology, 135 Wagar, 1474 Campus Delivery, Fort Collins, CO 80523, USA

Abstract

Fine-scale information on the occurrence of coastal cetaceans is required to support regulation of offshore energy developments and marine spatial planning. In particular, the EU Habitats Directive requires an understanding of the extent to which animals from Special Areas of Conservation (SAC) use adjacent waters, where survey effort is often sparse. Static passive acoustic monitoring (PAM) provides new opportunities to extend survey effort by using echolocation click detections to quantify levels of occurrence of coastal dolphins, but this does not provide information on species identity. In NE Scotland, assessments of proposed offshore energy developments required information on spatial patterns of occurrence of bottlenose dolphins in waters in and adjacent to the Moray Firth SAC. Here, we illustrate how this can be achieved by integrating data from broad-scale PAM arrays with presence-only data from visual surveys. Generalised estimating equations were used with PAM data to model the occurrence of dolphins in relation to habitat variables, and to predict the spatial variation in the cumulative occurrence of all dolphin species across a 4x4 km grid of the study area. Classification tree analysis was then applied to available visual survey data to estimate the likely species identity of dolphins sighted in each grid cell in relation to local habitat. By multiplying these probabilities, it was possible to provide advice on spatial variation in the probability of encountering bottlenose dolphins from this protected population at a regional scale, complementing data from surveys that estimate average density or overall abundance within a region.

1. Introduction

Robust data on the population size and distribution of cetaceans are required to support a wide range of management and conservation issues (Dawson et al., 2008, Evans and Hammond, 2004). Over the last 25 years, the requirement for these data has driven important developments in survey design and analytical methods that have greatly enhanced both our understanding of cetacean ecology and our ability to assess and manage threats to their populations (Hammond, 2010, Kaschner et al., 2006). These new approaches have been particularly successful in supporting management of issues such as harvesting and by-catch (Slooten et al., 2006, Williams et al., 2006). In such cases, the highly mobile nature of cetacean species means that conservation and management strategies must be considered at very large scales, typically involving collaboration across different national and international waters (Hammond et al., 2002, Smith et al., 1999). However, the results from broad scale studies of this kind can be of more limited use when data are required to underpin the assessment and management of smaller scale, regional and site-specific activities (Cubero-Pardo et al., 2011).

The need for finer-scale data on the extent to which cetaceans use coastal and shelf waters is becoming increasingly important following new conservation and marine spatial planning initiatives (Rees et al., 2013). In particular, better information is often required on temporal patterns of occurrence in relatively small areas (Dolman and Simmonds, 2010, Harris et al., 2012, Vanderlaan et al., 2009). In contrast, while available data sets typically provide good broad scale spatial coverage, they generally represent only a single time period or integrate data collected over longer time-scales. Data do exist at finer spatio-temporal scales for some resident or semi-resident populations of coastal cetaceans (eg. Gnone et al., 2011, Rayment et al., 2010, Wiseman et al., 2011) but, even in these cases, information on temporal patterns of occurrence in other parts of their range are often lacking. For example, in several European countries, bottlenose dolphins show high levels of fidelity to core-areas that have subsequently been designated as Special Areas of Conservation (SAC) under the EU Habitats Directive (Ingram and Rogan, 2002, Wilson et al., 2004). Focused studies within these areas have provided information on local distribution and abundance. However, individuals using these sites can range widely across neighbouring waters (Ingram and Rogan, 2002, Wilson et al., 2004), and much less is known about the extent of movements into more offshore areas. This uncertainty has constrained Habitat Regulations Assessments (HRA) required to assess whether new developments may impact populations that use a particular SAC. In the north east of Scotland, for example, uncertainty over the range of the bottlenose dolphin population that uses the Moray Firth SAC recently delayed licencing for oil exploration in the region, and additional studies have been required to assess whether this population may use areas proposed for offshore wind farm developments. Designing survey programmes that can be used to support these assessments is especially challenging because visual sightings are expected to be rare in peripheral parts of a population's range. Consequently, even intensive visual line-transect surveys can result in few encounters (Dawson et al., 2008), resulting in rather uncertain information on population distribution, and little or no understanding of temporal patterns in the way that animals use different parts of their range.

Static acoustic monitoring techniques provide opportunities to collect higher resolution data on temporal patterns of occurrence in selected areas (Van Parijs et al., 2009). The comparatively low-cost of TPODs and CPODs, passive acoustic monitoring (PAM) devices that have been designed to detect odontocete echolocation clicks, now permits the deployment of large arrays of these instruments (Brookes et al., In Press, Verfuss et al., 2007). These arrays can collect data for several months, allowing the detection of rare visits to different sampling sites and the collection of presence-absence data in weather and light conditions that would be unsuitable for visual surveys (Rayment et al., 2011, Teilmann and Carstensen, 2012, Thompson et al., 2010). However, these devices are unable to distinguish between echolocation clicks from different species of small odontocetes. In European waters, for example, whilst high frequency clicks from harbour porpoises (*Phocoena phocoena*) can be discriminated from mid-frequency dolphin clicks (Bailey et al., 2010a, Brookes et al., In Press, Simon et al., 2010), it is not currently possible to use this approach to discriminate between species such as bottlenose (*Tursiops truncatus*), white-beaked (*Lagenorhynchus albirostris*), common (*Delphinus delphis*) and Risso's dolphin (*Grampus griseus*), all of which are likely to occur in many coastal areas in the north east Atlantic (Reid et al., 2003).

The relative strengths and weaknesses of visual survey and acoustic monitoring data are complementary, highlighting the potential for integrating these approaches to provide more robust data on spatio-temporal patterns of occurrence of small cetaceans in particular areas of interest. In this paper, we illustrate this potential by combining data from arrays of static acoustic monitoring devices and a variety of different visual survey platforms. Our general approach was to use acoustic data in a habitat association model to predict spatial variation in the probability of occurrence of dolphins (Redfern et al., 2006, Soldevilla et al., 2011). Presence only data from visual surveys were then used in a classification tree analysis (De'ath and Fabricius, 2000) to assess the likely species identity of dolphins detected in different areas. The resulting data on spatial variation in the occurrence of bottlenose dolphins could then be used to characterise the baseline distribution required to assess the spatial overlap between bottlenose dolphins from the Moray Firth SAC and proposed developments in the offshore waters surrounding this protected area.

2. Methods

Passive acoustic data collection

Acoustic data were collected using a dispersed array of echolocation detectors (CPOD, Chelonia Ltd. UK) that were deployed across the Moray Firth between July and October of 2009, 2010 and 2011 (Figure 1). CPODs continuously monitor the 20-160 kHz frequency range for possible cetacean echolocation clicks, and record the centre frequency, frequency trend, duration, intensity, and bandwidth of each click. CPODs were moored in the water column, approximately five meters from the seabed, typically with a surface marker although acoustic releases were used at some sites in 2011. Once recovered, data were downloaded and processed using version 2.025 of the custom CPOD software (Chelonia Ltd., UK) to differentiate between dolphin and porpoise echolocation clicks and other high frequency sounds such as boat sonar. The output indicated the level of confidence in classification of the detection as a cetacean echolocation click train by classing each as CetHi, CetMod or CetLow. Only click trains categorized as CetHi or CetMod were used in subsequent analyses. These output files were used to determine whether or not dolphins (of any species) were detected in each hour within each of these deployments.

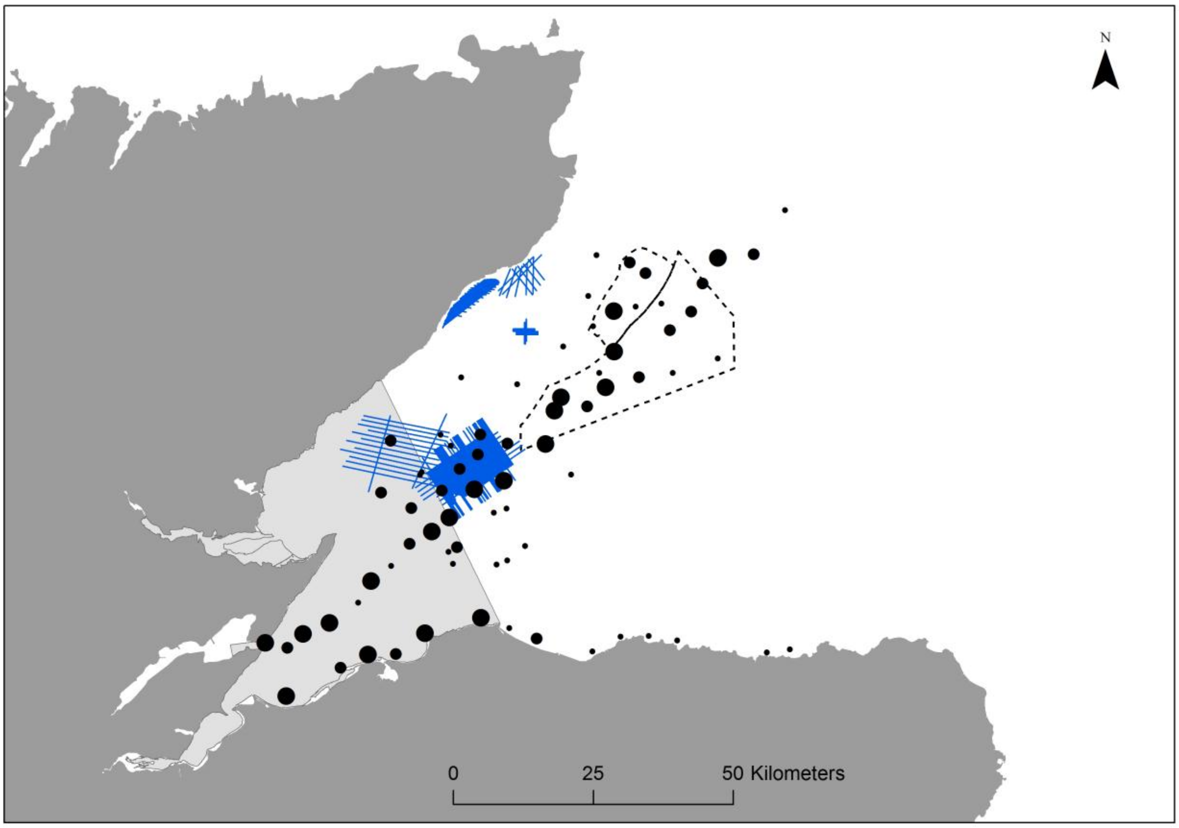


Figure 1. Map of the study area showing all CPOD sites used in the study. The size of each marker is related to the number of years for which data are available (1-3 years). The area within the Moray Firth Special Area of Conservation is shaded, and the map also shows the location of the offshore seismic surveys (solid blue lines) and wind farm development areas (dashed black outlines).

2.1 Visual survey data collection

Visual identifications of dolphins and estimates of group sizes were extracted from all publically available survey data sets from the Moray Firth. These included observations made between 1982 and 2010 from a variety of surveys, that each covered different sub-sections of our overall study area (Table 1). The minimum requirement was that surveys were carried out using experienced observers, and recorded the location, species and number of animals sighted. Thus, surveys included both effort related and presence only data, and observations of bottlenose, white-beaked, Risso's and common dolphins (see results).

2.2 Modelling spatial variation in the occurrence of dolphins using PAM data

Following the approach used to model porpoise distribution within the same study area (Brookes et al., In Press), raster grids for depth (SeaZone Hydrospatial Bathymetry) and polygon shapefiles for sediment type (SeaZone Seabed Sediment) were imported into ArcGIS 9.3. Slope in degrees, was calculated from the depth data and distance to coast was calculated from a shapefile of the UK coastline. Data were summarized into 4x4 km grid cells, with a value for each cell of mean depth, mean slope, mean distance from coast, the x and y coordinates from the centre of each cell, and the proportion of the cell’s sediments made up of sand and gravelly sand. ArcGIS 9.3 was then used to extract habitat variables for each of the grid cells containing CPOD sampling sites. There were few data at steeper slopes, and transformations were unsuccessful, so slope was converted into a categorical variable where 0-0.25=1, 0.25-0.5=2, 0.5-1.5=3 and 1.5-3.0=4. These static habitat variables were then combined with temporal data on hour of the day, Julian day and year (as a categorical variable) to explore which factors influenced variation in the probability of dolphins being detected within each hourly sample of acoustic data.

Due to the temporal correlation in dolphin detections between hours of the day at each POD site, data were analysed using a binomial generalised estimating equation (GEE) (Bailey et al., 2013, Photopoulou et al., 2011). The autoregressive correlation structure (ar1) was chosen as this specifies correlation as a function of time, meaning that the presence of dolphins in one hour affects the probability of dolphin presence in the next hour, but to a lesser extent in the following hour and so forth. This correlation structure was added to the data set, which gave a unique number to hourly data within each day at a particular site in a particular year, and specified the temporal correlation within groups (clusters), giving a cluster size of 24. As the GEE can only accommodate a single stratum of correlation and not a nested structure, the model assumed that different days and sites were independent. However, including a time covariate in the model accounted for the temporal variation in detections which might be expected to occur as a result of some correlation between adjacent days.

Table1. The number of sightings used from each of the datasets included in the classification tree analysis of visual sightings. Further information on individual data sources is provided in the project's 1st year report [1]

Dataset	Year	Survey method	Number of dolphin sightings	Source
1.	1980-1998	Boat and helicopter based line transect	45	JNCC Seabirds at Sea Database (see Reid et al 2003)
2.	1998-2006	Ad hoc boat based observations	23	JNCC Database of observations from seismic vessels (see Barton
3.	2010	Boat based line transect	8	Moray Offshore Renewables Ltd Environmental Statement
4.	2009-2010	Aerial visual and video line transect	4	The Crown Estate enabling actions
5.	2001	Boat based line transect	4	University of Aberdeen (see Hastie et al., 2003)
6.	2009	Boat based line transect	1	University of Aberdeen, (This study, see 1st Year report)
7.	2010	Aerial visual line transect	29	University of Aberdeen, (This study, see chapter 5)
8.	2004-2005	Boat based line transect	41	University of Aberdeen, (see Bailey and Thompson, 2009)
9.	1990-2010	Photo-ID boat based survey	828	University of Aberdeen, (Cheney et al., 2013)

1. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/50019/mf-results.pdf

Analyses were carried out using the package `geepack` within R version 2.12.1, and model selection was carried out based on QIC scores. Model fit was explored using the Wald-Wolfowitz test, where p values of <0.05 indicate that residuals were randomly distributed. Model residuals and fitted values were also plotted against spatial coordinates to investigate spatial autocorrelation.

2.3 Modelling spatial variation in the identity of dolphins species using presence only visual data

The presence-only data from visual surveys were used within a classification tree to assess the likely species identity of dolphins that might be detected within each 4x4 km grid cell, based upon the habitat available within that cell. Habitat variables included depth, sediment type (categorical), seabed slope, distance from coast and the x and y coordinates of the centre of the cell.

Individual sightings of each dolphin species were used in the classification tree. First, each of the sightings was assigned the habitat values averaged for the 4x4 km grid cell that it occurred within. The tree was then built using R version 2.12.1 and the `tree` package (Ripley, 2010). This involved repeatedly splitting the dataset in two, based on the value of a particular variable, until most animals were assigned to a unique species group. A tree, similar to a phylogeny was produced, weighted by the count of animals in each sighting. This allowed predictions to be made of the proportion of each species that might be expected in each 4x4 km grid cell within our study area given its habitat characteristics.

2.4 Integrating visual and PAM data to predict the distribution of different dolphin species

As the predictions from the classification tree are based upon presence only data, they cannot be used to estimate either the probability that dolphins might occur in a particular grid cell, or the number of animals that might be expected to be in that cell. Instead, the classification tree provides an estimate of the likely species composition that one would find in a cell if dolphins were present. In contrast, the analysis of PAM data provides an estimate of the probability that dolphins might occur in a given cell within a particular hour, but cannot be used to make inference about the likely species identity or numbers of dolphins occurring in that cell.

We therefore integrated these two model outputs using the predictions from the GEE for PAM data to estimate the probability that dolphins would occur in each grid cell within a given hour, and multiplied this by the output from the classification tree to predict the probability of bottlenose dolphins occurring within each grid square in the study area.

3. Results

3.1 Passive acoustic data

Dolphin echolocation clicks were detected during all deployments across the study area, but there was large variation in the level of detection across sites. At certain coastal sites, dolphins were detected on most days, for up to 21 hours per day. In contrast, detections sometimes occurred only once every few weeks at offshore sites, and typically occurred only within one or two hours on those days (Electronic Appendix).

The best fitting GEE model included two interaction terms, between distance to coast and proportion of sand and gravelly sand, and between slope and depth. It also included the x coordinate of the cell, the square of Julian day and year. Hour of the day was not significant and did not improve the QIC score and the simpler model, without this term, was therefore selected. The y coordinate was not included in any of the models as this was highly collinear with several of the other variables, such as distance to coast, and depth.

This best fit model was then used to predict the likelihood of dolphin presence in all grid cells across the study area (Figure 2), standardised for Julian day equal to 248 and year equal to 2010.

Table 2. Results from the GEE models exploring variation in the occurrence of dolphin acoustic detections at different sites in relation to local habitat characteristics.

a)a)

Explanatory variables	∆QIC
DistCoast*Psndgrvsnd+Slope*Depth+Xmean+JulianDay^2+Year	0
DistCoast*Psndgrvsnd+Slope*Depth+Xmean+JulianDay^2+Hour+Year	0
DistCoast*Psndgrvsnd+Slope*Depth+Xmean+JulianDay^2+Hour	78
DistCoast*Slope+Psndgrvsnd*Depth+Xmean+JulianDay^2	155
DistCoast*Slope+Psndgrvsnd*Depth+Xmean+JulianDay^2+Hour	156
DistCoast*Slope+Psndgrvsnd*Depth+Xmean+JulianDay	196
DistCoast*Slope+Psndgrvsnd*Depth+Xmean	312
DistCoast*Slope+Psndgrvsnd+Xmean+Depth	331
DistCoast*Slope+Psndgrvsnd+Xmean	770
DistCoast*Slope+Psndgrvsnd	1124
DistCoast+Slope	3185
DistCoast+Slope+Psndgrvsnd	3185
DistCoast	6445

b)

Parameter	Estimate	Std error	Wald	p-value
Intercept	-2.65000	1.57000	2.84	0.092 .
Julian day	-0.04660	0.00910	26.20	0.001***
Julian day^2	0.00009	0.00002	21.90	0.001***
Year (2010)	0.30100	0.05010	35.95	0.001***
Year (2011)	0.19300	0.05470	12.45	0.001***
Xmean	0.00001	0.00000	49.41	0.001***
DistCoast	-0.00016	0.00002	49.79	0.001***
Psndgrvsnd	-0.37800	0.12900	8.59	0.003**
Depth	-0.04220	0.00337	157.05	0.001***
Slope (2)	-0.58500	0.08900	43.23	0.001***
Slope (3)	-2.37000	0.23000	106.34	0.001***
Slope (4)	4.15000	0.21500	371.44	0.001***
DistCoast*Psndgrvsnd	0.00007	0.00002	10.78	0.001**
Depth*Slope (2)	0.01760	0.00328	28.68	0.001***
Depth*Slope (3)	0.02200	0.00881	6.25	0.012*
Depth*Slope (4)	-0.08900	0.00579	236.32	0.001***

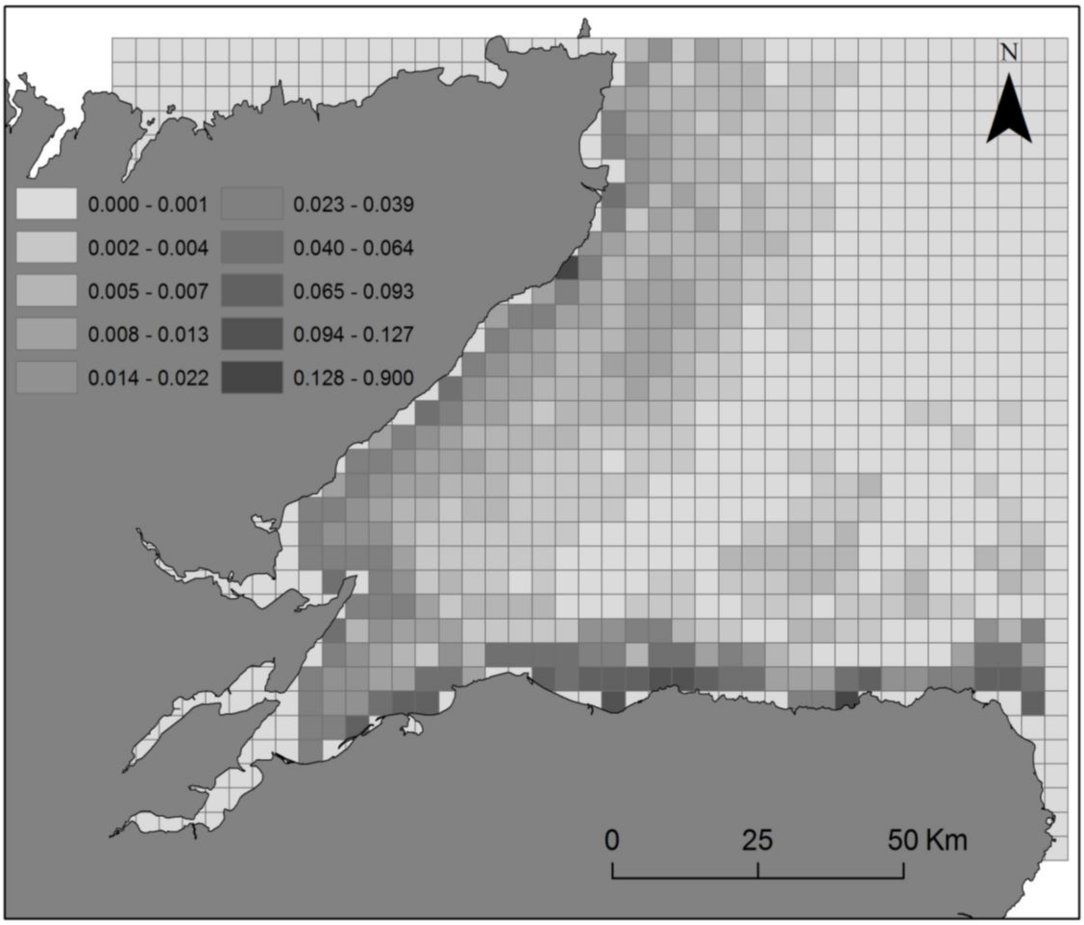


Figure 2. Spatial variation in the probability of detecting dolphins (of all species) across the Moray Firth. Predictions are based on the GEE analysis of passive acoustic data, and are standardised for Julian day equal to 248 and year equal to 2010.

3.2 Modelling spatial variation in the identity of dolphin species using presence only visual data

Overall, there were 988 sightings of dolphin groups that were identified to species, involving a total of over 7,000 individuals (Table 3). Most sightings were of bottlenose dolphins (Table 3) during coastal boat-based photo-identification surveys (Table 1). The other species recorded were white-beaked, common and Risso's dolphin, and these were more typically observed in offshore areas (Figure 3).

Table 3. The number of sightings and counts of individuals of each of the four species of dolphin observed on the visual sightings and included in the classification tree analysis.

Species	Number of sightings	Number of animals
Bottlenose dolphin	915	7465
Common dolphin	14	231
Risso's dolphin	4	6
White beaked dolphin	50	168

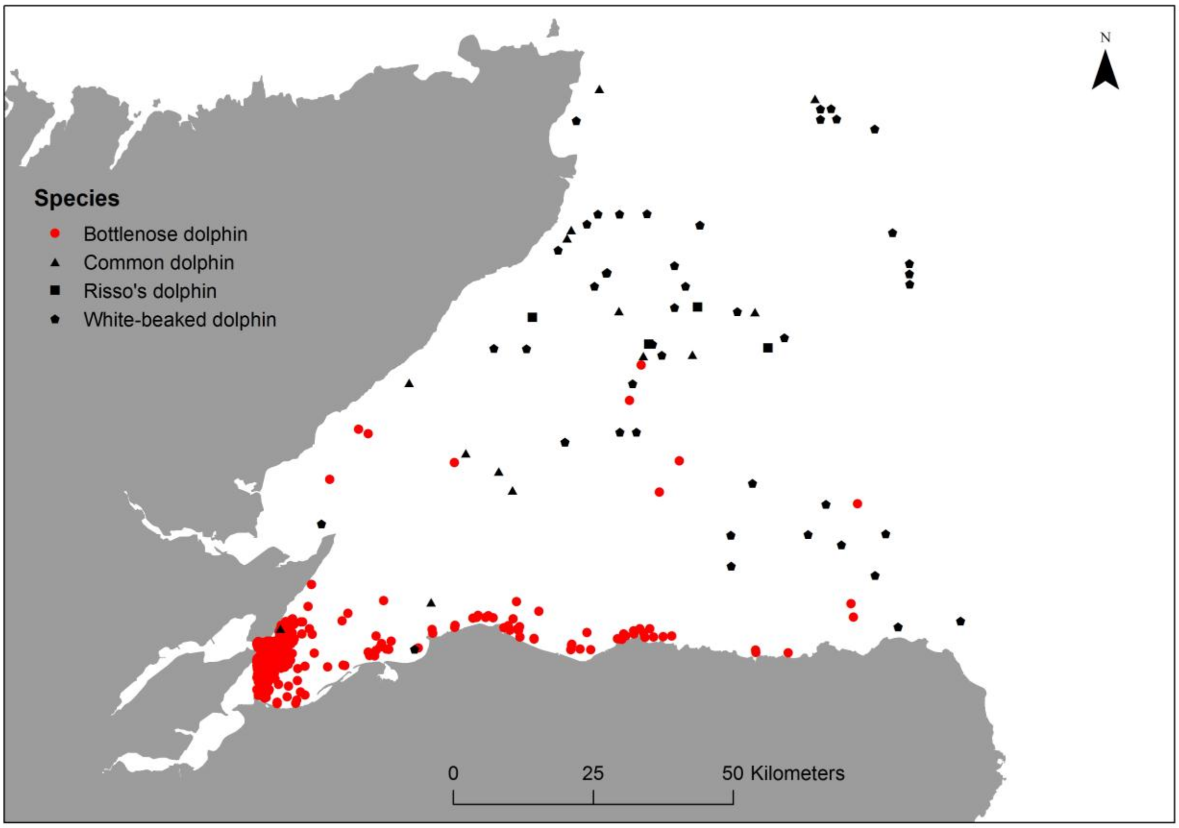


Figure 3. Locations of all the sightings of different dolphin species used in the classification tree. Data are from the sources listed in Table 1.

The classification tree based upon these data had 21 terminal nodes, and used depth, slope, distance to coast, sediment type and latitude to identify likely species composition in different parts of the study area. The misclassification rate was 0.014, which equated to 111 animals out of 7870 being wrongly classified, and the residual mean deviance was 0.0925.

Predictions from this tree indicate that any dolphins encountered along the coastal strip are most likely to be bottlenose dolphins, but that those encountered in offshore areas were, in general, more likely to be other species (Figure 4).

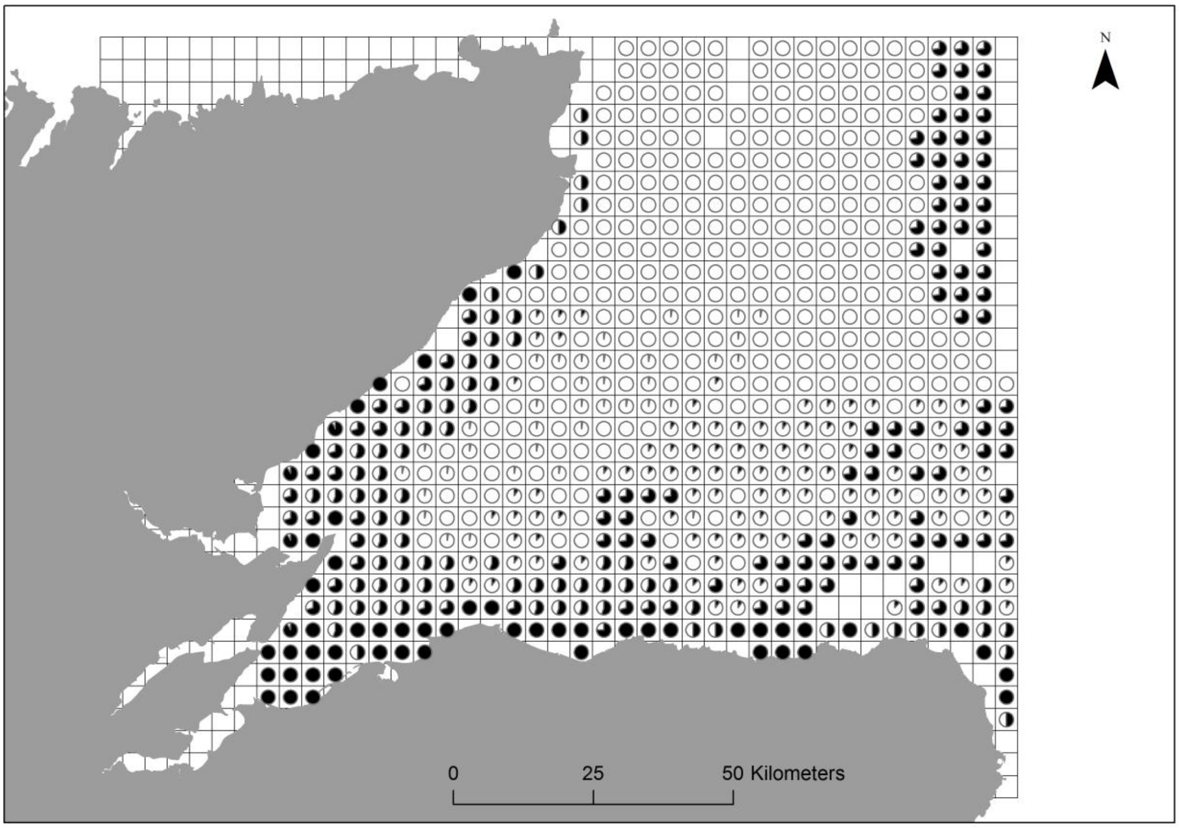


Figure 4. Prediction of the probability (black portion of pie chart) that dolphins encountered in each 4x4 km grid cell were bottlenose dolphins.

3.3 Integrating visual and PAM data to predict the distribution of different dolphin species

Predictions from the GEE (Figure 2) were integrated with those from the classification tree (Figure 4) to predict the probability of encountering bottlenose dolphins in different parts of the study area (Figure 5).

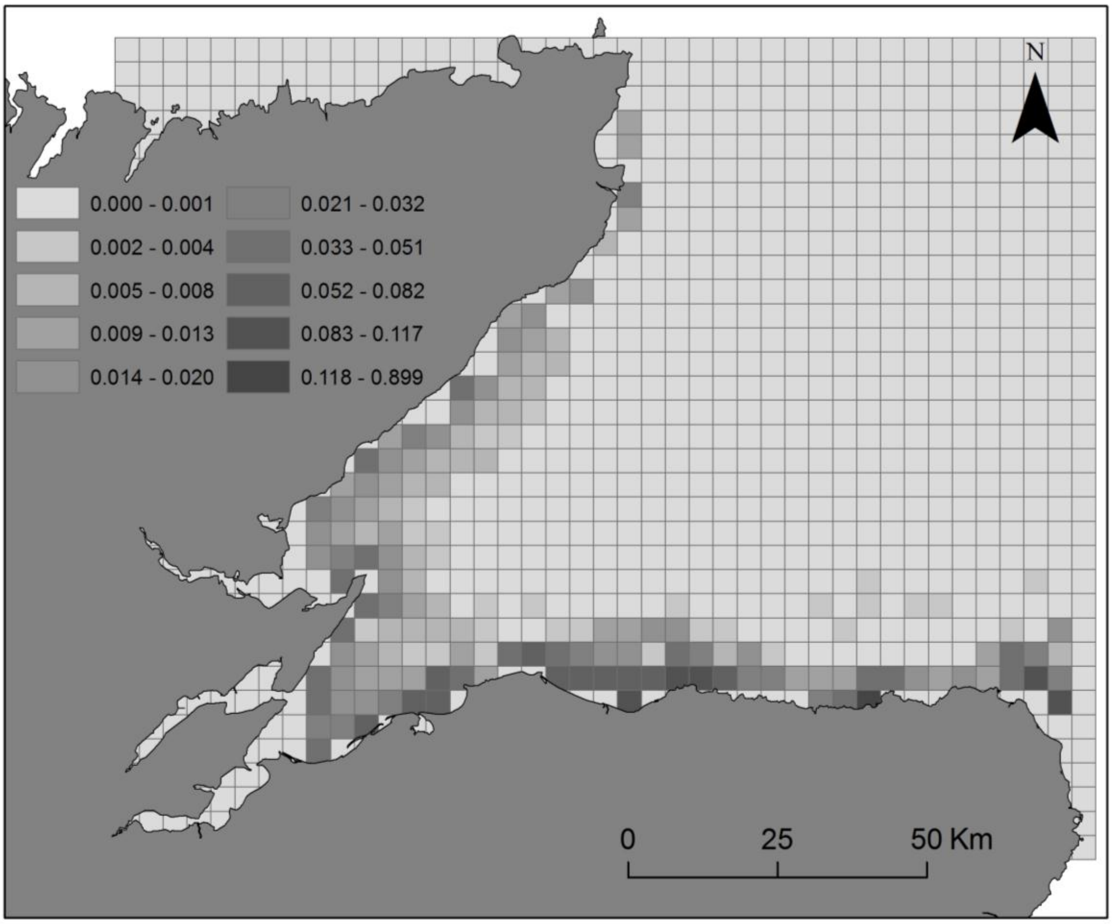


Figure 5. Predicted variation in the hourly probability of bottlenose dolphins occurring in different part of the Moray Firth.

4. Discussion

In recent years, an increasing number of marine protected areas have been established to protect coastal cetaceans (Hooker and Gerber, 2004, Hoyt, 2004). In European waters, this has been driven by the EU Habitat and Species Directive, where core areas have been designated as SACs (Cheney et al., 2013, Ingram and Rogan, 2002). Recognising the mobile nature of these protected populations, assessment of potential impacts must consider activities that occur outside site boundaries. However, data on spatio-temporal patterns of the distribution of these populations are rarely available at the scales required to assess current management issues. In the Moray Firth, for example, environmental assessments for oil and gas developments and offshore wind farms have had to consider potential impacts on the bottlenose dolphins using the Moray Firth SAC. However, there has been uncertainty over the extent to which these animals move outside their coastal core-range due to limited historic survey effort in offshore areas. In this study, we collected new acoustic and visual data, and integrated these data with historic sources to model likely variation in the occurrence of bottlenose dolphins at a regional scale. These analyses built on the strengths of these two survey techniques. The acoustic data demonstrated that dolphins occurred only rarely in offshore areas (Figure 2), and the visual surveys indicated that the dolphins that were seen in those areas were most likely to be offshore species such as white-beaked, common and Risso’s dolphin rather than bottlenose dolphins (Figures 3 & 4).

Typically, additional information to meet these management needs would have been sought through the collection of more visual survey data. However, boat and aircraft based surveys in offshore areas such as these are expensive and logistically challenging, and sightings rates are typically low (Dawson et al., 2008). Furthermore, as one moves to finer and finer spatial scales, it is more likely that cetaceans occupy sites of interest only temporarily, and frequent visual surveys would be required to detect rare visitors. Whilst temporal changes in occurrence could be assessed through repeated visual surveys, for example using alternative tools such as occupancy analysis (MacKenzie et al., 2002), sufficiently intensive survey campaigns are only likely to be practical within relatively small inshore sites. Further offshore, and at the regional scales of relevance in our study system, systematic regular visual surveys alone would be unlikely to produce the data required to satisfy other stakeholders that bottlenose dolphins were unlikely to be encountered around offshore developments sites.

In our study, we overcame this problem by integrating our data from a broad scale PAM array with the available data on visual identifications of dolphins. PAM is now often used for species that vocalise regularly, using either cabled hydrophones or a variety of seabed mounted data loggers (Sirovic et al., 2009, Soldevilla et al., 2011). In particular, the development of relatively low cost echolocation detectors (TPODs and CPODs) has demonstrated the potential for using larger arrays of data loggers to monitor cetacean echolocation activity across a number of sites over periods of weeks to months (Brookes et al., In Press, Verfuss et al., 2007). This approach has provided important information on spatio-temporal variation in the occurrence in harbour porpoises, and informed baseline distribution studies and impact assessments (Scheidat et al., 2011, Teilmann and Carstensen, 2012). However, whilst harbour porpoises can be positively identified from their echolocation click characteristics, it is not currently possible to discriminate between the clicks of different dolphin species.

Here, we used GEEs to model the PAM data and classification trees to model species composition, thus predicting how each varied in relation to different habitat characteristics. However, this general approach could be developed using alternative modelling tools. A GEE framework was chosen here because it was recognised that the PAM data were likely to be temporally auto-correlated. However, the GEE could not be used with a nested correlation structure. Thus, while we found no evidence of spatial auto-correlation in our acoustic data, it would be valuable to explore alternative frameworks that could cope with more complex correlation structures. Another alternative, for example, would be to use the acoustic data to model spatial variation in occurrence using occupancy analysis (MacKenzie et al., 2011). The data used in this analysis are available as an electronic appendix to encourage further exploration of alternative modelling frameworks.

Similarly, while the classification tree provided a convenient method for integrating the data sources available to us in this study area, alternative approaches might be more suitable in other cases. For example, Reid et al. (2003) used data from a variety of different effort based surveys to provide an indication of the relative abundance of different cetacean species in UK waters. Data from this publication could be used as an alternative to the classification tree analysis in other areas. We chose not to take this route because there have been a number of relevant studies in the Moray Firth since Reid et al.'s (2003) analysis (Table 1), and we required regional scale analysis that incorporated all these data. Our use of the classification tree analysis also allowed us to include additional presence only data that provided valuable information on the likely species identity of dolphins seen in different parts of the Moray Firth. Given the relatively small number of sightings of dolphins in offshore areas, there are clear advantages of using a framework that can incorporate such data sources. Given the increasing availability of high quality digital cameras and GPS receivers, geo-referenced verifiable records of sightings from recreational sailors and other marine users could also provide a valuable source of data for these studies, as found for individual based studies of bottlenose dolphins in remote Scottish waters (Cheney et al., 2013). In future, it may also be possible for this step of the process to incorporate data on dolphin species composition in different UK waters from the Joint Cetacean Protocol (http://jncc.defra.gov.uk/page-5657); a national database of cetacean line-transect survey data that will update and extend information provided in Reid et al. (2003).

Our study was based upon a PAM array that had been designed for impact assessment (see Chapters 5 & 6). This meant that we were unable to detect variation in occurrence over some of the variables that might be expected to influence bottlenose dolphins. Most notably, latitude was not included in any of our GEE models, even though this study area represents the northern extreme of this population's range (Wilson et al., 1999). This was not included as our array design resulted in co-variation between latitude and other key variables such as distance from shore. As a result, our final model appears to over-predict the importance of the north coast of the Moray Firth for bottlenose dolphins compared with the south coast when compared with other available data (Reid et al., 2003; Chapter 6). Future studies that aim to refine these models would benefit from additional sampling in areas such as the inshore waters along the north coast, and year-round PAM studies that could explore whether these patterns persist in other seasons. Similarly, such studies could use deployments of broad band acoustic data loggers to complement the visual data by providing information on dolphin species identity through analysis of whistle characteristics (Oswald et al., 2007, Soldevilla et al., 2011).

In conclusion, these analyses highlight the potential for integrating PAM and visual survey data to characterise spatial variation in the occurrence of coastal dolphins. Although our study design did not allow us to fully characterise variation in their use of different coastal waters, these analyses brought together available data to inform management issues requiring information on the relative occurrence of bottlenose dolphins in inshore and offshore areas. The approach developed in this study complements broader scale efforts to estimate abundance or density using other techniques such as mark-recapture or DISTANCE analysis (Hammond, 2010). These other methods provide an indication of the numbers of animals occurring over larger regions, but cannot be used to assess how often these animals occur in particular sub-areas within those regions. In contrast, our study provides a framework that can be used to predict how often animals may be encountered in different sub areas, but provides no information on the number of individuals involved. Use of these complementary approaches will be increasingly important as new marine spatial planning frameworks require better information on spatio-temporal patterns of occurrence to assess and mitigate risks from interactions between coastal dolphins and human activities such fisheries and marine energy developments.

Predictions from harbour porpoise habitat association models are confirmed by long-term passive acoustic monitoring

Kate L. Brookes[1,2], Helen Bailey[3] & Paul M. Thompson[1]

[1] Lighthouse Field Station, Institute of Biological & Environmental Sciences, University of Aberdeen, Cromarty, IV 11 8YL, UK.

[2] Current address: Marine Scotland Science, 375 Victoria Road, Aberdeen, AB11 9DB, UK.

[3.] University of Maryland Center for Environmental Science, Chesapeake Biological Laboratory, P.O. Box 38, Solomons, Maryland, MD 20688.

Abstract

Survey based habitat association models provide good spatial coverage, but only a snapshot in time of a species' occurrence in a particular area. A habitat association model for harbour porpoises was created using data from five visual surveys of the Moray Firth, Scotland. Its predictions were tested over broader temporal scales using data from static passive acoustic loggers, deployed in two consecutive years. Predictions of relative abundance (individuals per kilometer of survey transect) were obtained for each 4x4 km grid cell, and compared with the median number of hours per day that porpoises were acoustically detected in those cells. There was a significant, but weak correlation between predicted relative abundance and acoustic estimates of occurrence, but this was stronger when predictions with high standard errors were omitted. When grid cells were grouped into those with low, medium and high predicted relative abundance, there were similarly significant differences in acoustic detections, indicating that porpoises were acoustically detected more often in cells where the habitat model predicted higher numbers. The integration of acoustic and visual data added value to the interpretation of results from each, allowing validation of patterns in relative abundance recorded during snapshot visual surveys over longer time scales.

1. Introduction

Habitat association models have been widely used to investigate species' ecological requirements, to identify key conservation areas (e.g. Bailey and Thompson, 2009, Cañadas et al., 2005, Embling et al., 2010, Ingram and Rogan, 2002, Louzao et al., 2006, Péron et al., 2010), 2010), and to support spatial planning in order to minimize interactions with human activities (e.g. Brambilla et al., 2010, Forcey et al., 2011, Gontier et al., 2010, Muhling et al., 2011). These models may use either survey or telemetry data to identify habitat characteristics that influence the distribution or abundance of animals, and then predict over areas where data are sparse or absent (e.g. Nur et al., 2011). One fundamental assumption of these models is that the predictor gradients have been adequately sampled (Elith and Leathwick, 2009), and it is recognized that predictions outside this range of environmental variables will have increased errors. However, because independent data sets are rarely available for comparison, the predictive power of these models, even within the range of environmental variables studied, often remains uncertain.

Harbour porpoises *Phocoena phocoena* are widely distributed across European waters (Reid et al., 2003), occurring in a variety of habitats that range from offshore sandbanks in open waters (Hammond et al., 2002, Todd et al., 2009) to complex tidal streams around island archipelagos (Embling et al., 2010, Marubini et al., 2009, Shucksmith et al., 2009). Their protected status under the European Habitats Directive (1992), frequent interactions with fisheries (e.g. Leeney et al., 2008, Vinther and Larsen, 2004), and use of areas identified for offshore energy developments (Bailey et al., 2010b, Scheidat et al., 2011, Thompson et al., 2010) have led to a number of studies that have used habitat association modeling to identify key management areas (Bailey and Thompson, 2009, Embling et al., 2010). Most of these studies have been carried out in inshore waters, and indicate that the likelihood of porpoises being present increases in areas with bathymetric or oceanographic features associated with increased productivity and prey aggregation. Such features include increased tidal flow (Marubini et al., 2009) or fronts (Johnston et al., 2005, Shucksmith et al., 2009), but the detail varies between sites. Offshore, fewer studies have been carried out due to the logistic difficulties of surveying these areas, although studies using static passive acoustic devices have found that porpoises are likely to be foraging on the Dogger Bank in the central North Sea (Todd et al., 2009).

Habitat association models are often based on line transect survey data, which can only provide a snapshot in time. Consequently, these models are often unable to account for diel, inter-annual or seasonal changes in distribution or habitat use. For example, two large-scale surveys carried out a decade apart reported marked differences in harbour porpoise distribution in the North Sea (Hammond, 2006, Hammond et al., 2002). However, it was not clear whether these differences represented a genuine long-term range shift, or an interaction between slight changes in survey timing and a shorter-term seasonal change in distribution.

Static passive acoustic monitoring (PAM) offers the potential to study changes in the occurrence of animals over longer temporal scales, since devices can be deployed to record continuously for several months. Harbour porpoise have been shown to echolocate almost constantly (Akamatsu et al., 2007, Linnenschmidt et al., 2013), so it is likely that animals that are present will be detected acoustically. However, these techniques suffer the converse problem to that of habitat association modeling, of limited spatial coverage. Comparison of the results from survey based habitat association modeling with PAM within a particular area therefore provides an opportunity to explore whether predicted variations in spatial distribution are consistent over longer time scales. Here, we use visual survey data to develop a model of harbour porpoise habitat association in the Moray Firth, NE Scotland, and compare these predictions with PAM data collected from the same area over a two year period.

2. Methods

2.1. Data collection

2.1.1 Study site

The Moray Firth is a large triangular embayment of over 6000 km^2. Water depths gradually shelve from the coast, but in the central Moray Firth, there is a shallow sand bank of 40 to 50 m depth called the Smith Bank, a minimum of 15 km offshore.

Along the east of the southern coast is a trench with depths of up to 200 m (Figure 1). The slope is rarely more than 1°, except in the areas around the southern trench, where it reaches a maximum of 6.5°. Sediment types within the firth are generally sandy and gravelly, with some muddy sediments in the southern, deeper areas. The Smith Bank has historically been known to support sandeel *Ammodytes marinus* populations (Hopkins, 1986) and although no recent surveys have been carried out, fishery landings data (ICES, 2007) and analysis of diets of other predators (Greenstreet et al., 1998) suggest that this is still the case.

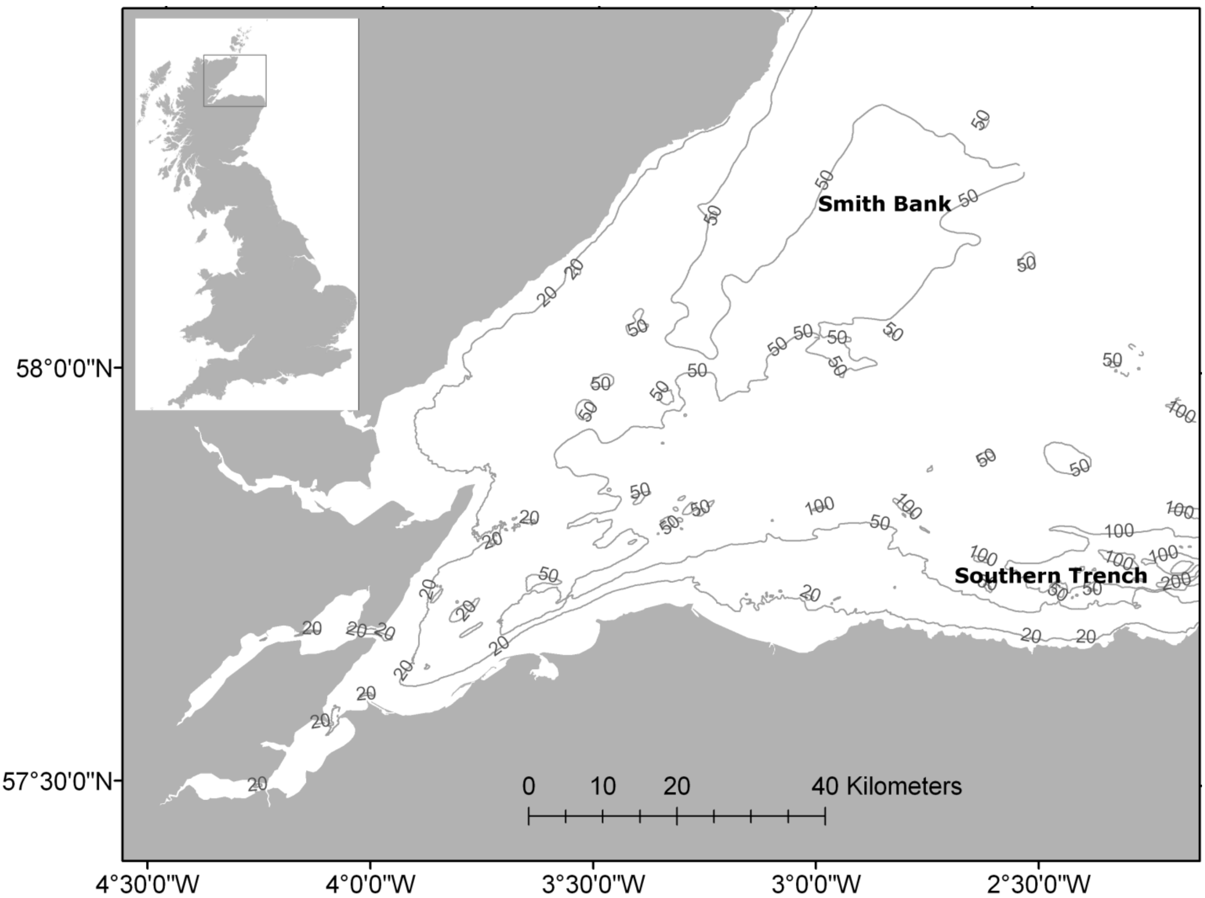


Figure 1. Map showing the bathymetry and location of the Moray Firth. The 50 m depth contour in the centre of the firth demarks the Smith Bank.

2.1.2. Survey methods

This study was based upon harbour porpoise sightings and counts collated from five different survey datasets. Four datasets were from boat-based line transect surveys, and one was from an aerial line transect survey. All data were collected between April and October, from 2004 to 2010 (Table I), with some datasets covering most or all months in that period, while the aerial survey dataset covered only August and September. Each dataset was collected using standard protocols for marine mammal surveys, and aimed to spread survey effort evenly through the survey windows presented in Table I. Boat based surveys used the European Seabirds at Sea (ESAS) methodology (Camphuysen et al., 2004, Webb and Durinck, 1992) and aerial surveys were conducted using the methodology described for the SCANS-II surveys (Hammond, 2006). Both aerial and boat surveys collected effort data in the format of transect distance surveyed. All surveys recorded the location, species and number of animals sighted and did not deviate from the track line when animals were sighted. For boat based surveys animal location was determined by combining the boat's GPS data with measurements of distance and angle from the trackline. For aerial surveys, animals were recorded at the moment they were abeam of the aircraft, the time of which was compared with the onboard GPS and the declination angle to the water was used to calculate distance from the trackline. Some details, such as vessel type, survey speed, the number of observers (Table I) and the area surveyed varied between datasets (Figure 2). In surveys where only one observer was present, the observer scanned a 180° arc forward of the vessel, while in surveys with two observers, each observer scanned a 90° arc abeam to forward of the vessel. The vast majority of data were collected in Beaufort sea state three or less, but occasionally conditions deteriorated during a survey and some small sections were surveyed in Beaufort sea state four.

2.1.3 Passive acoustic monitoring

Acoustic loggers (CPOD, Chelonia Ltd. UK) were deployed across the Moray Firth (for locations see results section) throughout the period from April to October in 2009 and 2010. CPODs continuously monitor the 20-160 kHz frequency range for possible cetacean echolocation clicks, and record the centre frequency, frequency

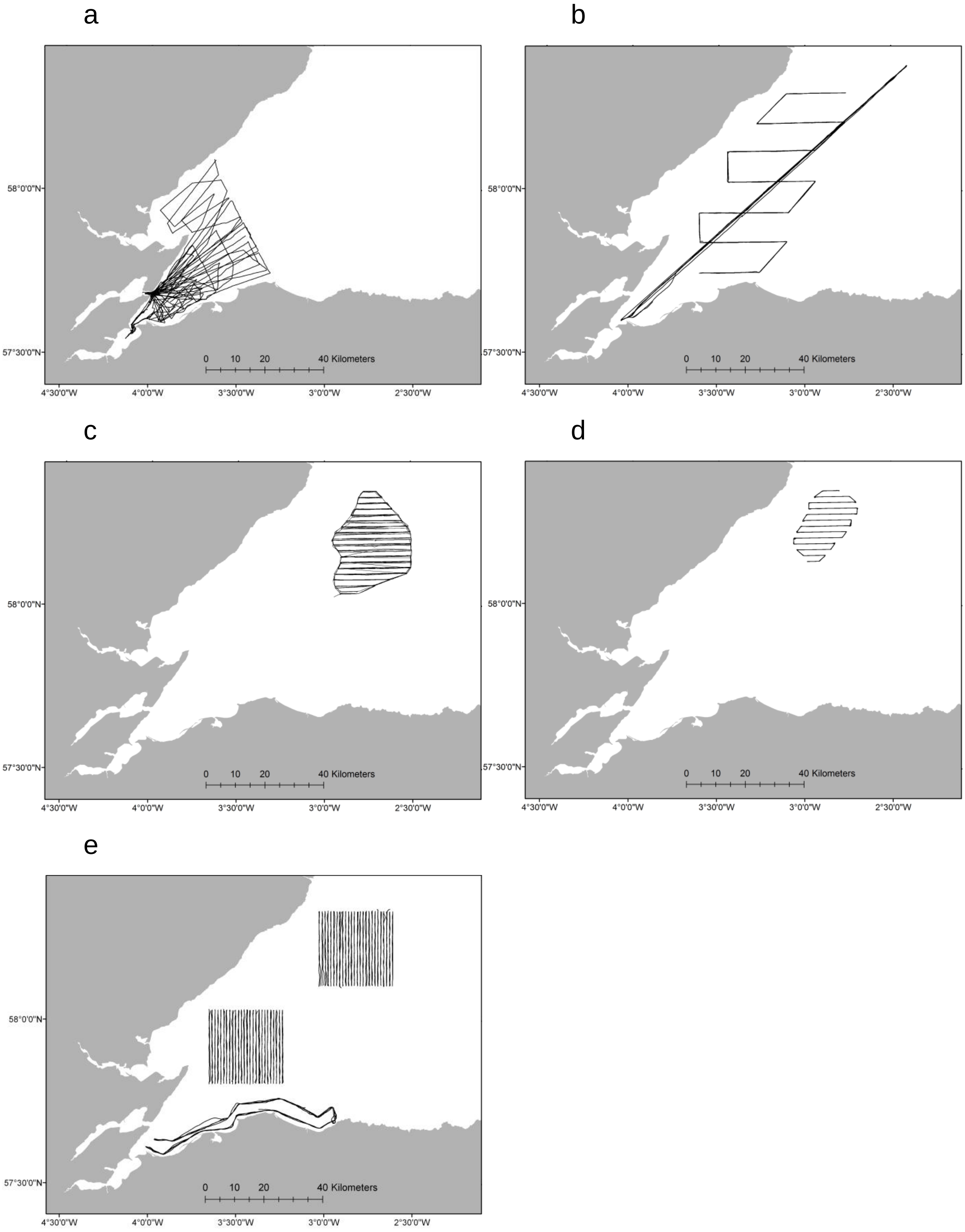


Figure 2. Spatial extent of effort from four boat based surveys (a to d), and one aerial survey (e) carried out in the Moray Firth in (a) 2004 (August, September, October) and 2005 (April, May, June, July), (b) 2009 (June, August, September, October), (c) 2010 (April, May, June, July, August, September, October), (d) 2010 (April, May, June, July, August, September) and (e) 2010 (August, September).

Table I. Details of five survey datasets of harbour porpoise, collected in the Moray Firth and used in habitat association modeling. Dataset a contains data previously published in Bailey and Thompson (2009)

Dataset	Years	Total survey days	Months of survey	Total trackline surveyed	Total porpoise count	Survey Vessel	Number of mammal observers	Survey speed	Survey platform height
A	2004 2005	10 15	August to October. April to July	251 km 1029 km	62	Boat	1	7 knots	3.5 m
B	2009	14	June, August to October	1618 km	131	Boat	2	8 knots	≥ 5 m
C	2010	24	April to October	3015 km	362	Boat	1	10 knots	≥ 5 m
D	2010	14	April to September	1390 km	177	Boat	1	10 knots	3 m
E	2010	13	August and September	4493 km	341	Airplane	2	100 knots	183 m

trend, duration, intensity, and bandwidth of each click. They are capable of detecting porpoise clicks within an omnidirectional range of up to 300 m (Chelonia Ltd. 2012a). The loggers were moored in the water column, approximately five meters from the seabed. Once recovered, data were downloaded and processed using version 1.054 of the custom CPOD software (Chelonia Ltd., UK) to differentiate between dolphin and porpoise echolocation clicks and other high frequency sounds such as boat sonar. The output indicated the level of confidence in classification of the detection as a cetacean echolocation click train by classing each as CetHi, CetMod or CetLow. Only click trains categorized as CetHi or CetMod were used in analyses.

2.2 Habitat association model

Raster grids for depth (6 arcsecond grid, approximately equivalent to 180 m grid) and polygon shapefiles for sediment type (1:250,000 scale) were used to provide habitat variables (SeaZone Hydrospatial Bathymetry; SeaZone Seabed Sediment), which were processed using ArcGIS 9.3. Data were summarized into 4x4 km grid cells as in Bailey and Thompson (2009), with a value for each cell of mean depth, mean slope, mean distance from coast and the proportion of the area of the cell containing sand and gravelly sand sediment types (Figure 3). This sediment variable was used because it is most likely to account for the suitability of the habitat for sandeels, which prefer fine and coarse sands (Holland et al., 2005) and along with whiting (*Merlangius merlangus*), which prefer sandy sediments (Atkinson et al., 2004), are key prey species for harbour porpoises (Santos and Pierce, 2003). Frequency histograms of the habitat variables within grid cells that had been surveyed showed that the distribution of depth was strongly right skewed and so cells with depth values greater than 80 m were excluded from the analysis.

The total number of harbour porpoises sighted and the total effort (meters of survey track) in each cell were calculated separately for each of the five datasets. In many cells, both effort and sightings were available from multiple datasets, so a mixed model approach was taken to account for correlation between observations within the same cell. The relationship between porpoise counts and depth was non-linear, so generalized additive modeling was used. Generalized Additive Mixed Models (GAMMs) were created using the mgcv package (Wood, 2008) in R version 2.12.1

(R Development Core Team, 2010). Models were constructed with a count of animals in each 4x4 km grid cell for each dataset as the response variable, along with a value for each habitat variable as explanatory variables. The log of the total transect length within each grid cell from each dataset was used as an offset variable. The use of different survey platforms means that is possible that sightings rates differed between the five data sets. If they exist, such differences are most likely between boat-based and aerial surveys, so we explored potential differences in sighting rate between these two main survey types by including method (aerial versus boat-based) as a variable in the model. Models were weighted by the ratio of effort to the maximum value of effort, thereby allowing cells with more effort to have more influence on the estimated values from the model. Cell identity was included as a random effect to account for correlation between observations within the same cell. The resulting model was then used to predict the number of harbour porpoises in each grid cell across the whole Moray Firth. This included the area surveyed, which was used to construct the model, and other areas outside of this where the cells had habitat variables that fell within the range of those used in the model. We applied a standard value for effort to allow comparisons to be made across cells which had received different levels of survey effort. This value of 1 km of transect line per grid cell, provided a relative index of porpoise abundance which we express as porpoise sightings per kilometer of trackline (porpoises km^{-1}).

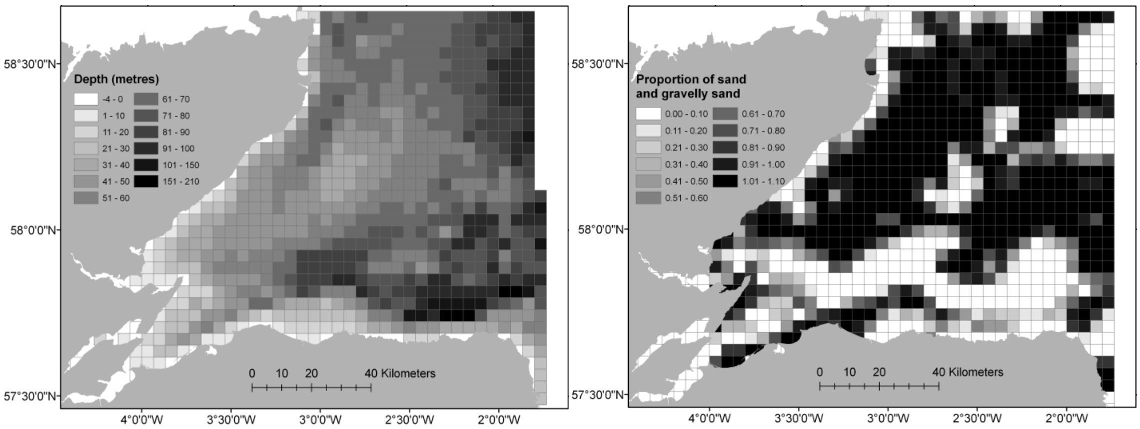


Figure 3. Habitat variables (depth and sediment type) summarized over a 4x4 km grid. Sediment type is coded as the proportion of the area of the cell that was classified as sand or gravelly sand. © Crown Copyright/SeaZone Solutions Ltd. All Rights Reserved.

2.3 Model comparison with acoustic data

In 2009 and 2010, between April and October, 69 CPODs (Chelonia Ltd., UK) were deployed within grid cells for which we were able to predict porpoise relative abundance from the habitat association model. Data from these CPODs were exported in four ways, summarizing the data over different time scales: the number of minutes per day that porpoise click trains were detected (porpoise positive minutes; PPM), the number of hours per day that porpoise click trains were detected (porpoise positive hours; PPH), the number of days on which porpoise clicks trains were detected (porpoise positive days; PPD) and the waiting time between detections (waiting time). The minimum waiting time allowed was one minute, so the data reflect new trains of porpoise clicks rather than the very short intervals between clicks within a train. Data were then pooled for 2009 and 2010, for the entire April to October sampling period for each site. The median value was calculated for PPM, PPH and waiting time, while the proportion of PPD was reported. If more than one CPOD was concurrently present within the cell, the device with the longest time series was used. The minimum duration of data collection at a site was 56 days. These data were then compared with the habitat association model predictions using a Spearman's rank correlation test between each of the acoustic metrics for the grid cells in which the CPODs were positioned and the modeled relative abundance predictions.

This analysis was carried out on the full dataset, and also on a dataset that excluded cells in which the model predictions had high standard error values. The full dataset of 69 observations had a mean standard error of 1.32, and a median of 1.23, with values ranging from 1.14 to 2.64. In our reduced dataset, removing observations with standard errors greater than 1.40 reduced the dataset by 15 observations but brought the mean standard error much closer to the median, with values of 1.22 and 1.21 respectively, effectively removing the tail of the distribution.

For the acoustic metric with the strongest correlation, we also grouped all cells in which there were acoustic data into three categories to represent areas in which model predictions of relative porpoise abundance were low, medium or high. The groups were of equal width of predicted values, with each group accounting for approximately a third of the range of predictions. The low group contained 26 cells containing CPODs, with predicted porpoises km^{-1} of 0.000-0.039. The medium group contained 33 cells with predicted porpoises km^{-1} of 0.040-0.079 and the high group contained 10 observations from cells with predicted porpoises km^{-1} of 0.080-0.130. We then compared the selected acoustic metric for sites in each of these groups using a Kruskal Wallis test. Where a significant effect was found, post hoc Wilcoxon tests were used to determine which groups were different from each other. This analysis was also carried out on the reduced dataset. The number of observations in the low, medium and high groups was 16, 29 and 9 respectively in this reduced dataset.

3. Results

In total, 1073 porpoise sightings were included in the model (Table 1). These were generally clustered in offshore areas where there were large amounts of survey effort (Figure 4).

3.1 Habitat association model

Data exploration indicated that depth and distance from the coast were highly collinear, so distance from the coast was removed from the model since its relationship with porpoise count was somewhat weaker. Initial models were found to be over-dispersed when using a Poisson distribution and the final models therefore used a negative binomial distribution (O'Hara and Kotze, 2010). The initial model included the explanatory variables depth, the proportion of the sediment that was sand or gravelly sand, slope, survey method and the log of effort length as an offset. Model selection, based on AIC scores (Akaike, 1974), resulted in the removal of slope, but retained a smoother, which was a 2D surface describing the relative abundance of porpoises using an interaction between depth and the proportion of sand and gravelly sand sediments (Figure 5, Table II). Survey method did not improve the AIC score of the model, so was not included in the final model, which contained only the 2D smoother and the effort offset as fixed effects, and cell identity as a random effect. The r^2 value of this model was 0.381.

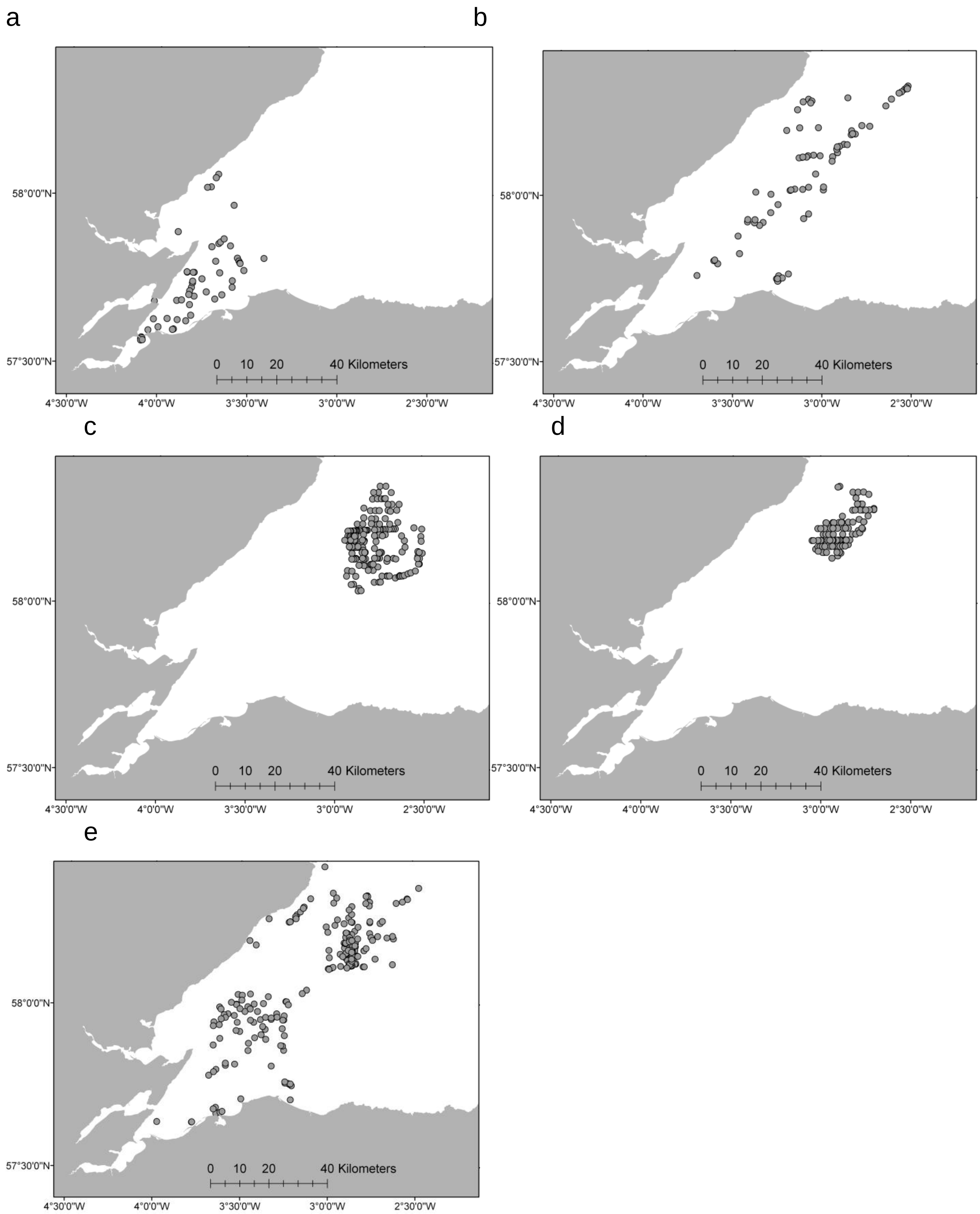


Figure 4. Location of harbour porpoise sightings from four boat based surveys (a to d) and one aerial survey (e) in the Moray Firth between 2004 and 2010.

Table II. Results of a negative binomial GAMM used to analyze harbour porpoise counts, using a tensor smoother, with an interaction term between depth and the proportion of sand and gravelly sand.

Parametric coefficients				
	Estimate	*Standard error*	*t*	*P*
Intercept	-3.010	0.084	-35.86	<0.001
Smooth terms				
	Estimated degrees of freedom	*Reference degrees of freedom*	*F*	*P*
2D smoother for depth & proportion of sand & gravelly sand	6.679	6.679	6.274	<0.001

The random effect in the model showed that there was a relatively strong correlation of 0.69 between observations from the same cell. This was calculated as:

$$a^2/(a^2 + b^2) \quad (1)$$

where a is variance of the random intercept and b is variance of the residual term (Zuur et al., 2009). In this case, *a* = 0.710 and *b* = 0.481.

The final model was then used to predict spatial variation in the relative abundance of porpoises across the Moray Firth (Figure 6).

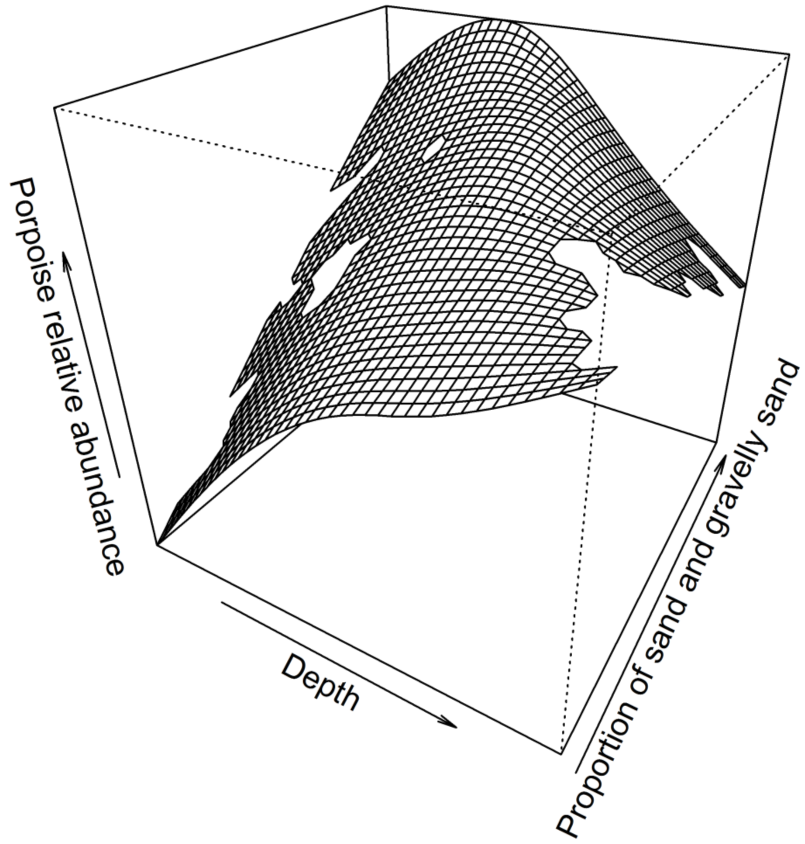


Figure 5. Two dimensional smoother used in the porpoise habitat association model to describe the interaction between depth and the proportion of sediments that were sand or gravelly sand, and the relationship between these habitat variables and harbour porpoise relative abundance.

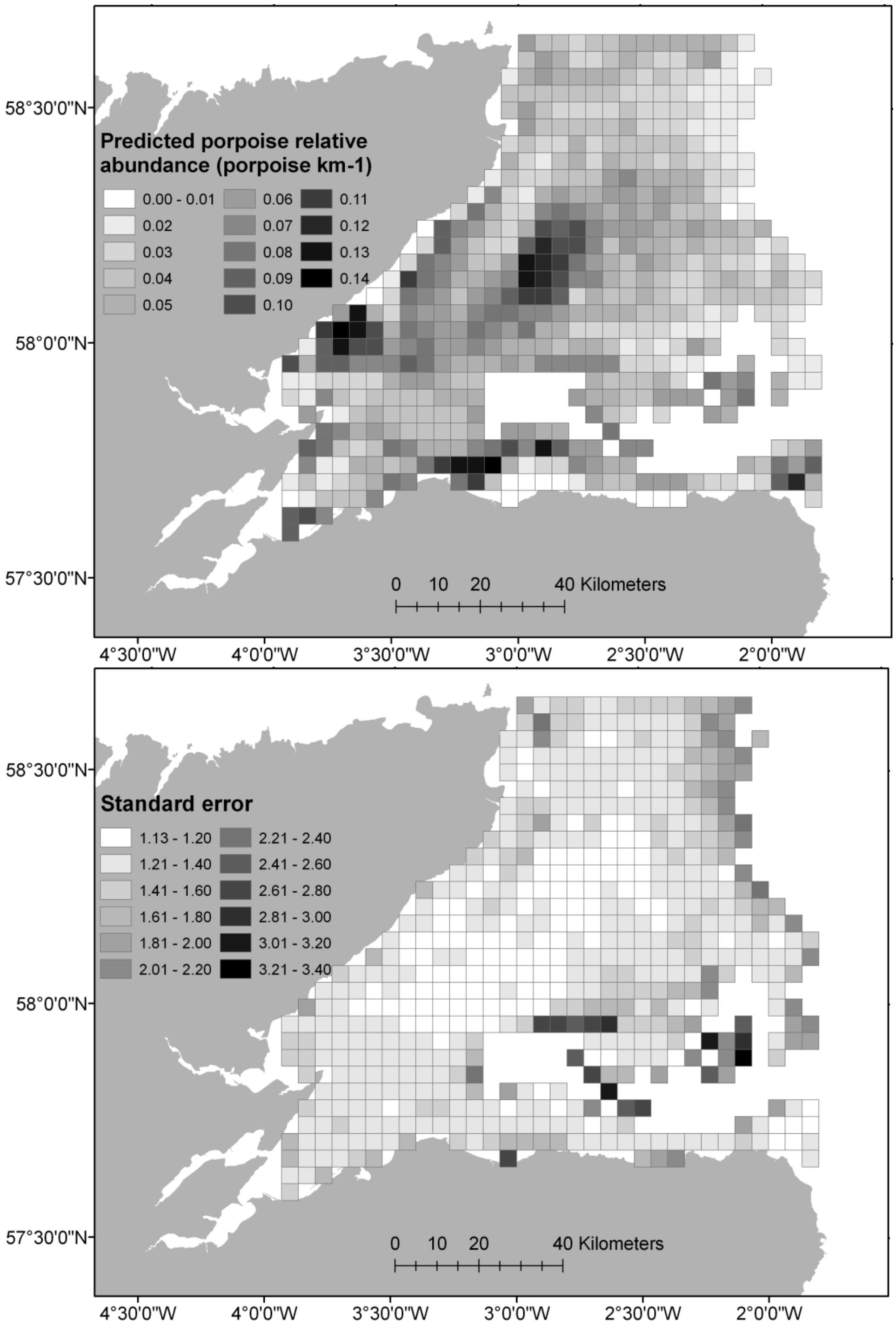
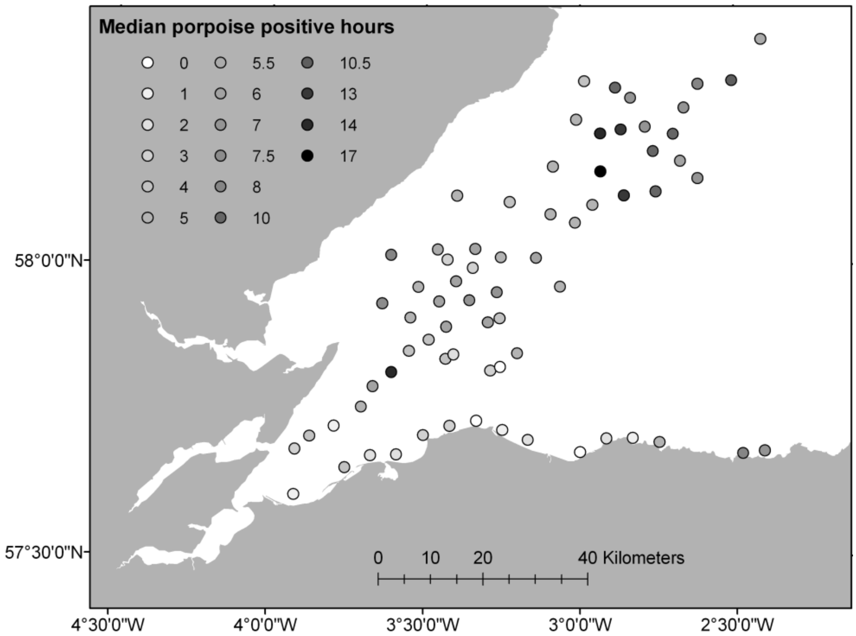


Figure 6. Maps of predicted relative abundance of porpoises (porpoise km^{-1}) and the standard error of the prediction, from a GAMM with depth and the proportion of sand and gravelly sand sediments, given 1 km of effort in each cell. Predictions were not made in cells where depth was greater than 80 m because no survey data were available to inform these predictions (white areas in the figures).

a)



b)

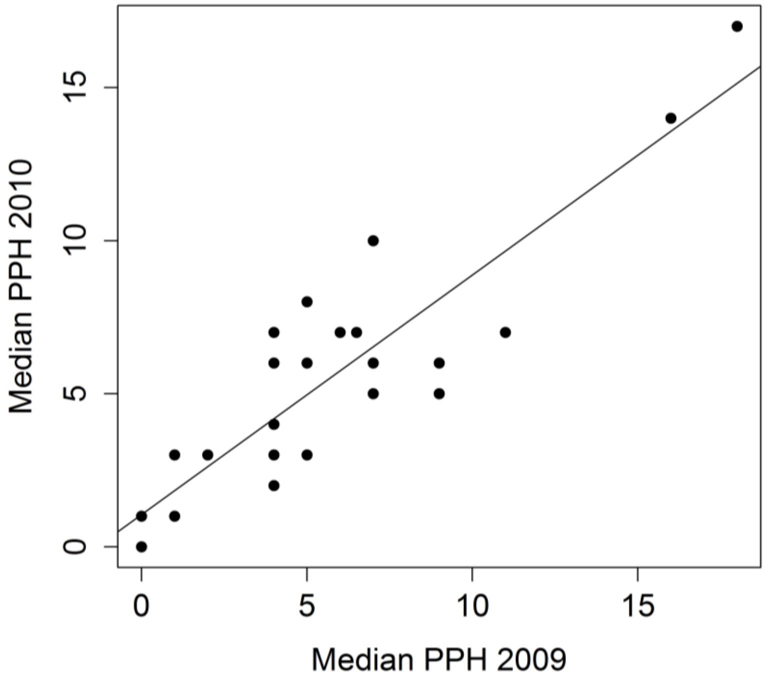


Figure 7. a) Spatial variation in median PPH detected on acoustic loggers deployed April to October in 2009 and 2010. Loggers less than 10 km from the coast are considered to be "coastal", while those further from coast are considered to be "offshore". b) Comparison of detection rates in 2009 and 2010 at the 30 sites where data were available from both years. Median PPH for the sites in both years is shown, along with the line of best fit from a linear model for illustration.

3.2 Model comparison with acoustic data

The CPODs used in this analysis were deployed for a median of 106 days. All of the metrics showed similar variation in the occurrence of porpoises across the Moray Firth between April and October, with lower detection rates in coastal regions (Table III). The four acoustic metrics (PPM, PPH, PPD and waiting time) derived from the CPOD data were compared with the predictions from the habitat association model for the cell in which they were deployed, using a Spearman's rank correlation (Table III). For both the full dataset and the reduced dataset, only PPH (Figure 7a) was significantly correlated with the model predictions. This metric was therefore preferred in further analyses. Comparison of data from the 30 sites where data were available in both 2009 and 2010 indicate that this spatial variation in median PPH was consistent between years (Spearman's rank correlation: $R = 0.834$, $S = 744$, $P < 0.001$; Figure 7b).

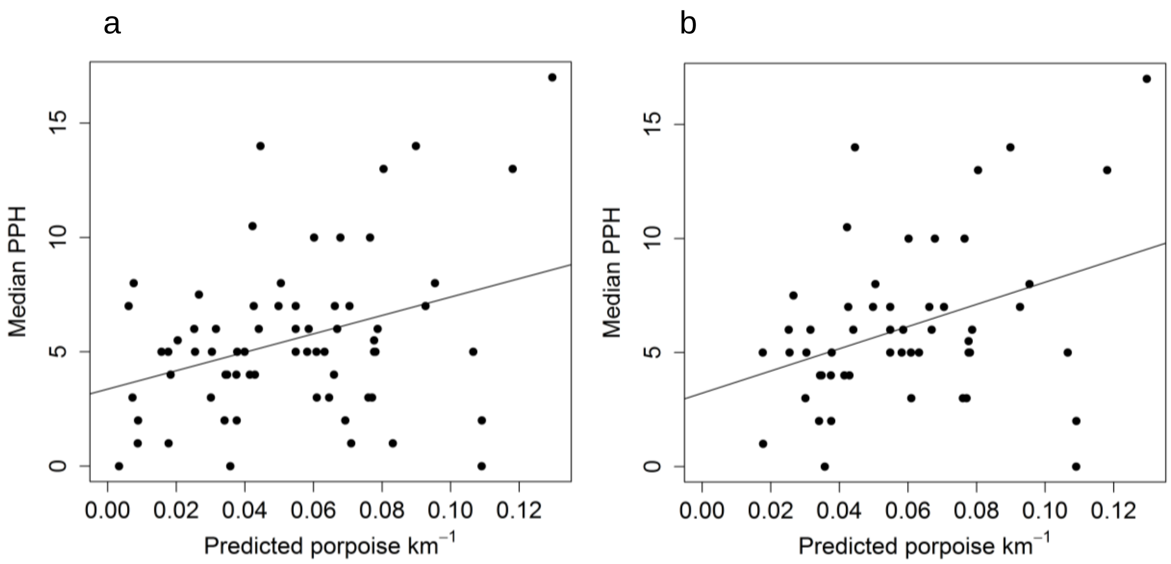


Figure 8. Plots of the predicted porpoises km^{-1} from the habitat association model, against the median hours porpoises were detected acoustically within the same cell. In a, data are included from all cells and in b only cells where the standard error of the predicted number of porpoises was less than 1.4 are included. The line of best fit from a linear model is plotted for illustration.

Table III. Comparison of CPOD metrics used in correlation analyses with the porpoise habitat association model, from 69 CPODs deployed from April to October of 2009 and 2010. PPD is the proportion of porpoise positive days, PPH is median porpoise positive hours per day, PPM is median porpoise positive minutes per day and waiting time is the median number of minutes between successive porpoise detections. Correlations are Spearman's rank, on the full and reduced datasets. Coastal CPOD locations are within 10 km of land.

	Coastal N=20			Offshore N=49				
Metric	Min	Max	Median	Min	Max	Median	Correlation (all data)	Correlation (SE<1.40)
PPD	0.07	1	0.84	0.21	1	0.99	R=0.148, S=46628, p=0.224	R=0.229, S=20233, p=0.096
PPH	0	8	2.5	0	17	6	R=0.239, S=41681, p=0.048	R=315, S=17973, p=0.020
PPM	0	60	8	0	178.5	29	R=0.169, S=45493, p=0.169	R=0.255, S=19534, p=0.062
Waiting time	19	6546	86	7	127	39	R=-0.054, S=57686, p=0.661	R=-0.164, S=30534, p=0.235

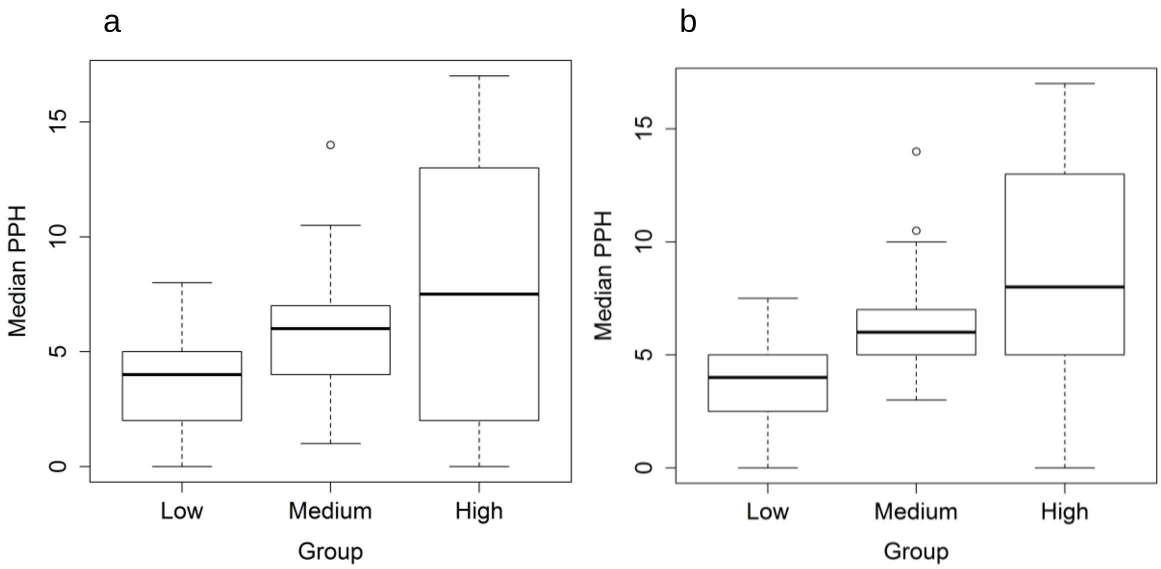


Figure 9. Boxplots of median number of detection positive hours from CPODs grouped by (a) predicted porpoise numbers for all cells in a habitat association model from visual survey data (N=69) and (b) for cells with predictions with standard errors less than 1.4 (N=54). The low group contains predicted porpoises km^{-1} values ranging from 0 to 0.039, the medium group contains values from 0.04 to 0.079 and the high group contains values from 0.08 to 0.13. Boxes represent the limits of the second and third quartile, while the bold central line represents the median. The range of the data (first and fourth quartiles) is shown by the dotted lines and outlying observations are represented by circles.

Using the pooled data from both years, there were significant differences in median PPH at sites within cells with low, medium and high predicted densities (Figure 9a; Kruskal Wallis, χ^2 = 7.979, d.f. = 2, P = 0.019). Post hoc analysis with Wilcoxon tests showed that there was a significant difference between the low and medium groups (W = 255.5, P = 0.008). Analysis of the reduced dataset (Figure 9b), also showed an overall significant effect of the groups (Kruskal Wallis, χ^2 = 10.810, d.f. = 2, P = 0.005). Post hoc analysis with Wilcoxon tests showed that there was a significant difference between the low and medium predicted relative abundance groups (W = 102.5, P = 0.002), and also between the low and high groups (W = 34.5, P = 0.035).

4. Discussion

Both habitat association modeling and static acoustic monitoring are well established methods of studying cetaceans (Bailey et al., 2010a, Bailey and Thompson, 2009), with habitat modeling providing good spatial coverage, and static acoustics providing good temporal coverage. Clearly, both techniques have weaknesses as well as strengths; visual survey are reliant on porpoises being visible at the surface, which is affected by sighting conditions, as well as the length of time they are under the water and acoustic data rely on animals echolocating in the vicinity of the devices to be detected. For harbour porpoise, the likelihood of this is high as they have been shown to produce high rates of echolocation clicks, particularly when foraging (Akamatsu et al., 2007, Linnenschmidt et al., 2013). Combining and comparing these complementary techniques in this study allowed us to determine whether spatial patterns observed in snapshot surveys were consistent over time.

The area covered by visual surveys was predominantly offshore, and the data used to build the habitat association model reflect this. Consequently, we were unable to determine whether harbour porpoises in the Moray Firth are associated with areas of high tidal strength or areas around islands which other studies have shown to be important (Embling et al., 2010, Marubini et al., 2009, Shucksmith et al., 2009). Instead, as expected from studies of other predators in this region (Greenstreet et al., 1998, Mudge and Crooke, 1986), we found high numbers of harbour porpoise sightings over areas such as the Smith Bank, which are likely to contain suitable habitat for potential prey such as sandeels (Hopkins, 1986, ICES, 2007). Sighting rates of harbour porpoise further inshore may also be affected by the presence of bottlenose dolphins *Tursiops truncatus* in coastal areas (Cheney et al., 2013, Culloch and Robinson, 2008), due to the risk of aggressive interactions between the two species (Ross and Wilson, 1996, Simon et al., 2010, Thompson et al., 2004).

The pattern of higher visual sightings in offshore areas remained clear even when effort was taken into account. We therefore modeled distribution based upon depth and the availability of sand and gravelly sand, a habitat that is likely to be favored by potential prey. Modeling species distribution using these static variables to some extent allowed us to avoid problems of trophic mis-match between environmental covariates and animal habitat preference that have been shown when using dynamic variables such as sea surface temperature and chlorophyll-*a* concentration (Grémillet et al., 2008). While such dynamic variables, which influence prey availability over tidal, diel and seasonal time-scales, can influence the distribution of both harbour porpoises and other marine top predators that they may interact or compete with (Scott et al., 2010), they generally do not directly influence marine predator distributions and instead tend to be used as proxies for prey availability.

Habitat association models allow species distribution to be predicted over large areas, but effort and sightings in even the highest density areas are typically low. In some studies in which dynamic variables have been included in habitat association models using visual survey data (e.g. Forney et al., 2012), survey effort has been divided into track line segments, but this requires then having to use interpolation and/or smoothing of the resulting model predictions to obtain values across the entire study area. This can introduce additional errors as it generally involves a distance-weighted interpolation that does not take into consideration the habitat characteristics in the areas not surveyed between the track lines. We instead used the approach of first gridding the data and then using the habitat characteristics of each grid cell to make predictions based on the habitat association model. Since our response variable was the sum of the number of porpoises for each survey, and these surveys generally occurred over several months, the values in each grid cell do not correspond to a single point in time. It was therefore not possible to match the number of sightings with a corresponding value for dynamic variables that would have changed over the course of the survey periods.

The standard error around predictions was particularly high in cells with habitat variables at the extremes of those surveyed, although the dataset used to build the model potentially contained additional sources of variability, such as the difference in numbers of observers used on surveys, observer experience, and the broad time scale over which surveys were carried out. In particular, we anticipated that sighting rates may differ between aerial and boat based surveys. However, the method of data collection did not contribute to a lower AIC value and we therefore pooled data from all surveys in the final model. While there may also have been some differences in sighting rates between the different boat based surveys, efforts to evaluate this were constrained by sample size and the limited spatial overlap between boat surveys. In practice, this between-survey variability should have been reduced by following standardized ESAS methodology and ensuring that most surveys were carried out in Beaufort sea state 3 or less.

The spatial pattern of acoustic detections also showed that porpoises were detected more often in offshore waters than in coastal areas (Table 3), with particularly high levels of detection around the Smith Bank area (Figure 7a). These acoustic data were collected at a resolution that allowed us to assess a range of metrics that have been used in previous studies (e.g. Brandt et al., 2011, Carstensen et al., 2006). When compared with habitat association model predictions, the strongest correlation was obtained using PPH as a metric. It is likely that PPD is too coarse to describe porpoise distribution since a porpoise need only be close to a device for a few seconds in a given day for it to record a positive value. Conversely, the broad scale of the habitat association model may not be captured when compared with finer scale variability in waiting times and PPM. Using PPH is also likely to reduce temporal auto-correlation, and previous studies using TPODs, the precursor to the CPOD, indicated that any impacts from slight differences in the sensitivity of individual devices were reduced when data were analyzed at the hour scale (Bailey et al., 2010a). Comparison of acoustic data collected in 2009 and 2010 suggest that this spatial variation in median PPH was consistent in the two years of our study (Figure 7b). Acoustic data from this broad suite of sites were not available earlier than 2009, but a three-year data set collected at a single site on the Smith Bank between 2005 and 2007 also found consistently high levels of detections in this offshore area (Thompson et al., 2010).

When using only visual survey data, a portion of the original survey data are commonly held back and used to validate habitat association models (Marubini et al., 2009), but this reduces the number of sightings available to build the model, which may reduce its power. It is therefore valuable to identify other sources of data which can be used to test model predictions. Embling (2007) compared the predicted core areas of porpoise abundance from models built on boat based survey sightings data with models built using passive acoustic detections. In that case, both visual and acoustic data were collected simultaneously from the same vessel. Models constructed with the two different types of data supported the use of different predictor variables, but the two models still predicted similar core areas (Embling, 2007). Sveegaard *et al*. (2011) took this one stage further, using independent data from mobile passive acoustic surveys to test the predictions of habitat association models built using tracking data from satellite tagged porpoises.

Our study also made use of independent data, which used different methods for detecting porpoises, to improve our understanding of spatial and temporal patterns in habitat association. Overall, the correlation between habitat model predictions and acoustic detections was significant, but not especially strong. However, some cells had large standard errors around the predictions, often because they had habitat variables that were at the extremes of those used to build the model or because a limited amount of survey effort had been concentrated on that particular combination of habitat variables. Further survey work could be targeted towards those habitats or water depths that were poorly represented to improve the precision of the model. Removing data associated with cells with high standard errors improved this fit, but the association was still relatively weak. This is likely to be partly due to differences in the type of data collected, with the acoustic data representing the presence or absence of porpoises within an hour, and visual surveys recording numbers of animals within an area. Nevertheless, at a coarser scale, where model predictions were grouped as low, medium and high porpoises km^{-1} for each cell, significant differences were evident in median PPH between the low group and the medium group (Figure 9). The high group was more variable, largely due to its smaller sample size, but when cells with a high standard error were excluded, this was also significantly different from the low group. Overall, many of the passive acoustic monitoring locations that had the highest rates of detection (Figure 7a) were within areas where the model predicted high numbers of porpoises km^{-1} (Figure 6). Similar analyses carried out by Sveegaard *et al*. (2011) showed that there were also more acoustic detections in the key areas predicted by telemetry data.

Overall, the integration of passive acoustic data and visual surveys can add value to the interpretation of the results of each. Visual survey techniques remain important where measures of absolute density are required (e.g. Hammond et al., 2002), and although there is an ongoing effort to establish methods for using C-POD data to estimate animal density (Marques et al., 2013), at present it is not possible to determine how variations in acoustic detections on these devices are influenced by the numbers of individuals present around the site. In this study we have demonstrated that passive acoustic techniques now offer the opportunity to collect data over broad temporal and spatial scales. Collection of year-round acoustic data is currently ongoing to assess how spatio-temporal variation in the occurrence of porpoises relates to a range of habitat characteristics, including both static and dynamic variables.

Characteristics of underwater noise from a 2-D seismic survey; comparison with noise propagation models used for marine mammal impact assessments.

Paul M. Thompson[1], Keith Needham[2] & Peter Ward[2]

[1] Lighthouse Field Station, Institute of Biological & Environmental Sciences, University of Aberdeen, Cromarty, IV 11 8YL, UK.

[2] Kongsberg Maritime Ltd, 11 The Briars, Waterberry Drive, Waterlooville, Hampshire, PO7 7YH, UK.

Abstract

Assessments of the potential impacts of anthropogenic noise on marine mammals require information on the characteristics and propagation of different noise sources. Here, we characterised the noise from air guns used in a 2-D seismic survey within the Moray Firth in 2011. We also measured received levels of noise at different distances from the seismic survey vessel, and compared these with predictions from acoustic propagation models used in environmental assessments. Measurements were made at 19 sites at distances of 1.6 – 61.8 km from the vessel and analysed using a broad suite of metrics used in bio-acoustic studies. Estimated peak to peak source levels were 242 - 253 dB re 1 µPa. Recordings at four sites (1.6 -14.2 km from source) were suitable for analyses of frequency spectra between 50 Hz and 96 kHz. These data confirmed that most energy occurred below 400 Hz, but that the signal contained high frequency components that would be detected by small cetaceans. Measured values showed a reasonable fit with two propagation models used within environmental assessments for the 2-D seismic survey. We tabulate summary data for each site, and provide measurements from each pulse in an electronic appendix, so that these data can be used to evaluate the performance of other propagation models.

1. Introduction

The potential impacts of anthropogenic noise on marine mammals are widely recognised, particularly for activities known to produce extremely loud source levels such as seismic exploration, navy sonar and pile-driving (Hildebrand, 2009, Southall et al., 2007, Tyack, 2008). However, effective management of these impacts is often constrained by limited understanding, first, of the characteristics and propagation of different anthropogenic noise sources and, second, of the physiological and behavioural consequences of different received levels of noise (Gordon et al., 2003, Southall et al., 2007).

Previous studies of the impacts of seismic surveys on marine mammals have focused on oil and gas development areas with important populations of baleen whales (Di Iorio and Clark, 2010, Gailey et al., 2007, Johnson et al., 2007), largely because the hearing ranges of these species overlap with the low frequencies that dominate signals from seismic air guns (Gordon et al., 2003, Southall et al., 2007). Nevertheless, observations around seismic surveys have also recorded responses from odontocete species with higher frequency hearing (Goold and Fish, 1998, Stone and Tasker, 2006, Weir, 2008). This suggests that there may also be important high frequency components within the air-gun noise signal. However, with rare exceptions (e.g. Breitzke et al., 2008), previous characterizations of noise from seismic air guns have been limited to low frequencies. Therefore, further information is required on noise levels within the higher frequencies most likely to impact small cetaceans.

Assessments of potential impacts upon marine mammals also require received levels at different locations to be estimated by modelling the propagation of underwater sound from the source. These levels can then be compared against criteria used to assess impacts upon different species (Breitzke and Bohlen, 2010, Erbe and Farmer, 2000, Southall et al., 2007). Various different propagation models have been used for these assessments, from simple spherical spreading models to more complex models based on the wave equation that take account of different boundary conditions. In addition, several companies have developed proprietary models to support Environmental Impact Assessments (EIAs) of pulsed noise sources such as seismic air guns and pile driving. This diversity of modelling approaches makes it difficult for regulators and other stakeholders to evaluate model predictions. This is partly because predictions from different propagation models have generally not been tested against field measurements, particularly in coastal environments. More crucially, there are no agreed noise exposure criteria against which to assess the likely disturbance of marine mammals from predicted levels of multiple pulsed noises (Southall et al., 2007). An alternative approach for predicting disturbance effects has drawn upon methods for assessing impacts of industrial noise upon humans. This uses information on each species' hearing ability to provide species-specific frequency weightings to assess the "perceived loudness" of a sound to the animal (Nedwell et al., 2007). This is similar to the approach used in cognitive studies of marine mammals that estimate "sensation levels", which represent received levels that are frequency-weighted according to the study species' hearing ability (e.g. Götz and Janik, 2010). However, Nedwell et al. (2007) extend this to suggest that animals will show strong avoidance reactions to levels at and above 90 dB_{ht} *(species)* and milder reactions to levels of 75 dB_{ht} *(species)* and above. Although widely used in many EIAs in the UK, this approach has remained controversial because these behavioural response criteria remain untested for marine mammals.

In 2011, the UK government gave consent for a series of 2-D seismic surveys within the Moray Firth, north-east Scotland. These coastal waters have a long history of oil exploration. However, due to the designation of a Special Area of Conservation (SAC) for bottlenose dolphins in the inner Moray Firth, more detailed assessments of the impacts of anthropogenic noise on these and other protected marine mammal populations were required in this area. This study formed part of a larger programme of work that assessed the responses of small cetaceans to these seismic surveys (Chapter 5 and 6).

This paper has two key aims. First, to characterise the noise from the air guns used for this 2-D seismic survey, including consideration of higher frequencies. Second, to measure received levels of noise at different distances from the seismic survey vessel, and compare with predictions from a variety of acoustic propagation models. Here, we draw a comparison with models used in the EIAs conducted prior to this survey programme being licenced. In addition, we provide a standard series of noise measurements at different distances from source to allow these to be used for future evaluation of alternative propagation models.

2. Methods

2.1 Study area & seismic survey characteristics

These measurements were made between 1st and 5th September 2011, during the first five days of a programme of 2-D seismic surveys across five sites within the Moray Firth. All noise recordings were made during the seismic survey of the first of these areas, Block 17/4b (Figure 1).

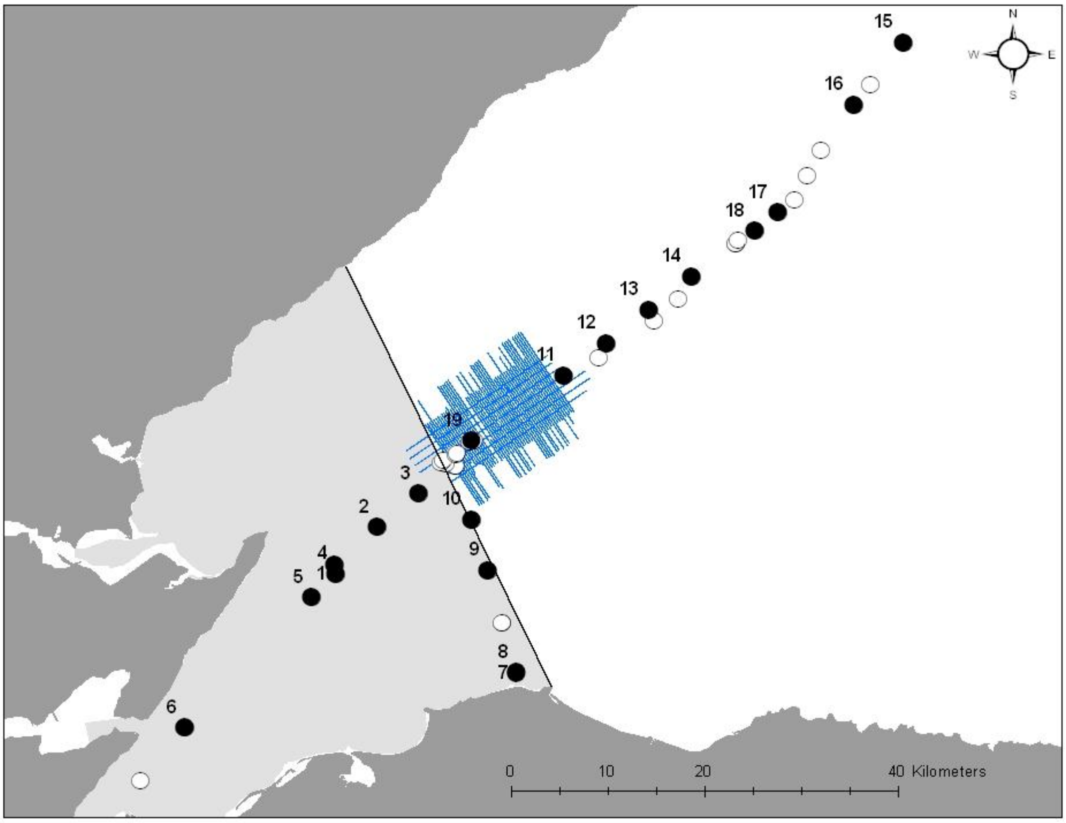


Figure 1. Position of seismic survey area in Block 17/4b and locations at which recording were made. Filled circles represent the 19 sites at which recordings were successfully made of the air-gun when it was operating at full power. Open circles represent sampling sites at which recordings could not be analysed due to clipping or other environmental noise. The area within the Moray Firth SAC is shaded grey.

Water depths in the Moray Firth shelve gradually from the coast to a maximum depth of 100 m. This seismic survey took place in water depths of around 40 m, over sea bed sediments that were predominantly gravel or sandy gravel with smaller patches of sand or gravelly sand (Wanless et al., 1997). Representative sound speeds for these waters in September were taken from the World Ocean Atlas (NOAA, 2009), and varied between 1498 m/s at the surface to 1489 m/s at 100 m depth (Electronic Appendix I).

Seismic surveys were conducted from MV Sea Surveyor, using a six air-gun phased array, operated by Gardline Geosurvey. Following guidelines to reduce potential impacts on marine mammals (JNCC, 2010), Marine Mammal Observers (MMO) onboard the vessel conducted visual and passive acoustic surveys of the area around the ship prior to the start of shooting to ensure that no marine mammals were within 500m of the guns. A soft start procedure was then initiated in which the volume of the discharge was gradually increased to its full operating volume of 470 cu inches over a 20 minute period. Most survey lines during our acoustic recording periods were 7km long, and took 75-80 minutes to complete, with a shot point interval of approximately 5-6 seconds. During each line turn, the volume of the gun discharge was reduced to 60 cu inches and the shot point interval increased to 4 minutes for approximately 30 minutes. A soft start was again initiated once the MMO had confirmed that the area was free of marine mammals.

2.2 Acoustic recording

Field recordings of underwater noise were made from an 11.5 m workboat. Our survey design aimed to obtain a series of 1-2 minute recordings at distances of between 500 m and 60 km from the seismic survey vessel. Recordings were collected along one transect that ran from the inner Moray Firth towards the seismic survey area, and a second that ran from the seismic area north-east into the outer Moray Firth. A third transect ran from the seismic survey area to the southern coast of the Moray Firth (Figure 1). Where possible, we aimed to make recordings at 5 km intervals along these transects, ensuring that these were obtained during a period when the air-gun was operating at full strength.

During each recording session, the recording vessel's engine and all electrical equipment other than that necessary for obtaining the noise measurements was turned off. The location of the recording vessel was obtained by GPS at the time of recording, and the position of the seismic survey vessel was later supplied by Gardline Geosurvey.

Over the side recordings were made using a RESON TC-4032 hydrophone that was suspended by a float system to reduce vertical displacement in the water and maintain the hydrophone at a depth of approximately 10m. The output from the hydrophone was fed via a RESON VP2000 conditioning amplifier into a National Instruments NI USB-6251 BNC 16-bit analogue to digital convertor. The signal was sampled continuously at 500,000 samples per second and recorded onto a laptop computer. Data were stored in separate one second contiguous datafiles, and the GPS position of the recording vessel was logged in the file header. The hydrophone, conditioning amplifier and analogue to digital convertor were all independently calibrated to international standards (Electronic Appendix II).

2.3 Assessment of source levels and frequency characteristics

Following the *SEG Standard for Specifying Marine Seismic Energy Source (Johnston et al., 1988)* we aimed to provide a quantitative description of this air-gun array's far-field signature, its amplitude spectrum and its cumulative energy flux, calculated back to 1 m. The air guns were arranged within a 15 m array but, as these typically interfere constructively (Caldwell and Dragoset, 2000), we considered the centre of the array (73 m behind the stern of the vessel) as a point source. Estimated source levels were based upon measurements at the closest distance at which recordings could be made without the hydrophone system being overloaded. A suitable series of measurements were made at ranges of 1587 to 1745 m on the 4th September and, from these, data at a mean range of 1662 m were used. The frequency spectrum of the signal at 1662 m was derived from the time-domain signal using a Fourier decomposition. Finally, back propagation using an underwater modelling approach to a reference point at 1 m was achieved by adding a frequency-dependent propagation loss to each spectral component.

As recommended by Madsen (2005) and Finneran et al. (2002), we estimated the amplitude spectrum and the cumulative energy flux of the noise pulses which marine mammals would be exposed to using 90% of the total energy. This measurement best reflects the sound that would be received by marine mammals in the area, as it integrates the characteristics of the source pulse from the air-gun and sub-bottom reflections (Breitzke et al., 2008). We took the average 1/3rd octave spectrum of the 90% energy region from the 20 closest recordings. To provide source spectral data we then back propagated this to an equivalent of 1 m from the seismic air gun using the ray-trace and parabolic models that incorporated the effects of local bathymetry and sediment (see section 2.5.1). Time- and site-specific environmental data were not available for back-propagating to estimate source levels for this process. Therefore publically available environmental databases containing spatially course data were used to obtain suitable sound speed profiles, bathymetry profiles and sediment geoacoustic data. Over the relatively short distances involved, uncertainty around these estimates is likely to be dominated by geoacoustic data, as geological charts indicate that there is considerable fine-scale variation in the nature of the seabed sediments, which range from sand to gravel. We therefore compared back-propagated estimates for both sand and gravel substrates, and used the more conservative, louder, figure for subsequent propagation modelling.

Measurements of the air-gun pulses were compared with measurements of underwater noise recorded between these pulses to identify system noise or other environmental noise sources. This was repeated at each of the 18 far-field recording sites, by measuring noise in the periods between 10 successive air-gun pulses.

2.4 Acoustic analysis

A number of different metrics are currently used for assessment of the potential impacts of anthropogenic noise. These include unweighted zero-peak or peak-to-peak pressure levels and, maximum received sound exposure levels (SEL) that may be calculated over different time periods or filtered according to the hearing characteristics of different functional hearing groups (Southall et al., 2007). In addition, dB_{ht} *(species)* values use the species audiograms to provide an assessment of received levels of sounds in the frequency bands which each species is most likely to hear (Nedwell et al., 2007).

Given the intention of this study to provide baseline information on the characteristics and propagation of air-gun noise, we analysed recordings so that noise characteristics could be presented using all of the metrics commonly used in studies of this kind. These were calculated as follows.

2.4.1 Unweighted zero-peak pressure levels:

This was calculated as the peak positive pressure during each air-gun pulse, using a standard reference pressure of 1µPa:

$$dB_{0-Peak} = 20 \cdot \log\left(\frac{\mathrm{P_{max}}}{1\mu\mathrm{Pa}}\right)$$

2.4.2 Unweighted peak-to-peak pressure level:

Calculated as the difference between the maximum and minimum pressure during each air-gun pulse, also using a standard reference pressure of 1µPa:

$$dB_{Peak-Peak} = 20 \cdot \log\left(\frac{\mathrm{P_{max}} - \mathrm{P_{min}}}{1\mu\mathrm{Pa}}\right)$$

2.4.3 90% energy duration (s):

The cumulative sum of the square of pressures begins as a low plateau in the region before the air-gun blast, rising rapidly through the air-gun blast and then plateauing to a high value in the region immediately following the blast. The 90% energy duration is the length of the period, in seconds, from 5% up the pre-blast plateau to 5% down from the post-blast plateau (Figure 2a).

2.4.4 $F_{95\%}$ (Hz):

The energy flux spectral density (see Breitzke et al., 2008) was calculated in a similar way to the 90% energy duration. A cumulative sum of the square of the pressure contribution in the frequency domain was performed from 0Hz upwards. $F_{95\%}$ was the frequency below which 95% of energy occurs (Figure 2b).

2.4.5 Unweighted sound exposure level (SEL):

These were calculated using a slightly modified form of the SEL described in Southall et al. (2007). Here, we followed the approach used by Lucke et al. (2009), and calculated a cumulative value for the 90% energy duration (see 2.4.3), where t_5 is the time of a 5% increase in energy for the total pulse energy and t_{95} is the time of 95% of the total energy of the pulse.

$$SEL = 10 \cdot \log \frac{\int_{t_5}^{t_{95}} p^2\,(t)dt}{1\mu\mathrm{Pa}^2}$$

Rather than calculating across all noise events as in Southall et al. (2007) , we provided SEL for single air-gun blasts. These can subsequently be used to calculate a cumulative value if required.

2.4.6 Unweighted combined third octave level (dB) (90%):

Individual third octave band levels within the 90% energy duration were calculated for frequencies from 10 Hz up to 250 kHz.

$$L_{Individual\ third\ octave\ band\ level} = 20 \cdot \log \frac{\sum_{i=1}^{Bandwidth} \mathrm{P_i}}{1\mu\mathrm{Pa}}$$

These were then combined according to Gelfand (2009):

$$L_{Combined\ third\ octave} = 10 \cdot \log \sum_{i=1}^{Third\ octave\ bands} 10^{\frac{\mathrm{L_i}}{10}}$$

2.4.7 Unweighted L_{rms} (dB):

L_{rms} was calculated as the root mean square over the 90% duration of the air-gun pulse, as outlined in Lucke et al. (2009), using a standard reference pressure of 1µPa:

$$L_{rms} = 20 \cdot \log\left(\frac{\mathrm{P_{rms}}}{1\mu\mathrm{Pa}}\right)$$

2.4.8 M weighted sound exposure levels (SEL):

M-weighted SELs were calculated according to Southall et al. (2007) for the four different functional groups of marine mammals; high frequency cetaceans (M_{hf}), mid frequency cetaceans (M_{mf}), low frequency cetaceans (M_{lf}) and pinnipeds in water (M_{pw}). As for unweighted SELs, we provide SEL for single air-gun blasts.

2.4.9 dB_{ht} (species):

Following the approach used by Nedwell et al. (2007), dB_{ht} (*species*) values were calculated for three key marine mammal species from the Moray Firth; bottlenose dolphins (dB_{ht} (*Tursiops*)), harbour porpoise (dB_{ht} (*Phoceona*)) and harbour seals (dB_{ht} (*Phoca*)). These values were calculated as the sum of all measured pressure contributions during the period defined by the 90% energy duration, filtered according to the species specific audiograms. This was accomplished by a point by point subtraction of the frequency dependent hearing threshold from the frequency spectrum for the 90% period, and summing those levels that exceed the hearing threshold. Available audiograms have been reviewed in Nedwell et al. (2004). Here, we based our calculations on Johnson (1967) for bottlenose dolphins, Kastelein et al. (2002) for harbour porpoises and Mohl (1968) for harbour seals. The data used are provided in Electronic Appendix III.

2.5 Propagation modelling

We compared our measured noise levels with the results of two different modelling approaches. The first used a combination of parabolic (http://cmst.curtin.edu.au/products/actoolbox.cfm/) and ray-trace models (http://oalib.hlsresearch.com/Rays/) that are publicly available, while the second used Subacoustech Ltd's proprietary model INSPIRE (http://www.subacoustech.com/index.php/modelling/inspire/). This model has been used regularly in the UK in noise assessments to determine the impacts of seismic surveys, including the EIA for the survey in Block 17/4b.

2.5.1 RAM & Bellhop models

Calculations of propagated, underwater sound fields were based upon the wave equation with appropriate boundary conditions (see for example Brekhovskikh and Lysanov, 2003). Different boundary conditions lead to one or other solutions to the wave equation, giving rise to a number of classes of models that are based on ray theory, normal mode, parabolic equation and full-field techniques (Buckingham, 1992, Etter, 2003). Each set of solutions is valid over a limited range of frequencies, and depths. For instance, ray theory is most suited to short ranges and high frequencies while normal mode and parabolic equation are applied to long ranges and low frequencies.

To cover the broad range of frequencies emitted by a seismic air-gun array, we therefore used more than one type of model to cover the whole frequency range of interest. At low frequencies, propagation modelling was carried out using the model RAM (Collins, 1993). This model used the fully range dependent parabolic equation code for fluid seabeds (de Milou et al., 2004, Jensen et al., 1994). The frequency at which RAM becomes less efficient is dependent on the wavelength of the signal and the water depth in which the source is located. For shallow water depths of around 50 m, the changeover frequency occurs around 500 Hz. At this and higher frequencies, the ray-trace model BELLHOP (Porter and Bucker, 1987) was used.

We modelled the propagation of seismic noise radiating out to the south-west, south and north-east of the survey area, and estimated received levels at each of our 18 far-field recording sites (see Figure 1). At each site, we identified the GPS locations of the seismic survey and recording vessel at the start, end and mid-point of the recordings. This provided three different paths between the noise source and the recording vessel for each recording site, resulting in three estimates of received noise levels at each site. Bathymetric profiles along each of the paths were obtained using SeaZone data within ARC GIS v8. Our measurements of source levels and spectral data (see results) were used as input for the model. Received levels of underwater sound were then calculated by applying the frequency dependent transmission loss for each third octave band centre frequency from 10 Hz to 63 kHz. Beyond the 63 kHz 3rd octave band, the signal contained high levels of background noise which when back propagated swamped the air-gun signal.

2.5.2 INSPIRE model

The propagation of the broadband noise resulting from the seismic survey operations was also modelled for us by Subacoustech Ltd using INSPIRE. Based upon information on air-gun size, the model predicts the most probable source levels and frequency based on a database of calibrated recordings from previous seismic surveys. Detailed information on the structure of this proprietary model are not available, but Subacoustech Ltd indicate that INSPIRE conservatively predicts propagation through relatively shallow coastal environments such as those in the Moray Firth. Data on bathymetry and sediment type were taken from SeaZone to predict propagation of noise along a series of transects that radiated out from the source location. Typically, results are presented as a series of contours around the source corresponding to different received levels. Here, we contracted Subacoustech to provide data on predicted received levels at different distances along the three recording transects used in our study (Figure 1). This was based upon the air-gun capacity and a mean source location (57.951079 °, -3.423115 ° (WGS84)) that was calculated from the positions of the seismic vessel during our field recording period.

3. Results

3.1 Air-gun noise characteristics and source levels

The far-field signature and amplitude spectrum of air-gun noise recorded at 1662 m are shown in Figure 2. Using these recordings, source levels were estimated to vary from 242 - 253 dB re 1 µ Pa, depending upon whether it was assumed that sand or gravel sediments dominated the area. The resulting source spectral data, in 1/3rd octave band levels, are shown in Figure 3. Comparison of these data with available published literature indicate that the estimated source levels for this air-gun array are in line with the general pattern of source levels increasing with array capacity (Figure 4).

3.2 Variation in received levels in relation to distance from source

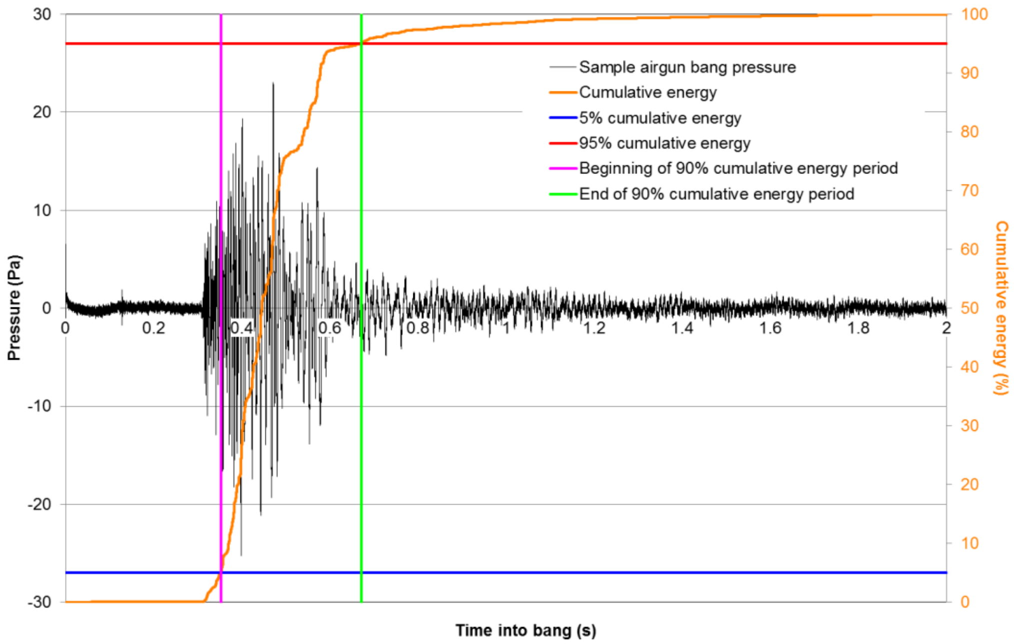
Recordings of the seismic air guns at full power were available from the near-field site at 1662 m, and at 18 different far-field sites which varied from 5 to 60 km from source (Table 1). An average of 32 air-gun pulses (range 5 to 105) were recorded at each site.

At each site, measurements of air-gun pulses were compared with the background noise recorded between pulses to explore how signal to noise ratios varied with distance from source. The resulting data from sites approximately 5km, 10km, 20km and 45 km to the south west of the seismic vessel are shown in Figure 5, and data from all 18 far-field sites are provided in Electronic Appendix IV. Typically, low frequency noise from the air guns (< 500Hz) was at least 40 dB greater than background noise. However, this difference decreased with increasing frequency, and this effect became stronger further from source (Figure 5).

The importance of the higher frequency components within the air-gun noise were therefore assessed using samples obtained from three sites (Table 1: sites 2, 3 and 11) where the signal remained at least 20 dB above background levels between 50 Hz and 96 kHz (eg Figure 5 a & 5 b). Analysis of 141 pulses recorded at these sites highlight that most of the energy from the air guns was below 400 Hz (Figure 6).

Tables 2, 3 and 4 present average measurements of received noise levels at all 19 of the recording sites using the different metrics described in the methods section. Data for each of the individual air-gun pulses recorded at each of these sites are available in Electronic Appendix V).

a)



b)

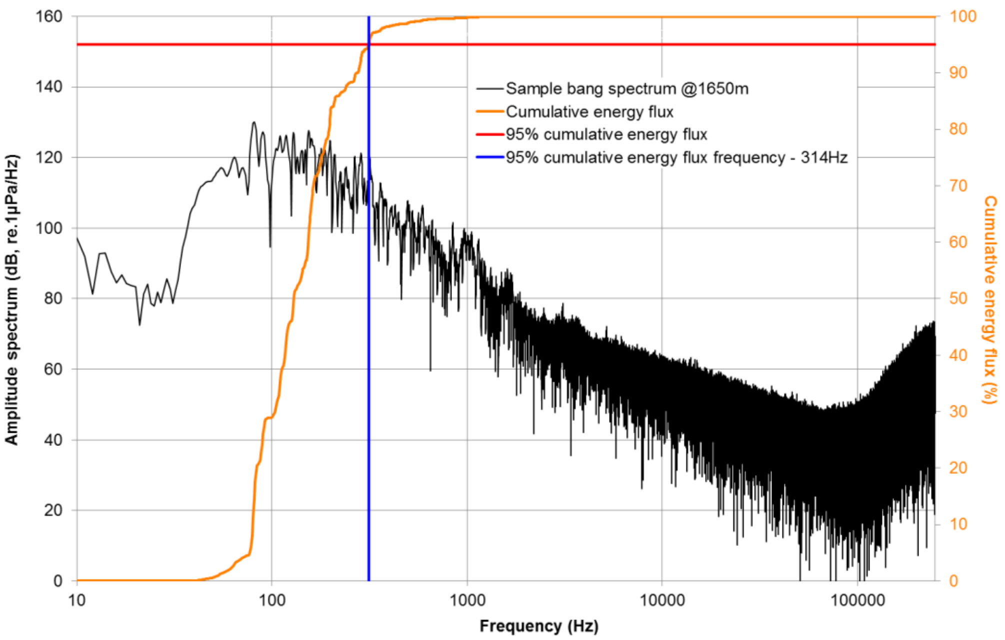


Figure 2. a) waveform of an air-gun pulse (black) measured at site 19, overlain by the cumulative energy sum plot (orange),showing the beginning and end of the 90% energy window that was used for measurements of the signal. b) amplitude spectrum for the 90% energy window.

Table 1. Details of each of the recording locations at which measurements of seismic air-gun noise could be made (shown as solid circles in Figure 1), with information on the mean range to the seismic vessel and the number of pulses (n) measured at each site.

Site	Date	Time	Recording vessel		Air Gun		Mean range (m)	n
			Latitude	Longitude	Latitude	Longitude		
1	03/09/11	10.49	57.836368	-3.655258	57.965067	-3.496666	17125	11
2	03/09/11	11.24	57.872119	-3.581419	57.931734	-3.453568	10062	21
3	03/09/11	11.55	57.903372	-3.509495	57.901585	-3.414846	5603	21
4	04/09/11	19.22	57.828011	-3.653235	57.971482	-3.463776	19512	36
5	04/09/11	19.46	57.805960	-3.694136	57.948684	-3.434517	22104	21
6	05/09/11	7.22	57.683853	-3.912542	57.948862	-3.337970	45065	27
7	02/09/11	10.09	57.736812	-3.337445	57.940547	-3.459718	23809	97
8	02/09/11	10.27	57.737887	-3.337465	57.922078	-3.436055	21321	105
9	02/09/11	12.23	57.832567	-3.387941	57.945967	-3.405839	12668	22
10	02/09/11	12.56	57.879740	-3.417377	57.977734	-3.446827	11047	23
11	03/09/11	13.38	58.013830	-3.256851	57.961266	-3.476686	14240	99
12	03/09/11	15.08	58.044159	-3.183516	57.965763	-3.492243	20193	23
13	03/09/11	15.42	58.074953	-3.107527	57.933100	-3.450291	25653	23
14	03/09/11	16.18	58.106142	-3.032855	57.898380	-3.405654	31913	22
15	04/09/11	9.49	58.322753	-2.658762	57.973129	-3.476159	61810	5
16	04/09/11	10.43	58.265216	-2.748034	57.919547	-3.412582	54859	5
17	04/09/11	13.09	58.165588	-2.882380	57.989944	-3.442059	38309	22
18	04/09/11	13.28	58.148452	-2.922715	58.007931	-3.464925	35542	14
19	04/09/11	17.13	57.952672	-3.417059	57.957452	-3.395088	1662	20

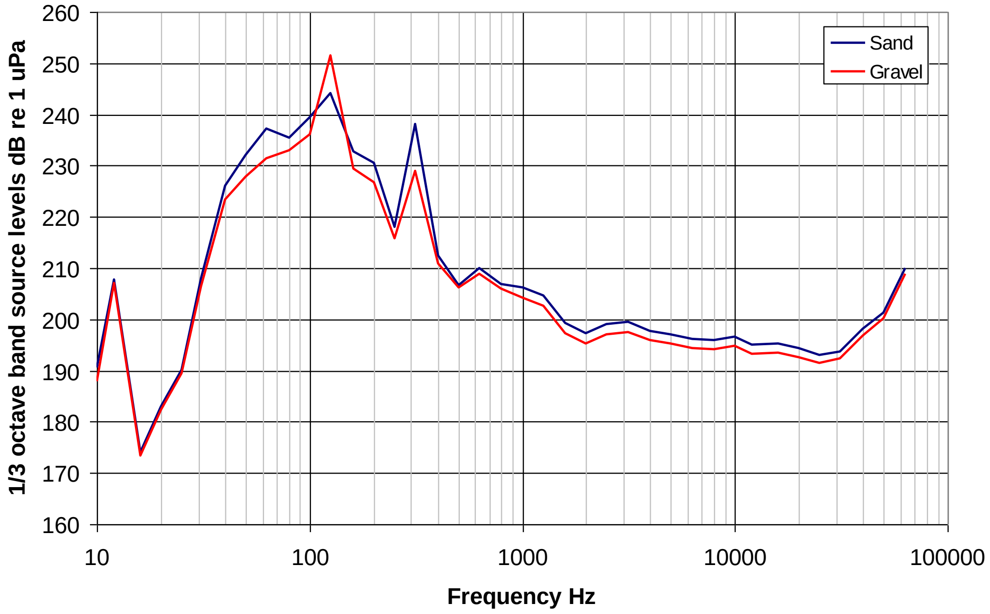


Figure 3. 1/3rd octave band source levels for air-gun blasts based upon measurements made at 1660 m and back propagated version to 1 m equivalent source level using sand (blue line) and gravel (red line) conditions

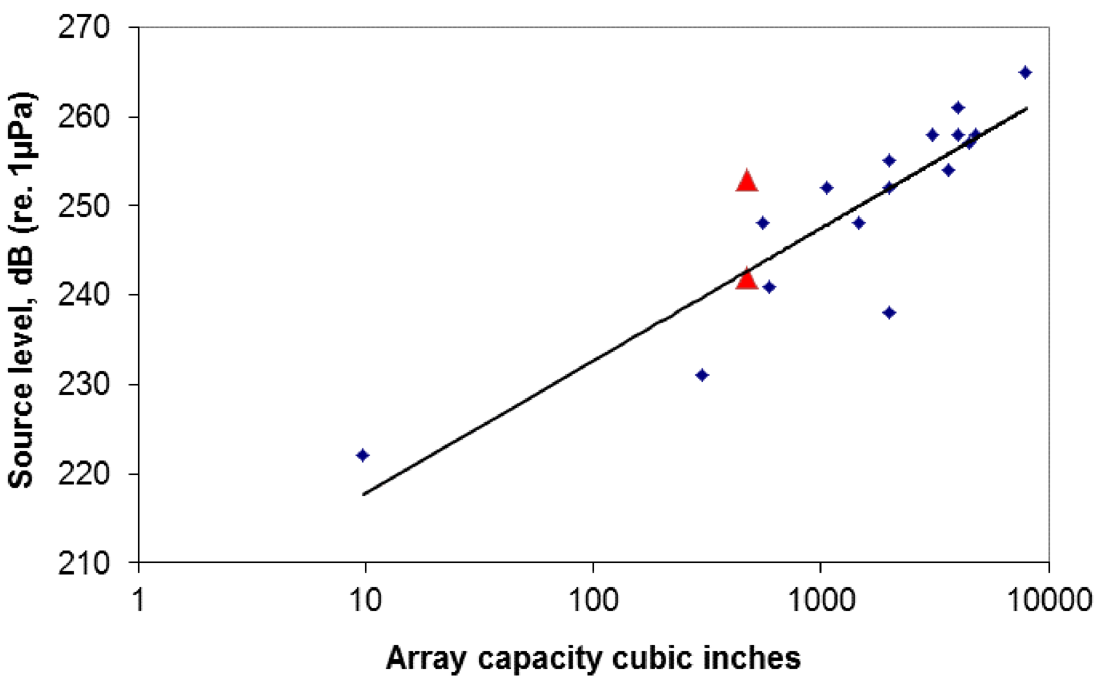


Figure 4 Relationship of air-gun source level to air-gun capacity from published data (blue diamonds) compared with Moray Firth array (red triangles). Published data are collated in Richardson et al. (1995).

Table 2. Mean values for measurements of the 90% energy window (see Figure 2) within seismic air-gun pulses recorded at each of the locations detailed in Table 1. ***0-Pk (dB)*** *= unweighted zero-peak SPL;* ***Pk-Pk(dB)*** *= unweighted peak-peak SPL;* ***SEL (dB)*** *= unweighted sound exposure level;* ***Durn 90% (s)*** *= duration of 90% window in secs;* ***$F_{95\%}$ (Hz)*** *the frequency below which 95% of energy occurs* ***; Combined (dB)*** *= Unweighted combined third octave levels;* ***L_{rms} (dB) =*** *unweighted root mean square over the 90% energy window*

Site	Range (m)	n	0-Pk (dB)		Pk-Pk(dB)		SEL (dB)		Durn 90% (s)		$F_{95\%}$ (Hz)		Combined (dB)		L_{rms} (dB)	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
19	1662	20	179.7	0.64	185.7	0.68	162.2	0.94	0.12	0.01	196.2	22.0	210.5	1.28	171.6	0.64
3	5603	21	157.9	1.32	164.1	1.21	143.3	0.65	0.69	0.10	230.2	9.3	175.4	1.77	144.9	1.17
2	10062	21	154.5	0.58	160.8	0.57	142.0	0.30	0.70	0.04	263.7	19.2	174.3	1.04	143.5	0.50
10	11047	23	153.5	0.52	158.5	0.40	136.6	0.28	0.37	0.03	370.1	27.4	175.4	1.08	141.0	0.54
9	12668	22	152.7	1.20	158.7	1.37	136.2	0.65	0.53	0.14	372.9	30.6	171.8	2.59	139.1	1.71
11	14240	99	159.5	0.70	165.4	0.83	145.3	1.47	0.62	0.14	330.1	18.1	179.2	2.62	147.5	2.04
1	17125	11	149.6	1.24	154.6	0.75	132.8	0.71	0.75	0.16	307.0	9.3	165.1	2.40	134.2	1.14
4	19512	36	150.2	0.75	155.9	0.70	134.7	0.78	0.48	0.17	238.4	24.5	170.2	2.73	138.1	1.40
12	20193	23	154.2	0.68	160.0	0.61	141.0	0.77	0.56	0.04	320.2	13.5	175.4	1.18	143.5	0.94
8	21321	105	149.5	0.79	155.7	0.83	133.2	0.62	0.40	0.09	322.1	21.0	171.3	1.86	137.3	1.03
5	22104	21	146.1	1.90	152.2	1.92	130.6	1.48	0.33	0.15	345.0	17.3	171.5	3.65	135.6	2.40
7	23809	97	150.1	1.52	156.9	1.49	134.8	1.16	0.33	0.08	313.4	24.4	174.5	1.73	139.7	1.14
13	25653	23	153.6	0.65	159.8	0.47	141.0	1.05	0.64	0.02	344.6	20.0	174.6	0.61	142.9	0.98
14	31913	22	149.4	0.72	155.6	0.58	137.8	0.54	0.76	0.03	275.8	11.8	168.9	0.72	138.9	0.46
18	35542	14	151.1	0.84	156.7	0.57	138.2	0.36	0.76	0.02	319.7	9.8	169.9	0.65	139.4	0.42
17	38309	22	150.2	0.69	156.0	0.73	137.8	0.46	0.90	0.03	302.1	12.3	167.7	0.56	138.3	0.45
6	45065	27	140.4	0.77	146.3	0.76	123.7	0.45	0.49	0.18	402.6	25.6	161.4	3.20	127.1	1.86
16	54859	5	135.3	1.11	141.8	1.66	122.1	1.51	0.70	0.28	255.0	24.1	156.0	3.21	124.0	1.61
15	61810	5	139.4	0.60	145.6	0.63	124.5	0.45	0.61	0.26	393.0	9.1	162.0	4.75	127.3	2.44

Table 3. *Mean values for weighted sound exposure levels (SEL)for each of Southall et al's (2007) functional hearing groups at each of the locations detailed in Table 1. M_{hf} = high frequency cetaceans; M_{mf} = mid frequency cetaceans; M_{lf} = low frequency cetaceans; M_{pw} = pinnipeds in water. Measurements were taken within the 90% energy window within seismic air-gun pulses (see Figure 2), and represent sound exposure levels for single pulses.*

Site	Range	n	M_{hf} SEL (dB)		M_{lf} SEL (dB)		M_{mf} SEL (dB)		M_{pw} SEL (dB)	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
19	1662	20	150.78	1.98	162.11	0.95	153.63	1.83	158.45	1.46
3	5603	21	133.66	0.80	143.20	0.66	136.21	0.78	140.32	0.70
2	10062	21	132.46	0.56	141.95	0.30	134.88	0.49	138.97	0.38
10	11047	23	129.13	0.34	136.57	0.29	131.06	0.32	134.32	0.29
9	12668	22	129.81	0.84	136.18	0.66	131.61	0.82	134.42	0.74
11	14240	99	138.48	1.16	145.29	1.47	140.47	1.23	143.48	1.38
1	17125	11	125.45	0.74	132.69	0.69	127.44	0.73	130.59	0.70
4	19512	36	124.68	1.19	134.61	0.77	127.31	1.06	131.68	0.86
12	20193	23	134.04	0.82	141.01	0.77	136.09	0.81	139.21	0.79
8	21321	105	125.26	0.50	133.19	0.62	127.27	0.49	130.68	0.52
5	22104	21	124.06	1.38	130.52	1.50	125.86	1.39	128.73	1.45
7	23809	97	127.09	1.19	134.74	1.15	129.12	1.15	132.43	1.11
13	25653	23	134.05	0.81	140.96	1.05	136.06	0.89	139.15	1.01
14	31913	22	129.28	0.55	137.72	0.54	131.58	0.53	135.26	0.52
18	35542	14	130.99	0.53	138.14	0.36	133.05	0.50	136.22	0.43
17	38309	22	129.87	0.55	137.78	0.46	132.06	0.51	135.54	0.47
6	45065	27	119.66	0.55	123.71	0.44	121.10	0.51	122.94	0.46
16	54859	5	113.60	1.21	122.01	1.40	115.90	1.10	119.49	0.99
15	61810	5	119.16	0.28	124.52	0.45	120.82	0.28	123.22	0.34

Table 4 Mean values for dB $_{ht}$ (species) weighted sound exposure levels for bottlenose dolphins (dB$_{ht}$ (Tursiops)), harbour porpoise (dB$_{ht}$ (Phoceona)) and harbour seals (dB$_{ht}$ (Phoca)) at each of the locations detailed in Table 1.

Site	Range	n	dB$_{ht}$ (Tursiops)		dB$_{ht}$ (Phoceona)		dB$_{ht}$ (Phoca)	
			Mean	SD	Mean	SD	Mean	SD
19	1662	20	100.79	0.64	107.36	0.54	92.48	0.78
3	5603	21	53.64	2.87	63.74	4.72	47.04	5.08
2	10062	21	54.48	1.70	64.07	4.30	48.24	5.29
10	11047	23	71.08	4.44	81.92	2.81	59.34	2.19
9	12668	22	65.28	5.12	79.38	3.03	51.12	6.54
11	14240	99	63.31	1.19	69.91	1.96	46.41	6.45
1	17125	11	49.54	5.76	67.01	4.51	52.72	8.71
4	19512	36	74.02	2.79	84.29	1.65	45.72	12.42
12	20193	23	58.65	3.97	61.79	6.50	29.05	7.61
8	21321	105	59.92	2.99	75.62	1.31	53.05	1.77
5	22104	21	78.00	2.00	88.96	3.71	41.30	4.54
7	23809	97	66.09	2.75	80.48	5.88	54.12	2.10
13	25653	23	60.55	0.55	72.75	1.40	50.96	0.66
14	31913	22	58.13	4.61	75.49	3.17	51.51	0.81
18	35542	14	54.32	0.93	55.84	2.39	10.22	15.40
17	38309	22	59.10	4.26	75.67	3.30	19.44	1.66
6	45065	27	75.35	3.64	85.47	2.44	39.80	5.15
16	54859	5	26.53	14.91	56.55	7.03	17.05	13.12
15	61810	5	70.13	6.50	80.31	4.46	59.69	2.74

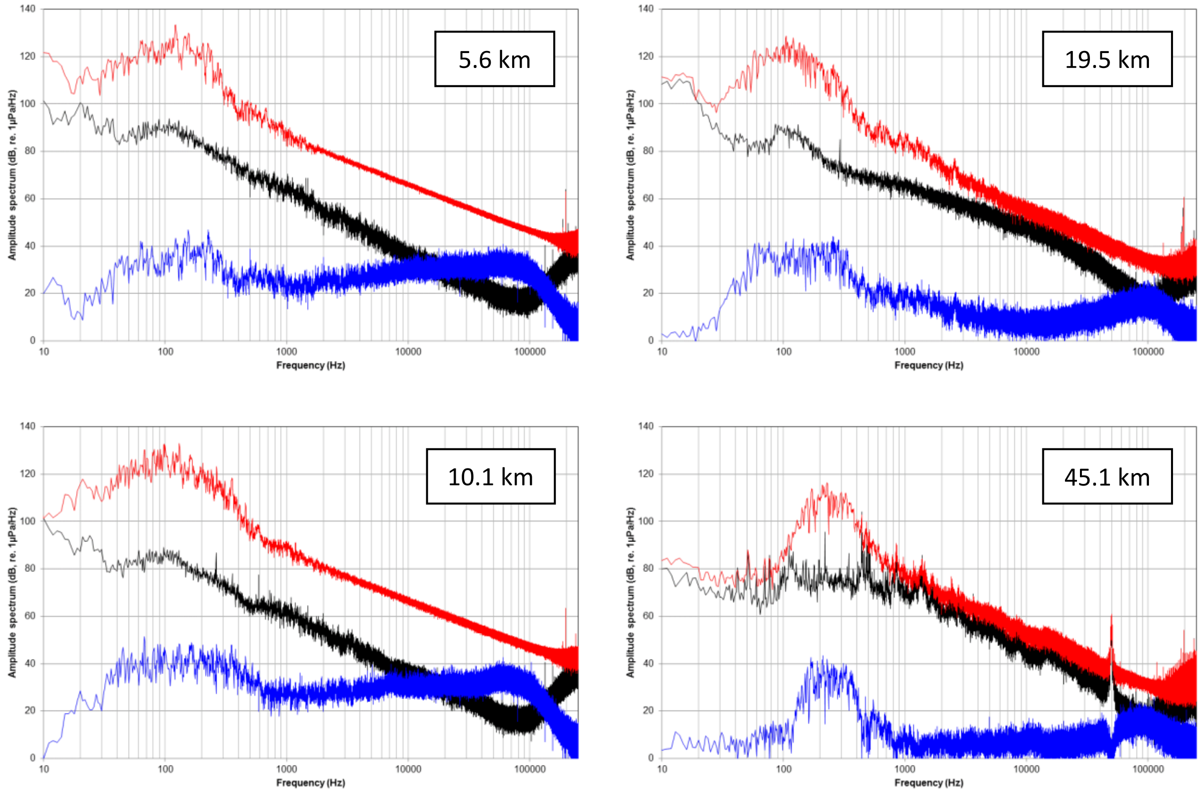


Figure 5. Examples of amplitude spectra for recordings during the 90% energy window of seismic pulses (red) and background noise from the inter-pulse interval (black) with the resulting signal to noise ratio shown in blue. Data are from sites 2, 3, 4 and 6 (see Table 1)

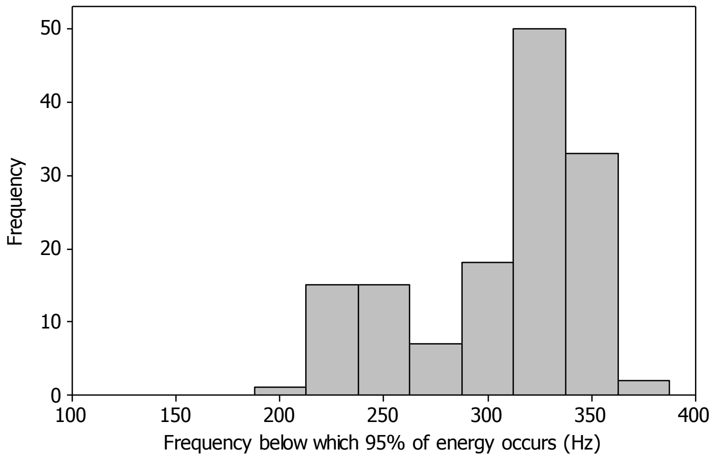


*Figure 6. Frequency distribution of values for **F $_{95\%}$,** the frequency below which 95% of energy occurs. Data are from measurements at those sites (2, 3, 11 & 19) where high frequency measurements could be made.*

3.3 Comparison of modelled and measured received levels

Using the RAM and Bellhop models, measured and modelled third octave SPL showed similar variation with distance from source (Figure 7). Mean measurements at each of the sampling sites were typically within a few dB of modelled values (mean = 3.15 dB, SD = 2.23, n = 18), and the maximum difference was 7.8 dB.

Figure 8 shows predicted changes in received levels of dB $_{ht}$ *(Tursiops)* dB $_{ht}$ *(Phocoena)* and dB $_{ht}$ *(Phoca)* along each of the three transects. These can be compared with weighted measurements using these metrics at the near-field site and three far-field sites where signal to noise ratios were sufficient to provide robust measurements across these species hearing range. Close to source, higher levels were observed than those predicted using INSPIRE, but at greater distances the predictions were all conservative (Figure 8).

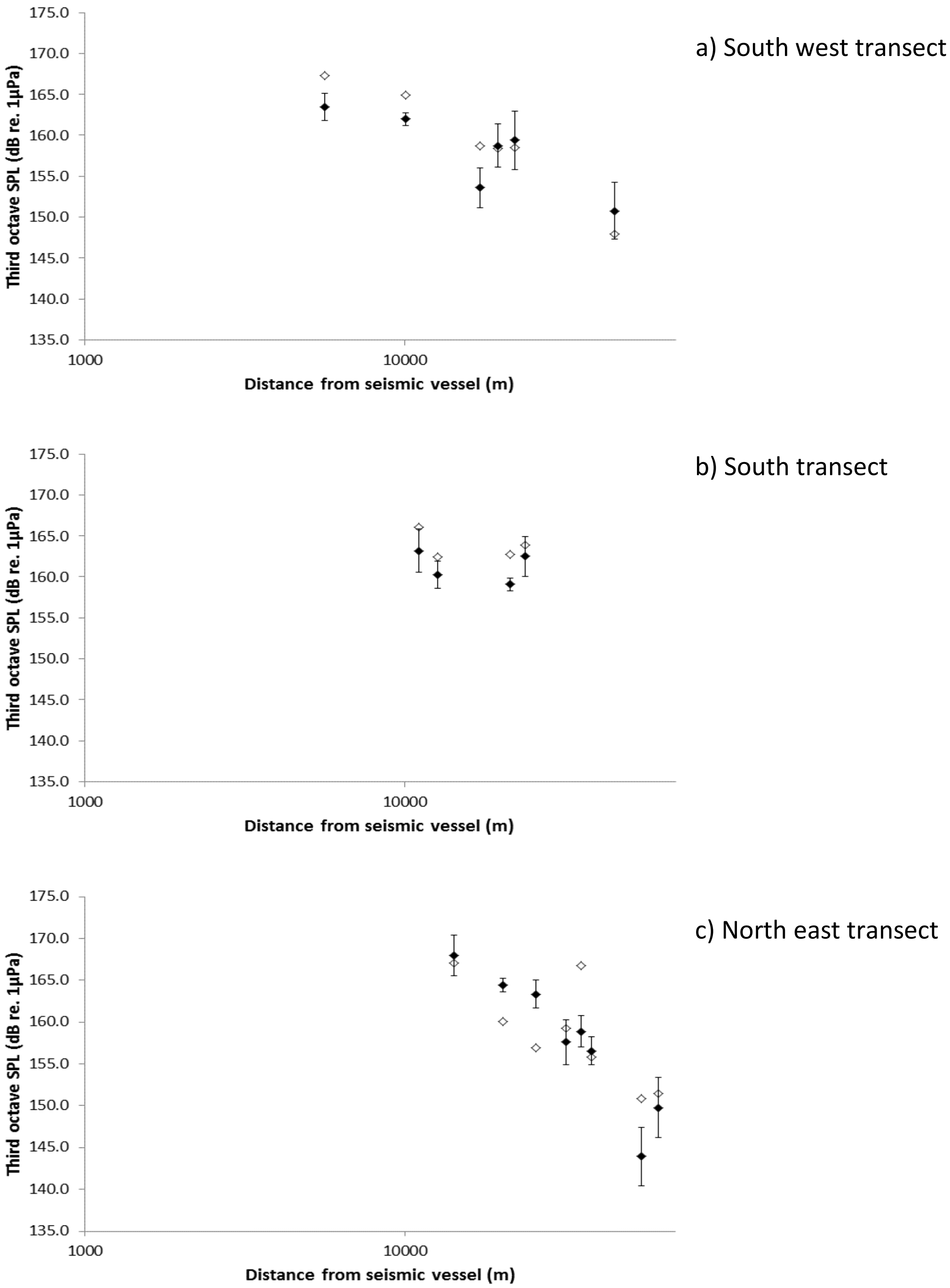


Figure 7. Variation in mean measured (solid diamonds) and modelled (open diamonds) values for received total third octave sound pressure level at different distances from the seismic vessel. Sample sizes for measure values varied between sites (see Table 1) and error bars represent 1 SD. Although modelled values are based on three different estimates at each site, standard deviations are not shown because they typically occur within the symbol.

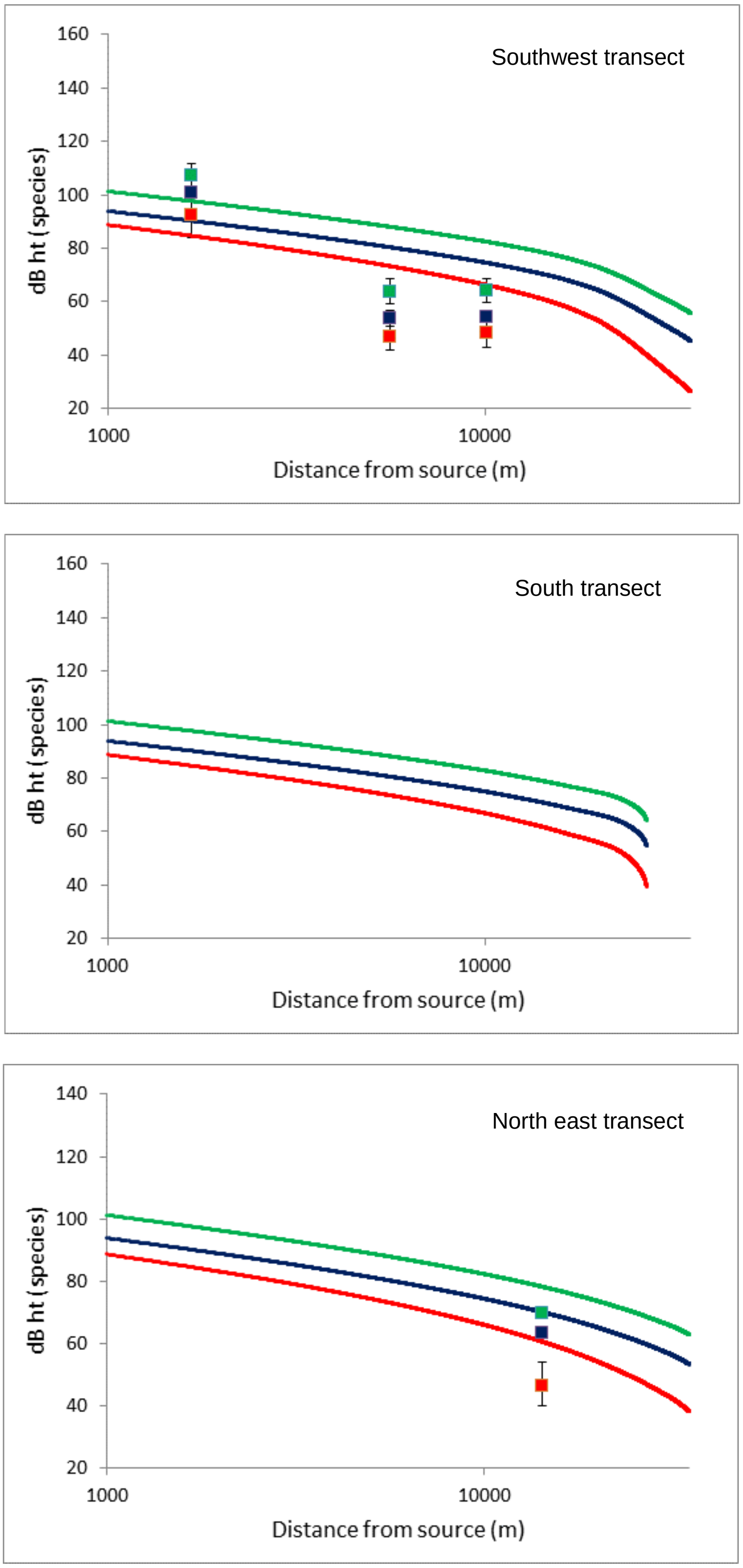


Figure 8. INSPIRE Predictions (lines) compared with measured values (squares) for harbour porpoise (green), bottlenose dolphin (blue) and harbour seal (red).

4. Discussion

To understand how seismic survey activity may influence marine mammal behaviour, air-gun noise must be characterized and quantified in ways that reflect how these sounds will be perceived by the animals (Madsen et al., 2006). Given the hearing ranges of marine mammals (Southall et al., 2007) and the large distances that low frequency air-gun noise may travel (Nieukirk et al., 2004), this requires broad-band measurements to be made at a range of distances from source, ideally across the full range of habitats and water depths in which marine mammals may be exposed to seismic survey noise. Here, we measured broad band noise at distances of 1.5 km to 61.8 km from a commercial 2-D seismic survey that was conducted over coastal waters of <50 m depth. Previously, the only studies to include broad band measurements above 22 kHz have been detailed characterisations of seismic sources used on research vessels (Breitzke et al., 2008, Tolstoy et al., 2009) or controlled exposure studies in which animal borne tags recorded both received noise levels (DeRuiter et al., 2006, Madsen et al., 2006) and behavioural responses (Miller et al., 2009). Our data therefore provide a novel baseline for assessing noise exposure in shallow shelf seas that are typical of areas where high levels of oil and gas exploration occurs in the vicinity of marine mammals (Thomsen et al., 2011).

Previous studies of seismic survey noise concentrated on lower frequencies for several reasons. As seismic pulses are designed to generate peak energy at around 50Hz, concern over potential impacts upon marine mammals has generally focused on those species which communicate at low frequencies (Gedamke et al., 2011). In addition, it is only relatively recently that equipment for recording high frequency components of these signals has become widely available, and earlier studies were also constrained by the 22 kHz limit of recording equipment (e.g. Goold and Fish, 1998, Greene and Richardson, 1988). However, observations suggesting that small cetacean species also responded to seismic vessels (Stone and Tasker, 2006, Weir, 2008) highlighted the need to extend the bandwidth of recordings, particularly given that higher frequency noise, above 300 Hz, may be heard several kilometres from the source under certain oceanographic conditions (Madsen et al., 2006). Our recordings confirmed the presence of high frequency components to these seismic signals (Figure 5), although most of the energy in each pulse typically occured at frequencies below 400 Hz ($F_{95\%}$ in Table 2). The straight line decay in the airgun frequency signature above 1 kHz was similar to that seen in recordings made up to 25 kHz by Tolstoy et al. (2009). In practice, low signal to noise ratios in many of the more distant recordings limited the extent to which these higher frequency components could be measured. This was partly because of the more rapid attenuation of high frequencies (Urick, 1983), meaning that signal to noise ratios for high frequencies declined more rapidly than those for low frequencies (Figure 5). In addition, other extraneous high frequency noises were recorded at some of our more distant recording locations, for example where boat sonar and the sound of wave action on beaches was heard near coastal sites. Above 60 kHz, measurements were also limited by increasing amounts of thermal noise (Urick, 1983).

We aimed to characterize received noise levels using the wide range of metrics that have previously been used in different research contexts and assessment frameworks. Following other air-gun propagation studies, we used the cumulative energy method to identify a 90% energy window from which the pulse characteristics could be extracted (Table 2). To inform assessments of potential impacts upon marine mammals, we also presented SEL's for single pulses, filtered using Southall et al.'s (2007) weightings for different marine mammal functional groups (Table 3). Finally, given the widespread use of Nedwell et al's (2007) dB $_{ht}$ *(species)* weightings in EIAs for offshore energy developments in the UK, we included measurements for those marine mammal species with available audiograms (Table 5). For completeness, these tables include mean values for each of these metrics at each recording site. Data for individual pulses are available in an electronic appendix. However, it should be recognised that these metrics vary in the extent to which they are influenced by the bandwidth of our recordings. First, this affects whether these data are directly comparable with previous studies, which have generally been based upon recordings made at lower sampling frequencies (Goold and Fish, 1998, Madsen et al., 2006, Tolstoy et al., 2004). Second, higher frequency measurements were constrained in many of our own recordings as a result of lower signal to noise ratios. Consequently, there were only four sites at which robust measurements were available within the full 20 Hz to 96 kHz range. However, inspection of these data highlights that most of the energy within the signal occurs at lower frequencies where signal to noise ratios are reasonable at all our recording sites. The unweighted metrics in Table 2 should therefore be reasonably comparable across sites in this study and with other studies. However, any internal or external comparison of the weighted metrics in Tables 4 and 5 requires more cautious interpretation and consideration of the bandwidth of these recordings.

One of our key aims was to assess how received levels varied with distance from source, and how these compared with modelled estimates. In general, we found that measured values were in agreement with values that were predicted using the ray-trace and parabolic models (Figure 7). As reported by Madsen et al. (2006) in deep waters within the Gulf of Mexico, received levels did not necessarily decrease with distance from source as expected from simple spherical or cylindrical spreading models. However, this variation was also captured in our model predictions (eg. Figure 7b). At some sites, modelled and measured values differed by up to 8 dB, but it was not possible to determine if this was due to measurement error or uncertainty in the model predictions. We produced three modelled estimates at each site, each using a slightly different propagation path that was based on the location of the recording vessel and seismic vessel at the beginning, middle and end of each recording period. However, these modelled estimates differed so little that the error bars around each mean value in Figure 7 cannot be seen around the symbol. We identified no obvious spatial pattern in the residuals between measured and modelled values, for example in relation to inshore versus offshore locations. In this study area, reasonable local information on bathymetric and sediment type gave us confidence in the static environmental input variables used in this model. However, propagation would also be influenced by fine scale variation in dynamic variables such as water temperature and stratification that were not captured in the summary data from the world ocean atlas. DeRuiter et al (2010) demonstrated how propagation within the Gulf of Mexico differed markedly between years as a result of changes in ocean stratification. This could also be important factor in coastal areas such as the Moray Firth, where there can be marked interannual variation in stratification as a result of factors such as wind-driven mixing (Sharples et al., 2006).

There is an increasing demand for assessments of potential impacts of noise upon marine mammals within EIAs for a range of different coastal and marine developments. Our comparisons suggest that ray-trace and parabolic models can provide reasonable estimates of received levels of seismic noise at intermediate distances from source in these shallow waters. However, several factors limit their widespread use in EIA for seismic surveys or other impulsive noise sources. Firstly, as shown by DeRuiter et al (2010), it can be difficult to accurately predict propagation patterns given uncertainties over variation in stratification during a future development. Secondly, these models are complex and labour intensive to run, and they have generally been used for military and research studies. This can constrain their use in EIA work, where an increasing number of developers are required to conduct noise assessments, typically within tight time-constraints. Although less of an issue when conducting EIA for oil and gas exploration, noise assessments for developments such as offshore wind farms also often require multiple modelling scenarios to explore different site design or construction scenarios. As a result, EIAs are often conducted using simpler noise propagation models, and a number of companies have developed their own proprietary models to support the needs of developers. Here, we compared our measurements with predictions from INSPIRE, the proprietary model that had been used in the EIA for this 2-D seismic survey in the Moray Firth. INSPIRE makes predictions using the dB_{ht} *(species)* metric, that weights received levels according to different species' audiograms. In practice, this made it difficult to compare modelled and measured value at most sites because these measurements required good signal to noise ratios throughout the entire hearing range of each species. This was possible at four sites, where the data suggest that INSIRE was over-predicting received levels at the nearest site, but was more conservative further from source (Figure 8). Based upon our measurements at the site 1.6 km from source, we estimated that peak to peak source levels were between 242 and 253 dB re 1 µPa. This is slightly higher than expected for this size of air-gun given the measurements from a range of air-gun sizes provided by Richardson et al. (1995) (Figure 4). Based upon existing data such as these, INSPIRE predicted that the unweighted peak to peak source level for this air-gun size would only be 218 dB re 1 µPa. This difference in source level used in the model probably explains the model's under-prediction at this closest site. However, at more distant sites, measurements of received levels were lower than INSPIRE predictions, providing some support for Subacoustech's suggestion that INSPIRE is conservative in the way it predicts of propagation losses.

This study provides broadband measurements of a seismic air-gun survey in shallow coastal waters. This information on received noise levels at near and intermediate ranges can now be compared directly with the results of parallel studies on behavioural responses of small cetaceans to the Moray Firth seismic survey (Chapters 5 & 6). Furthermore, we illustrate how these data provide a benchmark for comparing the performance of different noise propagation models. Our intention is that these data can now be used by others to refine and test models that are required to meet the growing need for EIA of the impacts of impulsive noise on marine mammals.

Short-term disturbance by a seismic survey does not lead to long-term displacement of harbour porpoises

Paul M. Thompson,[1] Kate L. Brookes,[1]† Isla M. Graham,[1] Tim R. Barton, [1] Keith Needham,[2] Gareth Bradbury,[3] Nathan D. Merchant [4]

[1] Lighthouse Field Station, Institute of Biological & Environmental Sciences, University of Aberdeen, Cromarty, IV 11 8YL, UK.

[2] Kongsberg Maritime Ltd, 11 The Briars, Waterberry Drive, Waterlooville, Hampshire, PO7 7YH, UK.

[3] WWT Consulting, Slimbridge, Gloucestershire GL2 7BT, UK.

[4] Department of Physics, University of Bath, Bath, Somerset, BA2 7AY, UK

†Current address: Marine Scotland Science, Marine Laboratory, Aberdeen AB11 9DB, UK

Abstract:

Assessments of the impact of offshore energy developments are constrained because it is not known whether fine-scale behavioral responses to noise leads to broader-scale displacement of protected small cetaceans. We used a passive acoustic monitoring array, in combination with digital aerial surveys, to study changes in the occurrence of harbour porpoises across a 2000 km^2 study area during a commercial seismic survey in the North Sea. Both acoustic and visual data provided evidence of fine-scale behavioral responses to seismic survey noise within 5-10 km, at received peak-to-peak sound pressure levels of 165-172 dB re 1 µPa and sound exposure levels of 145-151 dB re. 1µPa^2 s. However, animals were typically detected again at affected sites within a few hours, and the level of response declined through the 10 day survey. Overall, there was a significant decrease in acoustic detections over the survey period in the impact area compared to a control area. However, this effect was small in relation to natural variation, and porpoises were detected in the impact area for a median of 10 hours per day throughout the seismic survey period. These results demonstrate that prolonged seismic survey noise did not lead to broader-scale displacement into sub-optimal or higher-risk habitats. Harbour porpoises have high energy demands compared with many other marine mammals, and may be constrained to return rapidly to preferred habitats following disturbance. These findings suggest impact assessments should focus on sub-lethal effects resulting from changes in foraging performance of animals within affected sites.

1. Introduction

Marine seismic surveys operate over extensive areas, producing some of the most intense man-made ocean noise (NRC, 2003, Southall et al., 2007). Increasing awareness of the potential impacts of impulsive noise on marine mammals has led to the development of measures to minimize direct injuries (Compton et al., 2008), but uncertainty over the extent to which protected species are displaced from favored habitats remains a contentious issue for regulators of offshore energy developments (Stocker, 2011).

Field studies of the impacts of seismic surveys on cetaceans have been limited to localized interactions with endangered baleen whale populations (Gailey et al., 2007, Yazvenko et al., 2007) or fine-scale responses of a few individuals to experimental or opportunistic exposure to air-gun noise (Di Iorio and Clark, 2010, Miller et al., 2009). The only information available on behavioral responses of smaller cetaceans is based upon observations from seismic survey vessels (Potter et al., 2007, Stone and Tasker, 2006). Although aversive behavior has been reported (Weir, 2008), nothing is known about the spatial scale or longer-term consequences of these responses (Gordon et al., 2003, NRC, 2003). From a regulatory perspective, this is especially important because potential impacts on protected species must often be assessed in relation to longer-term population level consequences (Thomsen et al., 2011). Given increasing evidence of short-term responses to relatively low levels of noise, there are concerns that offshore energy developments could ensonify large areas, resulting in population impacts due to displacement from preferred habitats.

Here, we investigated whether a commercial 2-D seismic air-gun survey in the North Sea led to changes in the occurrence of harbour porpoises (*Phocoena phocoena*), a small cetacean that is widely distributed across northern shelf seas, and considered particularly sensitive to anthropogenic noise (Southall et al., 2007). Environmental Assessments conducted to support the consent applications required by regulatory authorities predicted that harbour porpoises would exhibit behavioral responses to this disturbance at distances of 10-20 km from the vessel. We used a broad-scale array of passive acoustic monitoring (PAM) devices and digital aerial surveys to detect changes in echolocation activity and surfacing porpoises across a 2000 km^2 area around the seismic survey. We aimed, first, to assess how changes in the occurrence of porpoises varied with distance from the seismic vessel and time since exposure. Second, to determine whether the seismic survey resulted in broader scale displacement.

2. Methods

2.1 Seismic survey characteristics

Seismic surveys were conducted from MV Sea Surveyor, operated by Gardline Geosurvey, under a contract from PA Resources to survey an area relating to their license for Block 17/4b, and from Caithness Petroleum Ltd to survey an area relating to their license for Blocks 11/23, 11/27 and 11/28 (the Helmsdale Prospect). These surveys were consented by the United Kingdom Department of Energy & Climate Change (DECC), following submission and consultation of the operator's applications and supporting EIA's, and an Appropriate Assessment undertaken by DECC as competent authority to meet the requirements of the EU Habitats Directive (DECC, 2011). Further details of survey protocols are provided in Chapter 4.

2.2 Measurements of noise levels

Calibrated recordings from 15 sampling sites were used to estimate received levels at different distances from source. Details of noise recording protocols are provided in Chapter 4.

Safe thresholds for received sound pressure levels noise are typically expressed on the dB scale relative to a reference root mean square (rms) pressure of 1 µPa @ 1 m (Southall et al., 2007), but this measure is highly dependent on time window used for analysis when applied to pulsed noise sources such as seismic air guns (Madsen, 2005). We therefore followed suggested protocols for measuring pulsed sounds and present data using 1) peak-to-peak SPL in dB re 1 µPa and 2) the sound exposure level (SEL) for single pulses in dB re 1 $\mu Pa^2/s$, using the region of the waveform that contains the central 90% of the pulse's energy (Lucke et al., 2009, Madsen, 2005).

Longer-term variation in relative noise levels at a site within the seismic survey area (57° 53.7'N 003° 25.9' W) was characterized by deploying a seabed mounted autonomous Environmental Acoustic Recorder (EAR) (Lammers et al., 2008) that recorded at 64,000 samples per second for 10 min in each hour between August and October 2011.

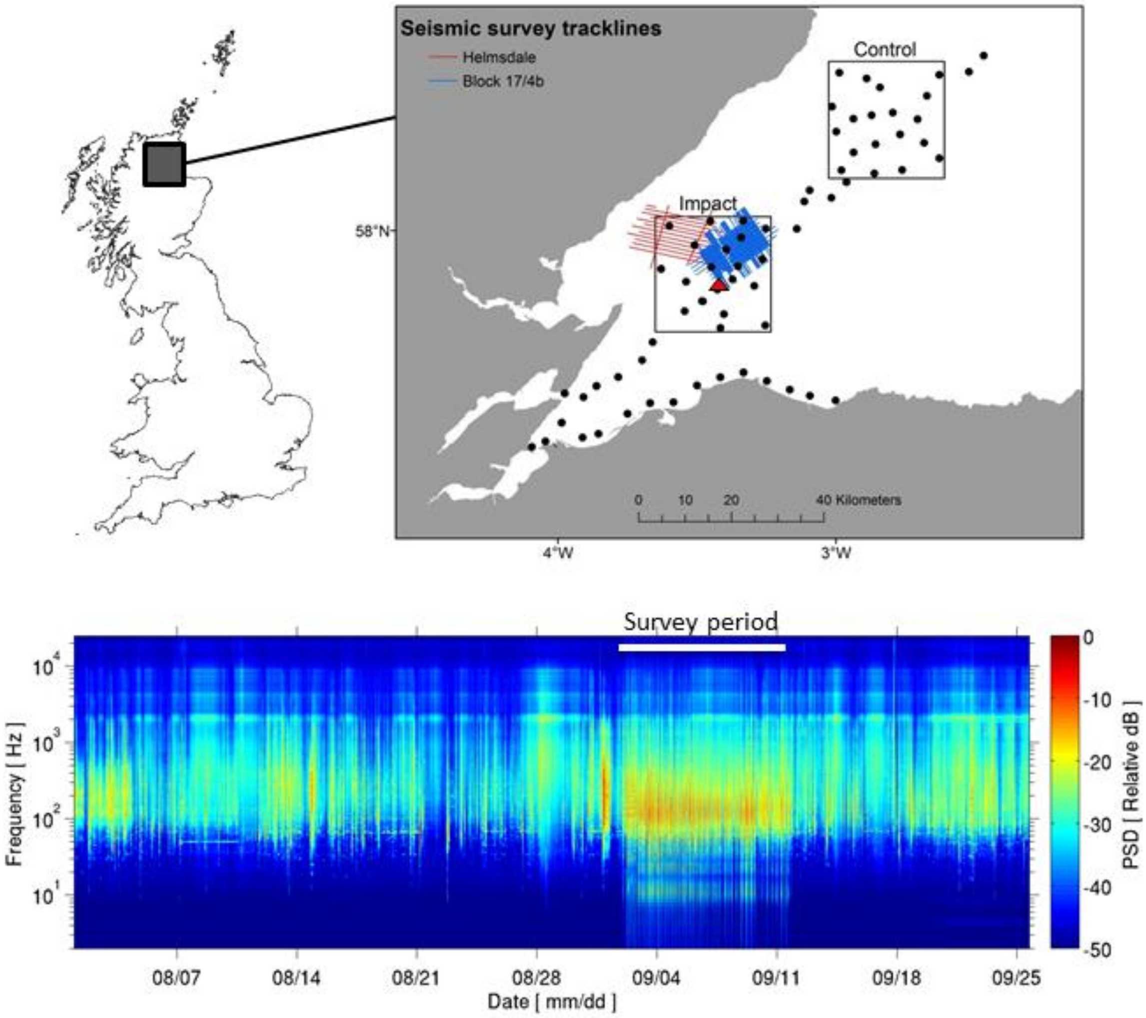


Figure 1. Top panel: Map of the study area showing the location of the 2011 seismic survey, PAM sampling sites used in 2010 and 2011, and the study's impact and control blocks. Bottom panel: Spectrogram showing variation in received noise levels in the impact block (red triangle on top panel) in August – October 2011.

2.3 Passive acoustic monitoring

Harbour porpoises regularly echolocate (Linnenschmidt et al., 2013), and we assume that variation in echolocation click detections provides an index of changes in the occurrence of harbour porpoises across the study area. We measured spatial and temporal variation in echolocation clicks using V.0 and V.1 C-PODs (www.chelonia.co.uk), the digital successor of the T-POD that has been used extensively to study changes in the occurrence of harbour porpoises (Brandt et al., 2011, Carstensen et al., 2006, Thompson et al., 2010). These long-term passive acoustic monitoring devices continuously detect and record click trains within around 400 m of fixed PAM sites (Villadsgaard et al., 2007). To assess how changes in porpoise occurrence varied with distance from the seismic vessel, we used a gradient design (Ellis and Schneider, 1997), with PAM devices deployed at distances of up to 70 km from the seismic vessel. To determine whether there was a broad scale impact over the whole survey period we used a Before-After-Control-Impact (B-A-C-I) design (Stewart-Oaten and Bence, 2001) with PAM devices deployed across 25 x 25 km impact and control blocks during August, September and October of 2010 and 2011.

In 2011, C-PODs were deployed at 70 sites in July, and devices with data were successfully recovered from 49 sites four months later. In 2010, C-PODs were deployed at 70 sites and 60 devices with data were recovered. Once recovered, data were downloaded and processed using v2.025 of the manufacturer's custom software to identify porpoise echolocation clicks with High, Medium or Low levels of confidence. Only click trains categorized with High or Medium confidence were used in subsequent analyses.

Two metrics derived from the C-POD data were used to compare spatial and temporal variation in the occurrence of porpoises. First, each data file was initially analyzed to determine whether porpoise clicks were detected in each hour of the deployment, and these data were then used to estimate the number of hours in each day that porpoises were detected at each site; hereafter referred to as detection positive hours (DPH) (Bailey et al., 2010a). Second, sequences of click trains within each deployment were used to estimate the waiting time between actual or control disturbance events and the next porpoise detection (Teilmann and Carstensen, 2012, Thompson et al., 2010). Waiting time was thus defined as Δt_p: the time elapsed between t_p and t_{detect}, where t_p was the time of the actual or control disturbance event and t_{detect} was the time of the first porpoise detection after t_p.

C-POD detection probability could vary either due to slight differences in the sensitivity of individual devices or to differences in water depth or other site-specific environmental conditions (Teilmann and Carstensen, 2012). We minimised the influence of device variability by using the metrics DPH and waiting times, rather than finer scale measures such as the number of detection positive minutes per day or click trains per minute. In addition, all analyses were based on relative changes within single C-POD deployments, using models that accounted for site specific differences resulting either from differences in device sensitivity or underlying differences in the baseline occurrence of porpoises.

2.4 Aerial surveys

Digital aerial surveys were flown in 2011 on 3 days before (6th, 22nd & 31st August) and four days during (2nd, 3rd, 4th & 5th September) the seismic survey using video techniques initially developed to survey seabirds around offshore energy developments (Buckland et al., 2012). Flights were made on days with suitable weather conditions (Beaufort sea state <4, swell <1.5 m, cloud base > 300 m), along a series of transects that provided a gradient of exposure to the air-gun noise (Fig. S 1). Flight height and camera characteristics were standardised so that the area within video frame was known. Data processing followed procedures established for birds, using trained analysts at Hi-Def Aerial Surveying Ltd (www.hidefsurveying.co.uk) to detect and geo-reference all objects from the video, and specialists at WWT Consulting Ltd to identify marine mammals and conduct standardised QA of all observations. Analyses were restricted to the 90% of small cetacean detections that were identified as either definite or probable harbour porpoises. Because aerial survey data collected during the seismic survey were pooled over 4 days, we estimated the density of surfacing porpoises in a series of 5 x 5 km blocks at increasing distance from mean position of the vessel over this period (Fig. S 1).

In 2010, visual aerial surveys were made to provide an estimate of absolute density of porpoises within the study area. We used standardised line-transect sampling techniques used for broad-scale porpoise surveys in the North Sea (Hammond, 2006, Hammond et al., 2002), and program Distance (Thomas et al., 2010) to calculate density from these data. We used a value of 0.45 for g(0) for harbour porpoises sighted under good conditions based upon the larger SCANS-II dataset (Hammond, 2006).

2.5 Modeling short-term changes in porpoise occurrence

To assess the spatial scale of initial short-term responses to the air-gun noise we calculated waiting times for each PAM site from the first soft start at 15:15 GMT on 1st September. Distances to the seismic vessel were calculated from the vessel's GPS position at that time. Baseline occurrence at each site was characterized by randomly selecting 100 control points from the week prior to the seismic survey (23rd - 30th August 2011), and calculating the waiting times from these points to the next porpoise detection. We then used generalised linear models to analyse the relationship between waiting times and distance, using a negative binomial error distribution to allow for over-dispersion. For any given site, we would expect part of the waiting time (or all if distance had no effect) to be predicted from the baseline occurrence at that site, so models included the log transformed median of the 100 randomly sampled waiting times for each site as an offset.

Within each 5 x 5 km block, the total area covered before and during seismic surveys was calculated from the length of survey line (based upon the aircraft GPS trail) and camera strip width (based upon flight height and camera specification). We then compared the density of porpoise sightings in each block in different periods.

2.6 Modeling changes in porpoise occurrence in relation to time since exposure

Return times following exposure were investigated by estimating waiting times following the point of closest approach during those occasions when the seismic vessel was firing air guns as it passed within 5 km of a PAM site. We excluded those occasions when the vessel returned to the site within an hour (based on average baseline waiting times at these sites). Each observed waiting time was then paired with a random waiting time from the same site in the week prior to the seismic survey, and a paired Wilcoxon test used to compare distributions. We then used a mixed modelling approach to explore whether minimum distance of approach, time since the start of the seismic survey or number of consecutive approaches influenced return times. The model was built using the gamm function in the mgcv library (Wood, 2008) using linear predictors and a negative binomial error structure. The median value of the 100 random waiting times for each site was used as an offset variable.

2.7 Modeling broad-scale displacement

Broad-scale variation in porpoise occurrence was explored using data from a subset of sites in the impact (n=12) and control (n=6) blocks where data were available from 1st August to 23rd October in both 2010 (no seismic survey) and 2011 (seismic survey). To avoid confounding effects of variation in device sensitivity (see above), our formal B-A-C-I analysis was restricted to single deployments in 2011, using data on DPH per day from August as our before time period and data from 2nd to 11th September as the during time period. In 2011, data from 13 sites in the impact block and seven sites in the control block were available to use in a generalised linear mixed model with a Poisson family error structure to account for the non-negative integer values in DPH per day. PAM site was included as a random intercept, which removed patterns in the residuals and improved the fit of the model. The fixed effects of the model were Block and Period and, crucially, an interaction term between these effects, the significance of which was used to detect whether or not there was an impact of seismic survey. Analyses were carried out in R version 2.15 (*48*).

3. Results and Discussion

The seismic survey was conducted over two areas licensed for oil and gas exploration in the central Moray Firth, between 1st and 11th September 2011 (Fig. 1). The vessel used a 470 cu inch air-gun array with a shot point interval of 5-6 sec, producing peak-to-peak source levels that were estimated to be 242-253 dB re 1µPa@1m. Individual survey lines of 7-15 km took 75 to 150 min to complete, resulting in regular noise exposure over a 200 km^2 area during the 10 day survey period.

Previous visual and acoustic studies identified spatial variation in the density of porpoises across this study area in the absence of seismic activity (Bailey and Thompson, 2009). We therefore used data from the week before the seismic survey to characterize baseline occurrence at each of our PAM sites, producing a null distribution of waiting times between randomly selected observation times and the next porpoise detection. Following the start of seismic surveys on 1st Sept, observed waiting times increased relative to baseline (Fig 2a), indicating that there was an initial response to the noise, but that this effect diminished with distance from source (Negative binomial GLM: X^2 = 10.2, d.f = 1 P = 0.001; Fig. 2b). Using passive acoustic methods alone, such changes could reflect either individual movement or a change in vocalization rate (Blackwell et al., 2013). However, comparison of detection rates of surfacing porpoises from digital aerial surveys made before and during the seismic survey (Fig 3) showed that density decreased within 10 km of the survey vessel and increased at greater distances (GLM: $F_{1, 14}$ = 6.28, $P < 0.05$; Fig. 2c), confirming that seismic operations resulted in short-term aversive movements. Calibrated noise measurements made along this same impact gradient indicate that received peak-to peak sound pressure levels (SPL) in the region 5 to 10 km from source varied from 165-172 dB re. 1µPa, whilst sound exposure levels (SEL) for a single pulse were 145-151 dB re. 1µPa^2 s (Fig. 4).

a)

b)

c)

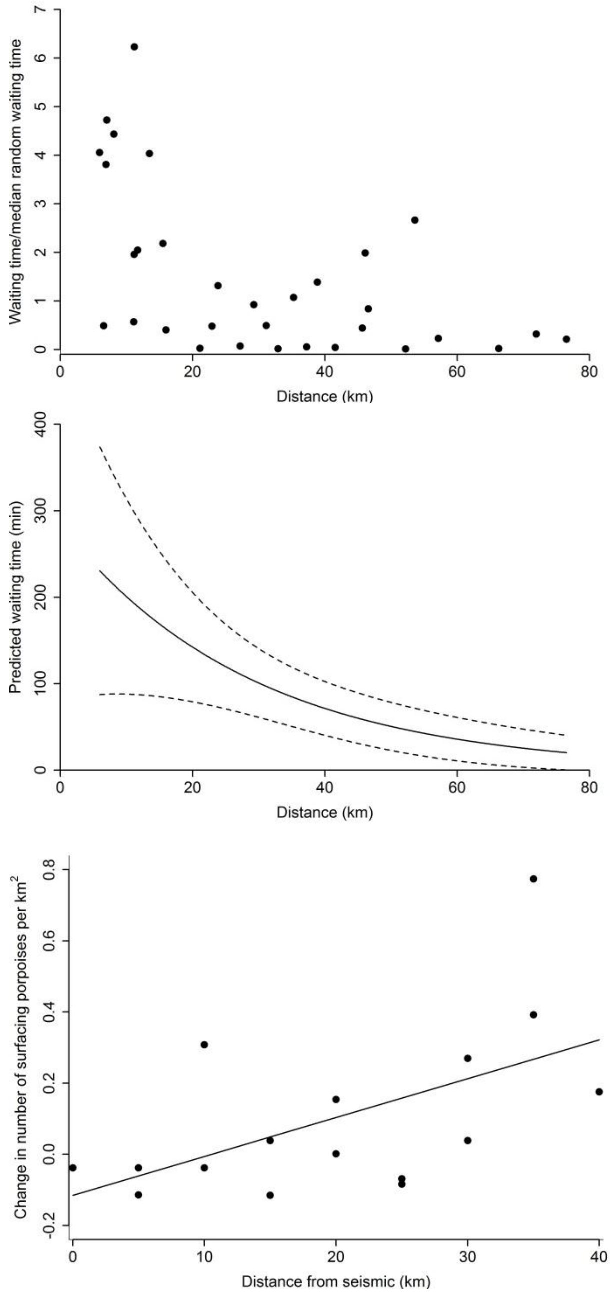
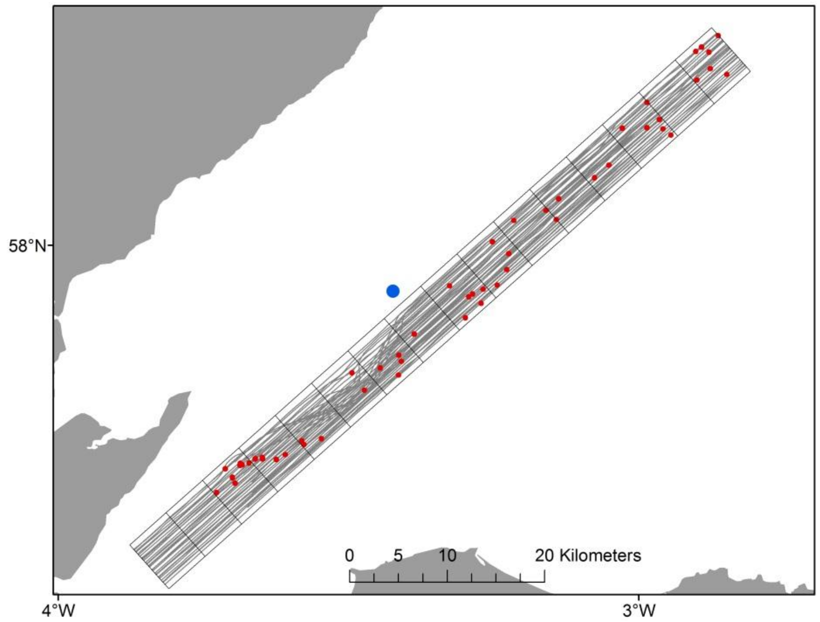


Figure 2. Changes in the occurrence of harbour porpoises in relation to distance from the seismic vessel. a) Ratio of observed to baseline waiting times after the first air-gun activity from PAM. b) Predicted waiting times after initial exposure (solid line) and 95% confidence intervals (dashed lines) from a GLM, standardised for the median baseline waiting time of 84 min. c) Observed changes in the relative density of surfacing porpoises from digital aerial surveys carried out before and during

seismic surveys. Points are original data for each 5 x 5 km survey block (see Fig. S 1), the solid line is the linear model fit (y = 0.011x - 0.115).

a)



b)

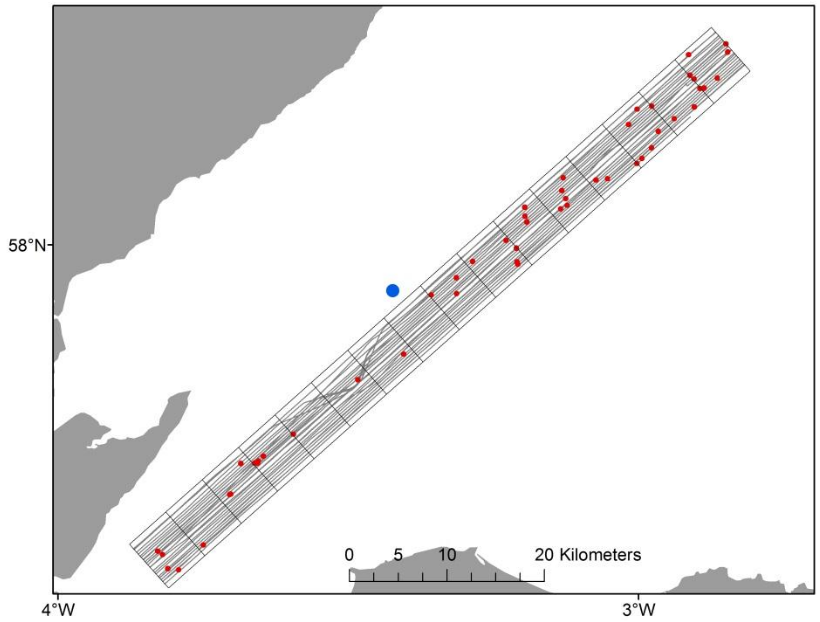
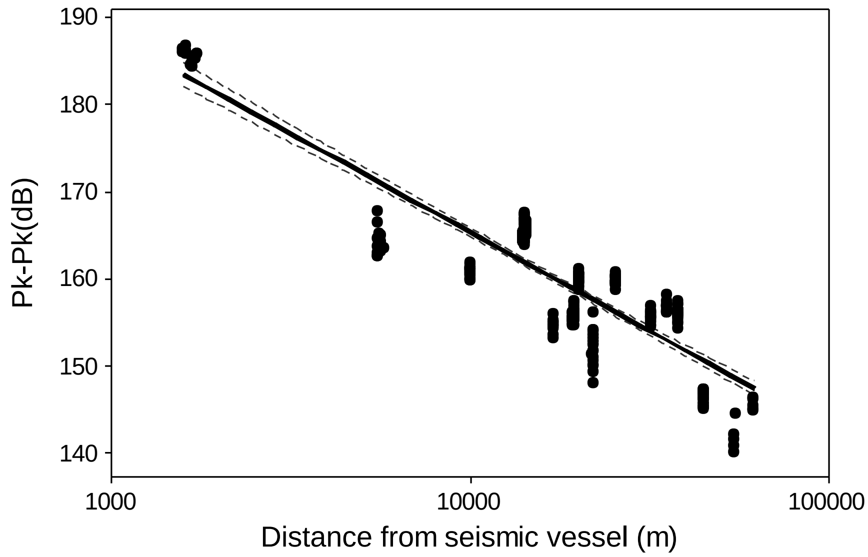


Figure 3. High definition video survey effort (grey lines) and sightings (red dots) within each 5 x 5 km analysis block a) before the seismic survey and b) during the seismic survey. The blue dot on each map indicates the mean position of the seismic vessel during high definition video surveys carried out between 2nd-5th September.

a)



b)

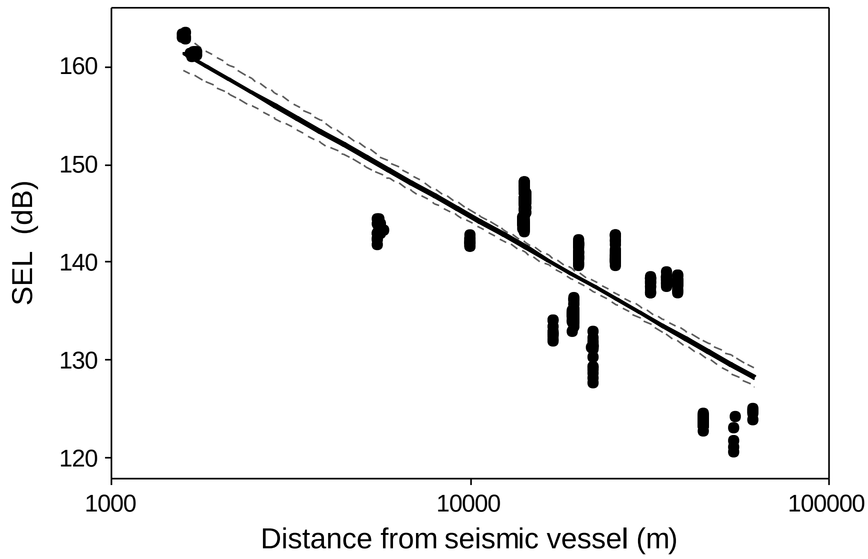
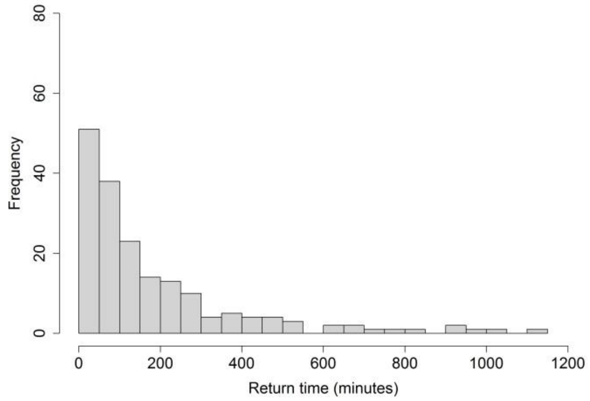


Figure 4. Variation in received noise levels at different distances from the seismic air gun array, expressed a) as peak-to-peak SPL (dB re 1 µPa) and b) as SEL (dB re. 1µPa^2 s) integrated over the central 90% of each pulse. Equations for the fitted logarithmic spreading loss are: SPL = 255.77 – 22.6 log (range) ($F_{1,\,266}$ = 1245.5, p< 0.001, r^2 = 0.77); SEL = 227.95 – 20.8 log (range) ($F_{1,\,366}$ = 716.55, p <0.001, r^2 = 0.66).

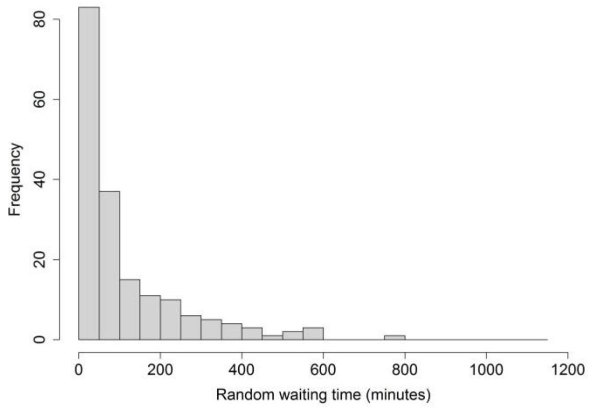
The seismic vessel was firing air guns as it passed within 5 km of a PAM site on 181 occasions. The frequency distribution of waiting times following these occasions show that porpoises were detected again at all sites within 19 hours (median = 183 min), but that this was significantly longer than matched random waiting times (median = 57 min) from the week before the seismic survey (Fig. 5; Wilcoxon test, $V = 10907.5$, $P < 0.001$). A decrease in waiting times through the 10 day seismic survey suggested that responses to this disturbance declined with increased exposure (Fig. 5; Table 1).

Analysis of porpoise detections through the three month period that centered on the seismic survey demonstrated consistently high levels of porpoise occurrence in impact and control areas in both 2011 and 2010, with evidence of seasonal and inter-annual variability (Fig. 6). Harbour porpoises echolocate regularly, and we assume that variations in acoustic detections provide an index of underlying changes in density in these areas. This is supported by data collected in 2010, when different rates of acoustic detections in the control and impact area reflected absolute estimates of density obtained from visual aerial surveys (Table 2). In 2011, observed seasonal declines in occurrence resulted in reductions in acoustic detections in both impact and control areas during the seismic survey. Nevertheless, a Before-After-Control-Impact analysis using 2011 data identified a significant impact of the seismic survey, with a reduction in porpoise detections of 12.5% (to a median of 14 hrs per day) in the control block compared to a reduction of 16.7% (to a median of 10 hrs per day) in the impact block (Table 3).

a)



b)



c)

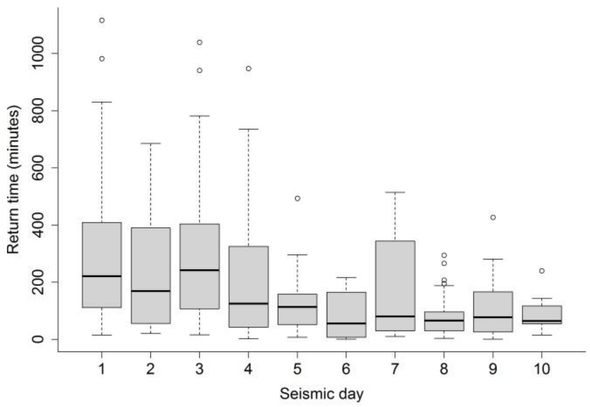


Figure 5. Distribution of waiting times until the next porpoise detection a) following a close approach of the seismic vessel in comparison to b) random points in the week before the survey. c) Shows the modelled reduction in these waiting times through the seismic survey campaign, with day 1 representing 2nd September 2011.

Table 1. Results of the generalised linear mixed model of return times of porpoises to PAM sites following a close approach by the seismic vessel. A negative binomial distribution was used and the random effect was site.

	Estimate	Standard error	P value
Intercept	1.1710	0.4360	0.008
Minimum distance of approach	-0.0001	0.0001	0.173
Days since start of seismic survey	-0.1463	0.0604	0.017
Number of consecutive approaches	0.3668	0.0748	<0.001
Min Dist x Days since start	0.0000	0.0000	0.168

Table 2. Comparison of acoustic detections (from PAM devices) and estimates of absolute density of porpoises (from visual aerial surveys) in the impact and control areas in August and September of 2010, the year before the seismic survey.

Area	Acoustic estimates				Direct estimates	
	Detection +ve hrs/day		Waiting times			
	Median	IQ range	Median	IQ range	Density	95% CI
Impact	9	6-12	65	28-152	0.50	0.36-0.68
Control	14	10-18	42	21-88	0.75	0.38-1.48

Table 3. The results of a Poisson generalised linear mixed model used to investigate the effect of a seismic survey on acoustic detection of porpoises, before (1^{st} – 31^{st} August 2011) and during (2^{nd} – 11^{th} September 2011) the survey in the control and impact block.

	Estimate	Standard Error	P value
Intercept	2.721	0.090	<0.001
Block	-0.224	0.112	0.044
Period	-0.143	0.037	<0.001
Block : Period interaction	-0.102	0.048	0.035

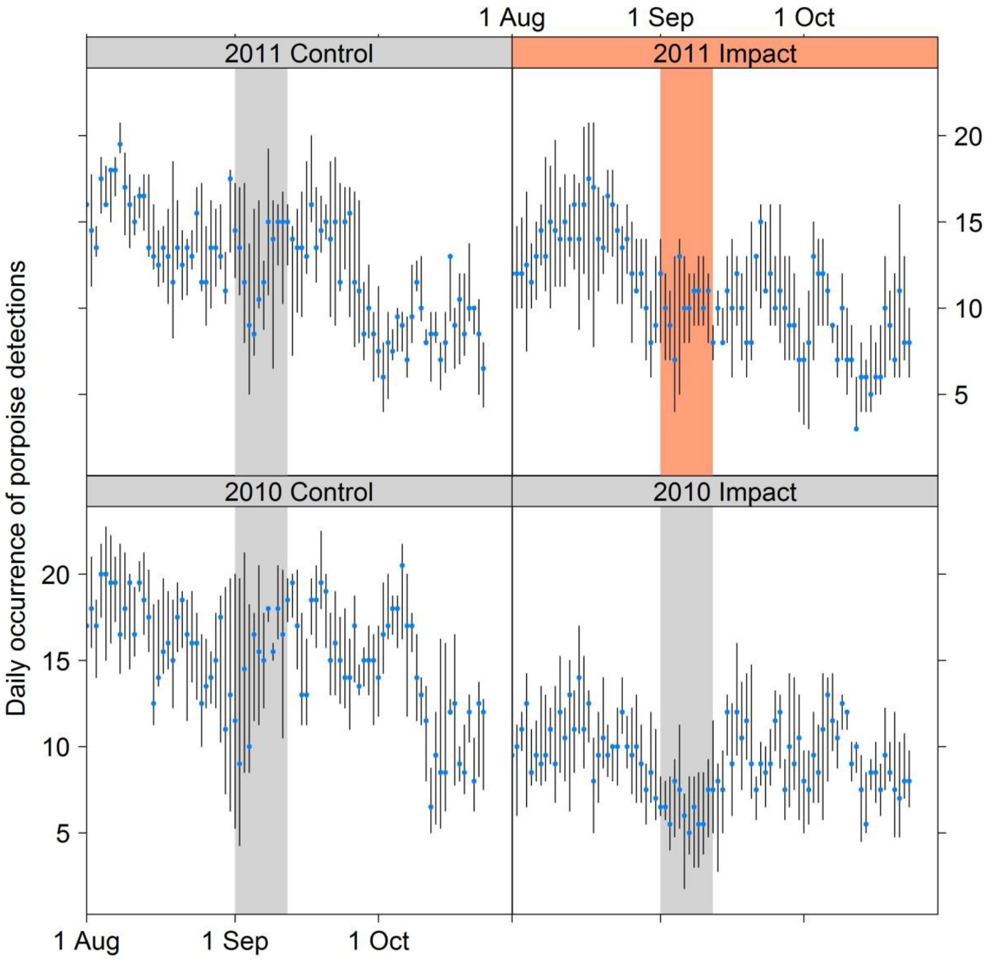


Figure 6. Variation in the median number of hours (with inter-quartile ranges) that porpoises were detected on PAM devices in the impact and control blocks in the summers of 2011, when the seismic survey was carried out, and in the previous baseline year. The timing of the seismic survey is shaded red in the panel for the impact block in 2011 and equivalent periods are shaded grey in other panels.

4. Conclusions

Fine-scale tracking of a few individual large cetaceans has previously detected behavioral responses at noise levels below thresholds used in the US to identify potential harassment to cetaceans (Miller et al., 2009, Tyack et al., 2011), and studies of baleen whales on localized foraging grounds (Gailey et al., 2007) and migration routes (Ljungblad et al., 1988) also detected fine-scale behavioral responses to seismic vessel noise. Captive porpoises exposed to air-gun noise exhibited aversive behavioral reactions at peak to peak SPL above 174 dB re. 1µPa, and an SEL of 145 dB re. 1µPa^2 s (Lucke et al., 2009). Our data indicate that animals were exposed to similar levels of received noise within 5-10 km of the seismic vessel, resulting in fine-scale aversive movements. Similar responses have been reported from studies of harbor porpoise responses to other impulsive noise sources such as pile-driving around offshore wind farms (Brandt et al., 2011, Dähne et al., 2013, Tougaard et al., 2009), However, our data show that either these or other individuals returned to impacted areas within a day (Fig. 4). Furthermore, while a significant decrease in occurrence was detected over the entire seismic survey period (Table 3), this effect was small in relation to natural variation, and porpoises continued to occur in the impact study block for around 10 hrs per day even during the seismic survey (Fig. 5).

Responses to anthropogenic noise are expected to vary in relation to both the species of marine mammal (Southall et al., 2007) and context (Ellison et al., 2012), and additional work is now required to assess the generality of our findings. Nevertheless, our focus on harbor porpoises makes these results relevant to the management of northern hemisphere shelf seas, as this is the most common cetacean in many areas currently or potentially exposed to offshore energy developments (Thomsen et al., 2011). On the one hand, this species' relatively high sensitivity to anthropogenic noise may provide a conservative indication of the level of response by other small cetaceans using these areas (Lucke et al., 2009, Southall et al., 2007). However, like many other parts of the North Sea, our study area has a long history of exposure to impulsive noise and other anthropogenic activity (Halpern et al., 2008, Thomsen et al., 2011). In combination with our evidence for a decrease in response levels over the 10 day seismic survey (Figure 4c), it seems likely that stronger responses may be expected in populations that have previously had little exposure to anthropogenic noise (Heide-Jørgensen et al., 2013). Amongst baleen whales, modification of song characteristics in the presence of seismic survey noise (Castellote et al., 2012) suggests that displacement from ensonified areas is a direct response by animals to reduce masking of communication calls. This is unlikely to be a factor affecting observed fine scale responses in harbor porpoises and other small cetaceans, because most of the energy from seismic air guns is well below the frequencies used by these species to communicate (Breitzke et al., 2008, Tolstoy et al., 2009). We cannot rule out the possibility that the observed fine-scale responses by harbor porpoises were an indirect response to the noise, mediated through changes in prey behavior (Engas et al., 1996). However, it seems more likely that aversive responses to anthropogenic noise in small cetaceans reflect anti-predator responses (Frid and Dill, 2002), with the level of response resulting from a trade-off between fear and the costs of moving to different habitats (Gill et al., 2001). Harbor porpoises have high energy demands compared with other small cetaceans (MacLeod et al., 2007) and, like small passerine birds, may therefore be constrained to return rapidly to high quality feeding patches under even relatively high predation risk (Gentle and Gosler, 2001). This highlights that the likelihood of harbor porpoises being displaced by long periods of impulsive noise could vary in relation to habitat quality. Density estimates in our study area (Table 2) were comparable with those recorded in high density areas within the North Sea (Hammond et al., 2002), suggesting that our study area represented relatively high quality porpoise habitat. Longer-term displacement may therefore be more likely following industrial activity in marginal habitats.

Mitigation of the potential impacts of anthropogenic noise on cetaceans focuses on reducing near-field injuries (Compton et al., 2008), and risk assessments are based on the assumption that animals flee from loud noise sources. Our results support this assumption, but observed declines in the response to air gun noise during the survey period suggest that it would be valuable to explore the effectiveness of using additional aversive sounds (Nowacek et al., 2004). This decline in response could have resulted either from habituation or tolerance to air gun noise, meaning that one cannot assume that the outcome of the disturbance is neutral (Bejder et al., 2009). In some development areas, there are concerns that animals could be exposed to an increased risk of mortality should they be displaced from high quality habitats (Heide-Jørgensen et al., 2013), or into areas where there was a higher risk of by-catch (Herr et al., 2009) or inter-specific competition (Ross and Wilson, 1996). Our evidence of continued use of areas impacted by noise from a seismic survey provides a clearer focus for the assessments of population consequences of acoustic disturbance that are increasingly required to support development proposals (Thomsen et al., 2011). These findings suggest that broader scale exclusion from preferred habitats is unlikely. Instead, individual fitness and demographic consequences are likely to be more subtle and indirect, highlighting the need to develop frameworks to assess the population consequences of sub-lethal changes in foraging energetics of animals occurring within affected sites (New et al., 2013, NRC, 2003).

Abundance and occurrence patterns of bottlenose dolphins in relation to a 2-D seismic survey in the Moray Firth

Paul M. Thompson[1], Kate L. Brookes[1,2], Barbara Cheney[1] & Isla M. Graham[1]

[1] Lighthouse Field Station, Institute of Biological & Environmental Sciences, University of Aberdeen, Cromarty, IV 11 8YL, UK.

[2] Current address: Marine Scotland Science, 375 Victoria Road, Aberdeen, AB11 9DB, UK.

Abstract

Uncertainty over the extent to which small cetaceans are displaced by air-gun noise can constrain seismic survey activity within or near sensitive habitats. Here, we illustrate these issues using this case study from the Moray Firth, NE Scotland. Background is provided both on the history of seismic exploration and oil production in the area and on the development of the Moray Firth Special Area of Conservation (SAC) for bottlenose dolphins. This new EU legislation has required more detailed assessments of the potential impacts of recent seismic surveys. Given the limited baseline data in the proposed survey area, additional monitoring was required to better define bottlenose dolphin distribution. The subsequent Appropriate Assessment (AA) identified no likely long-term impacts of the seismic survey. Given the sensitivity of this population however, additional monitoring was conducted during the survey. Photo-identification estimates of the number of dolphins using the SAC were similar throughout the period 2009-2012. However, passive acoustic studies provided evidence of short-term behavioural responses in the part of their range closest to the seismic survey. The occurrence of dolphins at PAM sites on the southern Moray Firth coast increased during the survey, most likely the result of animals being displaced inshore, away from the survey vessel.

1. Introduction

The introduction of anthropogenic noise to the marine environment during oil and gas exploration has the potential to impact cetaceans either through direct injury or disturbance (Hildebrand, 2009, Southall et al., 2007, Thomsen et al., 2011). Measures to mitigate near-field effects from injury are widely adopted in many areas (Compton et al., 2008, Weir and Dolman, 2007), but potential far field effects, and the longer-term consequences of any short-term disturbance occurring around seismic vessels, are poorly understood (Gordon et al., 2003). Currently, for example, insufficient data are available to produce noise exposure criteria for behavioural disturbance from multiple pulsed sounds such as seismic noise (Southall et al., 2007), making it difficult to identify appropriate levels of mitigation (Weir and Dolman, 2007).

Previously, concern over potential disturbance from seismic surveys has focused on those relatively rare cases where developments overlap with critical habitat of resident or semi-resident populations (Blackwell et al., 2013, Yazvenko et al., 2007). More recently, three factors have raised the profile of these potential interactions, resulting in increased levels of scrutiny in Environmental Assessments for new oil and gas developments. Firstly, increased survey effort and advances in spatial modelling techniques have demonstrated that cetaceans can frequent areas not previously recognised as important habitats for these species (Harwood and Wilson, 2001, Kaschner et al., 2011, Thomsen et al., 2011). Furthermore, new tools that permit individual identification have highlighted high levels of individual or group fidelity to some of these areas (eg. Cheney et al., 2013, Hooker and Gerber, 2004, Smith et al., 1999). Secondly, technical developments, in parallel with efforts to identify new hydrocarbon resources, have expanded the industry's global footprint (Gautier et al., 2009). As a result, there may be potential impacts upon populations or habitats not previously exposed to oil and gas exploration (Heide-Jørgensen et al., 2013). Finally, new legislation can lead to additional demands upon regulators to give greater consideration to environmental impacts before permitting new developments (Salter and Ford, 2001). In Europe, for example, the introduction of the EU Habitats & Species Directive requires regulators to place the effects of any disturbance in the context of longer-term population consequences should those operations occur near an SAC.

We highlight these issues using a case study from the North Sea, where recent exploration activity was carried out in the Moray Firth. Although the area has a long history of seismic exploration and oil production (Addy, 1987), higher levels of assessment and protection are now required due to the presence of an SAC for a resident population of bottlenose dolphins. Plans to undertake seismic surveys in the Moray Firth resulted in significant objections, on the grounds that there could be adverse effects on the protected bottlenose dolphin population. As a result, additional monitoring was required to better define bottlenose dolphin distribution. The subsequent AA identified no likely impacts from the seismic survey on the protected bottlenose dolphin population, and permission was granted to undertake a 2-D seismic survey in the area in September 2011. However, given the sensitivities surrounding this issue, studies were subsequently conducted on the distribution and abundance of bottlenose dolphins in relation to the occurrence of the seismic survey.

In this paper, we first describe the background to the issue, and present the findings from the offshore aerial surveys and passive acoustic monitoring studies that provided sufficient information on the population's distribution to support the decision to licence seismic surveys in the area. We then present the results of studies carried out in 2011 to monitor the responses of bottlenose dolphins to those surveys, drawing on baseline information on variation in abundance and occurrence of bottlenose dolphins within the SAC and in those parts of their range closest to the seismic survey area.

2. Background

2.1 Moray Firth SAC

Studies in the early 1990's highlighted that the inner Moray Firth was a core-area for the population of bottlenose dolphins that occurs through coastal waters on the east coast of Scotland (Wilson et al., 1999, Wilson et al., 1997). Repeated sightings of recognisable individuals over two decades have confirmed that this is a resident population, which was recently estimated to contain approximately 200 individuals (Cheney et al., 2013) .

Following the introduction of the EU Habitats & Species Directive in 1992, the inner Moray Firth was identified as one of two candidate SACs in the UK for this species (Figure 1). At 1513 km^2, this is the largest marine SAC in UK inshore waters, and is the only SAC for bottlenose dolphins in the North Sea. A management group representing all those bodies with statutory responsibilities in the area subsequently developed the SAC Management Plan in 2001 and the site was formally designated as an SAC in 2005 (Moray Firth SAC Management Group, 2009).

As a result of this designation, statutory regulators must conduct an AA for any new developments that could affect the conservation objectives of the site (Soderman, 2009, Therivel, 2009). As the population is mobile, ranging into other waters off the east coast of Scotland, an AA can be required for developments well outside the SAC boundary.

2.2 Oil & gas activities in the Moray Firth

Seismic exploration has been conducted in the Moray Firth since the late 1960's. Since then, 2-D seismic surveys have covered all but the shallowest parts of the Moray Firth, particularly during the 1970's and 1980's. The Beatrice Oilfield, lying 12 nautical miles off the north coast in the central Moray Firth, was discovered in 1976 and production began in 1978 (Davies and Pirie, 1986). The Captain Field in the eastern part of the Moray Firth was discovered in 1977 but production was not possible until 1997 following developments in horizontal drilling technology (Rose, 1999). Recent exploration activity has focussed on identifying additional fields that can be integrated into the existing infrastructure at the Beatrice field, or nearshore fields that could be exploited by directional drilling from land.

Following the discovery of the Beatrice field, a detailed environmental monitoring programme was established in the Moray Firth (Addy, 1987). This included focused studies of contaminants and benthic communities around both the oil rigs (Davies and Pirie, 1986, Tibbetts and Large, 1986) and the onshore terminal (Raffaelli and Boyle, 1986, Tibbetts, 1986), and broader scale monitoring of seabirds both at breeding colonies (Mudge, 1986) and across potential foraging areas (Mudge and Crooke, 1986). The lack of any environmental assessment or monitoring for local marine mammal populations (see Addy, 1987) highlights how much conservation priorities have changed over the last forty years. Growth in marine mammal research and stakeholder interest mean that the ecological importance of cetacean communities over shelf waters is now well recognised within the Strategic Environmental Assessments that are required for offshore energy developments (Fidler and Noble, 2012). Furthermore, the introduction of the EU Habitats & Species Directive requires more detailed assessments for new oil and gas developments that occur in the vicinity of SACs. However, compared to other key groups such as seabirds, current assessments can be constrained by the lack of historic monitoring of marine mammal populations.

These issues were raised in 2007, during the UK's 24th Licencing Round. In response to the EU Habitats & Species Directive, the UK Government conducted an AA to support their decision to offer new licences for oil and gas exploration in Block 17/3, on the boundary of the Moray Firth SAC (BERR, 2007). During public consultation, concerns were raised over the lack of evidence to support the conclusion that proposed developments in this area would not impact bottlenose dolphins using the SAC. In particular, it was argued that limited survey data from offshore areas provided insufficient evidence to conclude that bottlenose dolphins from the SAC did not occur in these areas, and a lack of historic monitoring of these species prior to 1990 prevented any assessment of how the population may have responded to long-term changes in oil and gas activity in the region (BERR, 2008).

In response to these concerns the UK's Department of Energy & Climate Change (DECC) commissioned the studies described below to improve understanding of the broader distribution of bottlenose dolphins using the Moray Firth SAC. At the same time, two companies (Caithness Petroleum Ltd. and PA Resources Ltd.) applied to conduct 2-D seismic surveys for up to one month in the central Moray Firth. Based upon the additional studies reported here, an AA to support the consenting of these two seismic surveys was undertaken by DECC in 2011. The AA indicated that bottlenose dolphins were unlikely to be in the vicinity of the seismic survey vessel, and the risk of near-field impacts was therefore extremely low. Furthermore, noise propagation modelling carried out for the developers and DECC indicated that animals were only likely to be displaced at distances of around 11 km or less from the survey vessel. The AA concluded that consenting seismic surveys over this relatively short period would not cause an adverse effect on the integrity of the bottlenose dolphin population that uses the Moray Firth SAC (DECC, 2011).

2.3. 2011 Seismic surveys in the Moray Firth

In September 2011, 2-D seismic surveys of 5 areas (Figure 1) were undertaken from MV Sea Surveyor, operated by Gardline Geosurvey (Table 1). The vessel arrived on site in the Moray Firth at 07:00 on 31st August 2011 and spent approximately two days balancing the streamer and undergoing trials before the first soft start was initiated at 15:15 on 1st September 2011. The first full survey line was carried out at 03:14 on 2nd September 2011 and surveys were completed on 23rd September 2011. Table 1 provides information on the timing of surveys in each area.

All surveys followed guidelines to reduce potential impacts on marine mammals developed by the UK Joint Nature Conservation Committee (JNCC) (Weir and Dolman, 2007). Prior to the start of seismic shooting, Marine Mammal Observers (MMO) onboard the vessel conducted visual and passive acoustic surveys of the

Table1. Details of the 2-D seismic surveys carried out in the Moray Firth in 2011. The location of each area is given in Figure 1.

Area	No of lines	Length (km)	Survey Start		Survey End	
			Date	Time	Date	Time
Block 17/4b	62	490	1/9/11	15:15	9/9/11	18:22
Helmsdale	14	196	9/9/11	21:43	11/9/11	20:20
Forse	26	180	14/9/11	01:19	22/9/11	16:39
Braemore	11	62	19/9/11	14:30	20/9/11	20:42
Burrigill	18	54	22/9/11	19:52	23/9/11	19:56

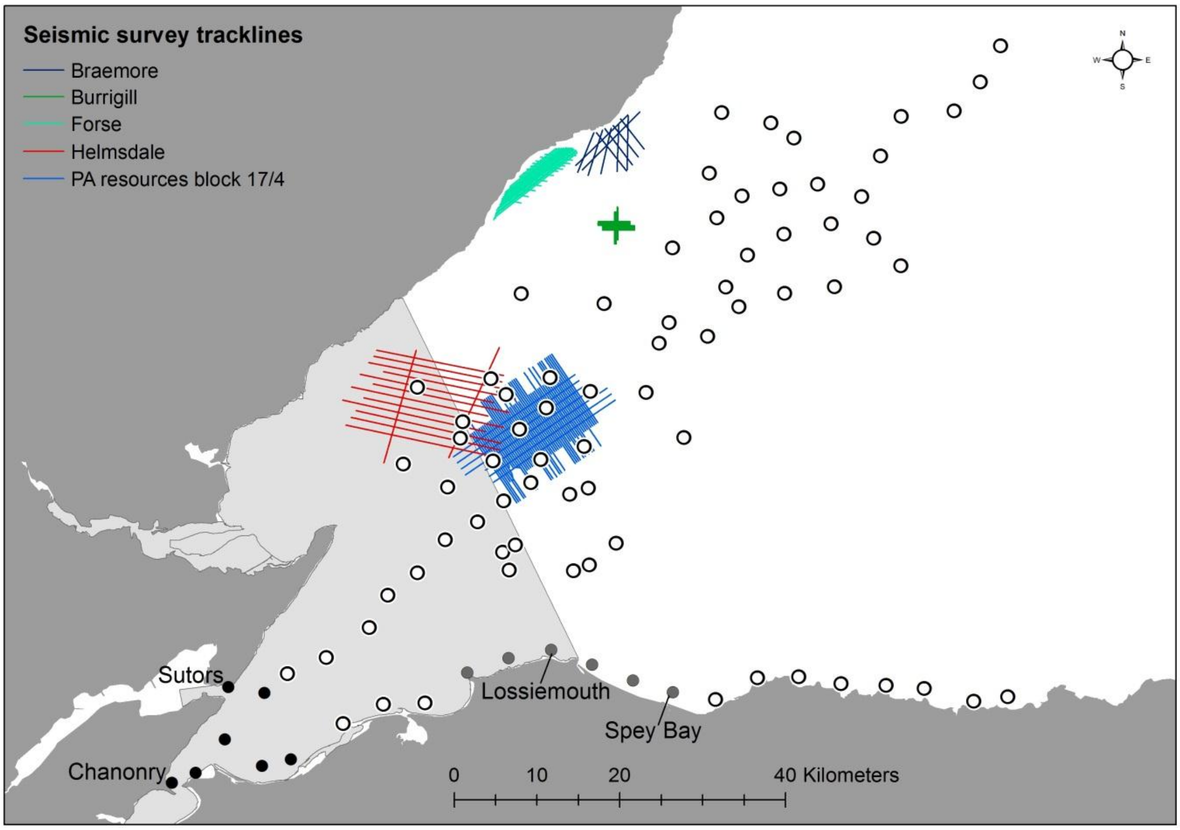


Figure 1. Map of the Moray Firth showing the boundary of the Moray Firth SAC, the seismic survey areas detailed in Table 1, and the location of Passive Acoustic Monitoring devices deployed to monitor variation in the occurrence of cetaceans. Grey and black filled circles indicate the location of the six "impact" and seven "control" sites respectively used in the BACI analysis.

area around the ship to ensure that no marine mammals were within 500 m of the guns. A soft start procedure was then initiated in which the volume of the air-gun discharge was gradually increased to its full operating volume of 470 cu inches over a 20 to 30 minute period, using a shot point interval of approximately 5-6 seconds. During each line turn, the volume of the gun discharge was reduced to 60 cu inches and the shot point interval increased to 4 minutes. Prior to the start of the next line, a soft start was again initiated once the MMO had confirmed that the area was free of marine mammals.

3 Methods

3.1 Broad-scale distribution of bottlenose dolphins

3.1.1 Passive acoustic monitoring

Passive acoustic monitoring techniques were used to collect information on temporal patterns in the occurrence of dolphins at a suite of coastal and offshore sites in 2009, 2010 and 2011 (Figure 1). Data from a sub-set of core sites were also available from 2008 and 2012.

Data were collected using V0 and V1 C-PODs as described in Chapter 2. The mooring type, location, and temporal coverage of devices varied between years as a result of logistic issues affecting deployment and recovery, and loss of equipment. In general, however, we aimed to collect data during the late summer, with deployments being made in June and early July and recoveries after late October. Here, we focus on presenting data for the three month period around the September seismic survey (1 August – 31 October) to provide the greatest spatial coverage. In addition, data are presented from four core sites where we aimed to maintain year-round data collection from June 2008 to October 2012.

As described in detail in Chapter 2, data were downloaded and train filtered using version 2.025 of the custom CPOD software (Chelonia Ltd., UK) to identify which echolocation clicks were produced by dolphins. These detections could either be from bottlenose dolphins or one of several other species that typically occur in more offshore areas (see Chapter 2). We previously used these data to model the distribution of dolphins in different parts of the Moray Firth in relation to habitat characteristics. Here, we use these data to illustrate broad-scale spatial variation in the occurrence of dolphins by estimating the proportion of days during the period August – September in which dolphins were detected at each passive acoustic monitoring site.

3.1.2 Visual aerial surveys

To reduce uncertainty over the species identity of dolphins using coastal and offshore parts of the Moray Firth, a series of aerial line transect surveys were conducted during the summer of 2010. The surveys were designed with the dual aim of estimating the density of harbour porpoises in two 25 x 25 km offshore blocks (see Chapter 5) and gathering data on the dolphin species occurring in these offshore survey blocks, along a transect through the central Moray Firth, and within coastal waters along the north and south coasts of the Moray Firth.

Surveys were conducted from a Partenavia 68 aircraft fitted with observer bubble windows, operated by Ravenair Ltd. The aircraft and team of surveyors were positioned at Inverness Airport throughout the period 16th August – 27th September 2010, and surveys were flown on all days with suitable weather conditions during that period. We used a line-transect survey methodology based on that developed for the broad-scale SCANS and SCANS II surveys (Hammond, 2006, Hammond et al., 2002). Within the two offshore blocks, parallel north/south transect lines spaced at 4 km were flown at a height of 600 feet on each survey. An offset of 1 km was used so that during the course of the survey period, the blocks were covered at 1 km spacing. On the coastal transects, the aircraft flew parallel to the coast at a distance of 1 km offshore, followed by a return transect approximately 5 km offshore (Figure 4).

During each survey, two experienced observers, working from different sides of the aircraft, recorded sightings into voice recorders. Time, species, number of animals and the declination angle to each sighting were recorded as a minimum. GPS data were recorded automatically every five seconds and these data were subsequently interpolated to give the location of the aeroplane when the sighting was made.

3.2 Patterns of abundance and occurrence in relation to seismic survey activity

3.2.1 Boat-based photo-identification surveys

Since 2001, annual boat-based photo-identification surveys have been conducted within the inner Moray Firth using survey routes that were chosen to maximise sighting probability within the inner Moray Firth (Cheney et al., 2012) . Data have also been collected during less regular and frequent surveys in other parts of the population's range (Cheney et al., 2013) and in 2009, 2010 and 2011 we aimed to make additional surveys along the southern Moray Firth coast; the area within the bottlenose dolphins' confirmed range that was closest to the seismic survey area.

All surveys were made from a 5.8 m rigid inflatable boat with outboard engines (Cheney et al., 2013, Wilson et al., 1997). When a group of dolphins was encountered, the time and position were noted and the boat was manoeuvred at slow speed around the dolphins to allow dorsal fin photographs to be obtained. We aimed to obtain high quality pictures of as many individuals as possible, whilst minimising disturbance, and ensuring that there was an equal probability of photographing different members of the group. Photo-identification pictures were later graded for photographic quality (Wilson et al., 1999) and analyses were restricted to the highest quality photographs (Cheney et al., 2013). Each photograph was matched against a catalogue of known individuals from the east coast of Scotland and all matches were confirmed by at least two experienced researchers.

Annual estimates of the abundance of bottlenose dolphins in the SAC were based on data collected within the SAC between May and September. We used a modification of the approach developed by Wilson *et al.* (1999), in which estimates were based only upon well-marked individuals with nicks in their dorsal fins. These individuals could be identified from both sides, and a single capture matrix for each year represented whether or not a well-marked individual was seen in a high quality photograph on each trip (Cheney et al., 2012). Following Wilson *et al*. (1999), we used the Chao *et al.* (1992) M_{th} model, implemented in the programme CAPTURE (Rexstad and Burnham, 1991), to estimate the number of well-marked individuals. High quality pictures of all dolphins photographed on each survey were then used to model the proportion of the population that were well-marked (θ), and this was then used to inflate the mark-recapture estimates of well-marked animals to estimate total annual abundance:

$$N_{total} = \hat{N} / \theta \qquad \text{(eqn 1)}$$

where N_{total} is the estimated number of individuals and $\hat{N}$ is the mark-recapture estimate of the number of well-marked animals. Upper and lower 95% confidence intervals were estimated by dividing and multiplying N_{total}, respectively, by:

$$e^{1.96\sqrt{\ln\left(1 + var(N_{total}) / N_{total}^2\right)}} \qquad \text{(eqn 2)}$$

where

$$var(N_{total}) = N_{total}^2 \left(\frac{var(\hat{N})}{\hat{N}^2} + \frac{var(\theta)}{\theta^2}\right) \qquad \text{(eqn 3)}$$

3.2.2 Passive acoustic monitoring

We assessed temporal variation in the occurrence of dolphins using data from the C-POD array described above. Here, we focussed on those sites within the core areas known to be used by bottlenose dolphins. In particular, we aimed to explore variation in occurrence in relation to seismic survey activity using data from sites along the southern Moray Firth coast.

Train filtered data from each C-POD were used to determine whether or not dolphins were detected in each hour, and the temporal pattern of occurrence at each site was expressed in terms of variation in the median number of detection positive hours (DPH) per day (Bailey et al., 2010a, Brookes et al., In Press).

We used a BACI analysis (Stewart-Oaten and Bence, 2001) to assess whether dolphin detections at the six “impact” sites along the southern Moray Firth coast changed during those seismic surveys conducted near to these sites (Block 17/4b and the Helmsdale prospect). Data from seven more distant sites within the inner Moray Firth were used as “control” sites. We used data on DPH per day from August (before the seismic survey) and data from 2nd to 11th September (during the seismic survey) in a generalised linear mixed model with a Poisson family error structure that accounted for non-negative integer values in DPH per day. PAM site was included as a random intercept, which removed patterns in the residuals and improved the fit of the model. The fixed effects of the model were Block ("impact" and "control" sites) and Period (before and during), and the significance of the interaction between these terms was used to detect whether or not there was an impact of seismic survey. Analyses were carried out in R version 2.15 (R Core Team, 2010).

4 Results

4.1 Broad-scale distribution of dolphins

Figure 2 shows spatial variation in the proportion of days that dolphins were detected at different PAM sites in 2009, 2010 and 2011. Similar patterns were seen in all three years. Detections were highest in the inner Moray Firth, where dolphins were present on most days throughout this period. Detections were also made on most days along the southern Moray Firth coast. Dolphins were recorded on a much smaller proportion of days in the central Moray Firth, but detection rates then increased at sites in the north-east of the study area.

Year-round data were available from four of these PAM sites, for periods of between two and five years depending upon site and month of the year (Table 2). All sites showed a summer peak in occurrence, with higher median values of DPH at those sites in the inner Moray Firth (Figure 3) where dolphins were also detected on a higher proportion of days (Figure 2).

Aerial surveys were made on 12 different days during August and September 2010 (Table 3). Dolphins were seen on 38 occasions. Most sightings were of bottlenose dolphins, all of which were recorded in the inner Moray Firth or along the southern Moray Firth coast. Most of these bottlenose dolphin sightings were within 5 km of the coast, but two groups were detected further offshore at 7 and 12 km from the south coast (Figure 4 b). In contrast, most aerial survey effort was further offshore (Figure 4 c) where all dolphin sightings were of white-beaked dolphin, common dolphin or Risso's dolphin (Figure 5).

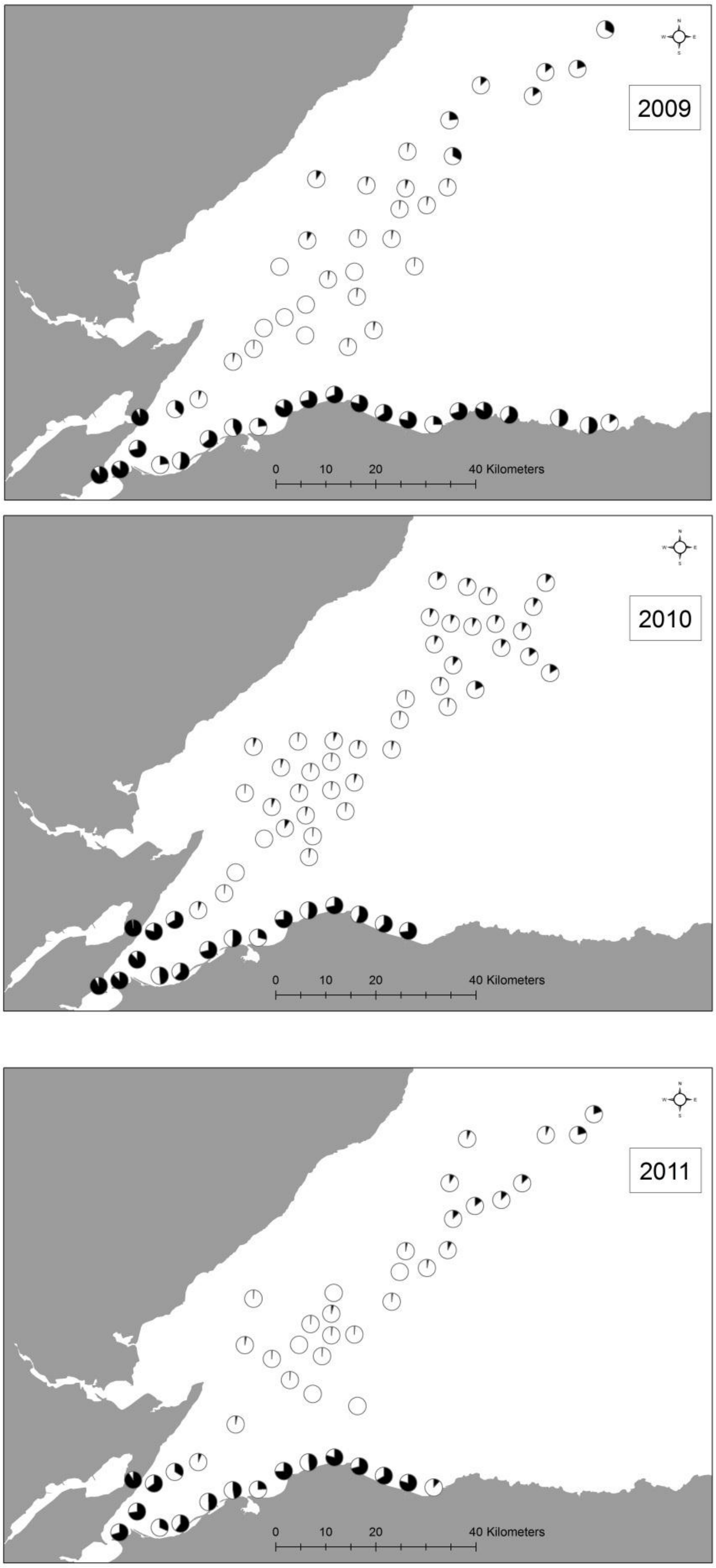


Figure 2. Spatial variation in the proportion of days that dolphins were detected at different passive acoustic monitoring sites in August, September & October of 2009, 2010 & 2011.

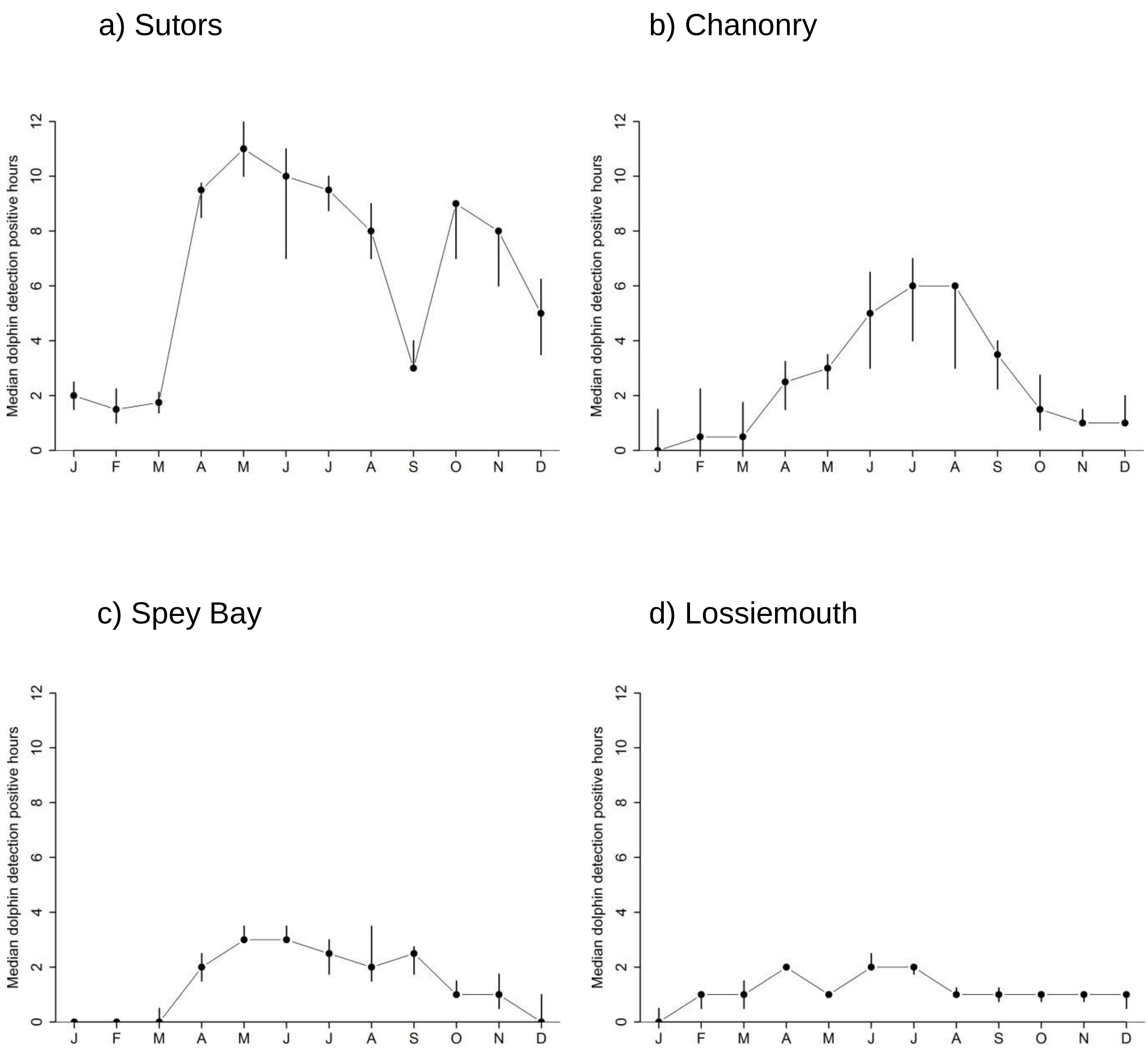


Figure 3. Seasonal patterns of occurrence of dolphins at PAM sites in the inner Moray Firth (a. Sutors and b. Chanonry) and on the southern Moray Firth coast (c. Spey Bay and d. Lossiemouth). Data are medians (with inter-quartile ranges) of the monthly median values for between two and five years. Sample sizes for each month are provided in Table 2.

Table 2. Number of years of data used to produce graphs of monthly median dolphin detection positive hours for the four core sites.

Month	Sutors	Chanonry	Lossiemouth	Spey Bay
Jan	4	4	3	3
Feb	4	4	3	3
Mar	2	4	3	3
Apr	3	4	3	3
May	5	4	3	3
Jun	5	5	3	3
Jul	4	5	4	4
Aug	5	5	4	3
Sep	5	4	4	3
Oct	5	4	4	3
Nov	5	5	4	3
Dec	4	4	3	3

Table 3. Details of aerial surveys conducted in the offshore blocks and coastal transects.

Date	Areas surveyed	Total on effort survey time	Total on effort survey distance (km)
17th Aug 2010	Blocks and transect	02:18:50	455.13
18th Aug 2010	Blocks and transect	02:39:52	453.20
19th Aug 2010	Blocks, transect and N coast	03:00:46	563.33
25th Aug 2010	N coast	00:37:44	109.41
26th Aug 2010	Blocks and transect	02:25:25	457.12
1st Sept 2010	Blocks, transect and S coast	03:20:00	603.47
2nd Sept 2010	S coast	00:25:10	72.58
9th Sept 2010	Blocks, transect and S coast	03:33:55	601.60
19th Sept 2010	Blocks, transect and N coast	03:14:55	562.53
21st Sept 2010	S coast	00:51:45	143.25
22nd Sept 2010	N and S coasts	01:37:05	266.66
26th Sept 2010	Blocks, transect and N coast	03:09:11	566.03
27th Sept 2010	Blocks, transect and N coast	03:09:56	591.996

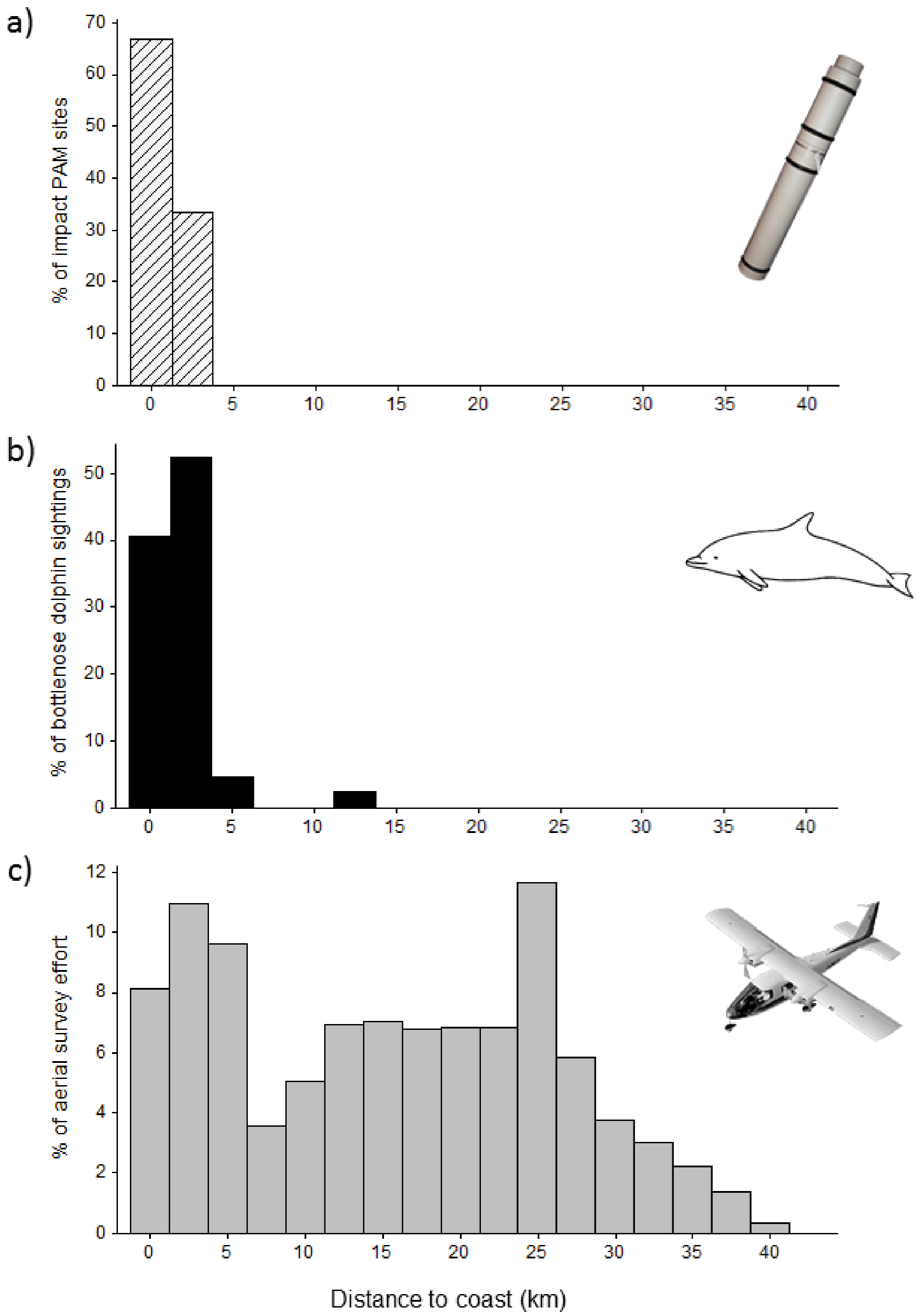


Figure 4.Frequency histograms showing the distance from shore at which a) CPODs were moored within the "impact" area along the southern Moray Firth coast b) bottlenose dolphins were sighted during the 2010 aerial survey and c) aerial surveys were conducted in 2010.

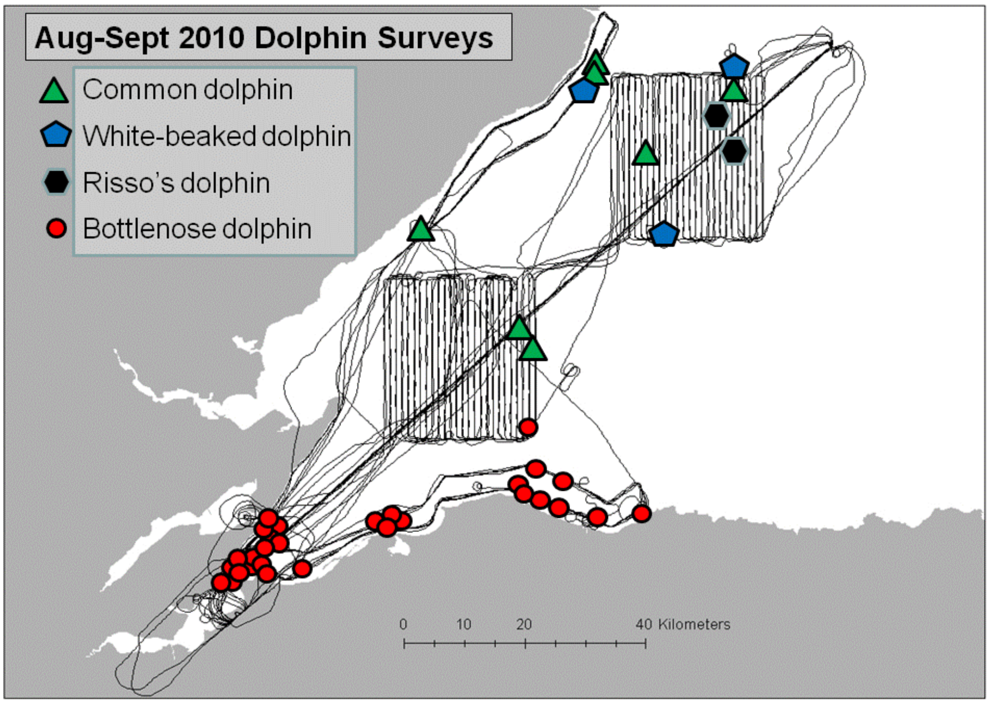


Figure 5. Aerial survey data showing the survey lines for all aerial surveys (see Table 3) and the locations for all encounters with different dolphin species.

4.2 Patterns of abundance and occurrence in relation to seismic survey activity

Dolphins were detected regularly throughout August and September at sites both in the inner Moray Firth and along the southern Moray Firth coast (Figure 6). In general, as seen from the core sites (Figure 3), detections were higher in the inner Moray Firth, but the relative importance of these two areas varied slightly between years.

The BACI analysis using 2011 data identified a significant impact of the seismic survey, with an increase in dolphin detections of 200% (to a median of 3 hrs per day) in the southern Moray Firth coastal sites compared to a reduction of 50% (to a median of 1 hr per day) in the inner Moray Firth sites (GLMM: $X^2 = 45.8$, d.f = 1, P <0.001; Figure 6 and Table 4). Repeating the BACI analysis using data from the same periods in 2010 and 2009 data found no significant interaction between block ("impact" and "control" sites) and period (GLMM 2010: $X^2 = 2.96$, d.f = 1, P = 0.09; GLMM 2009: $X^2 = 1.25$, d.f = 1, P = 0.26; Figure 6).

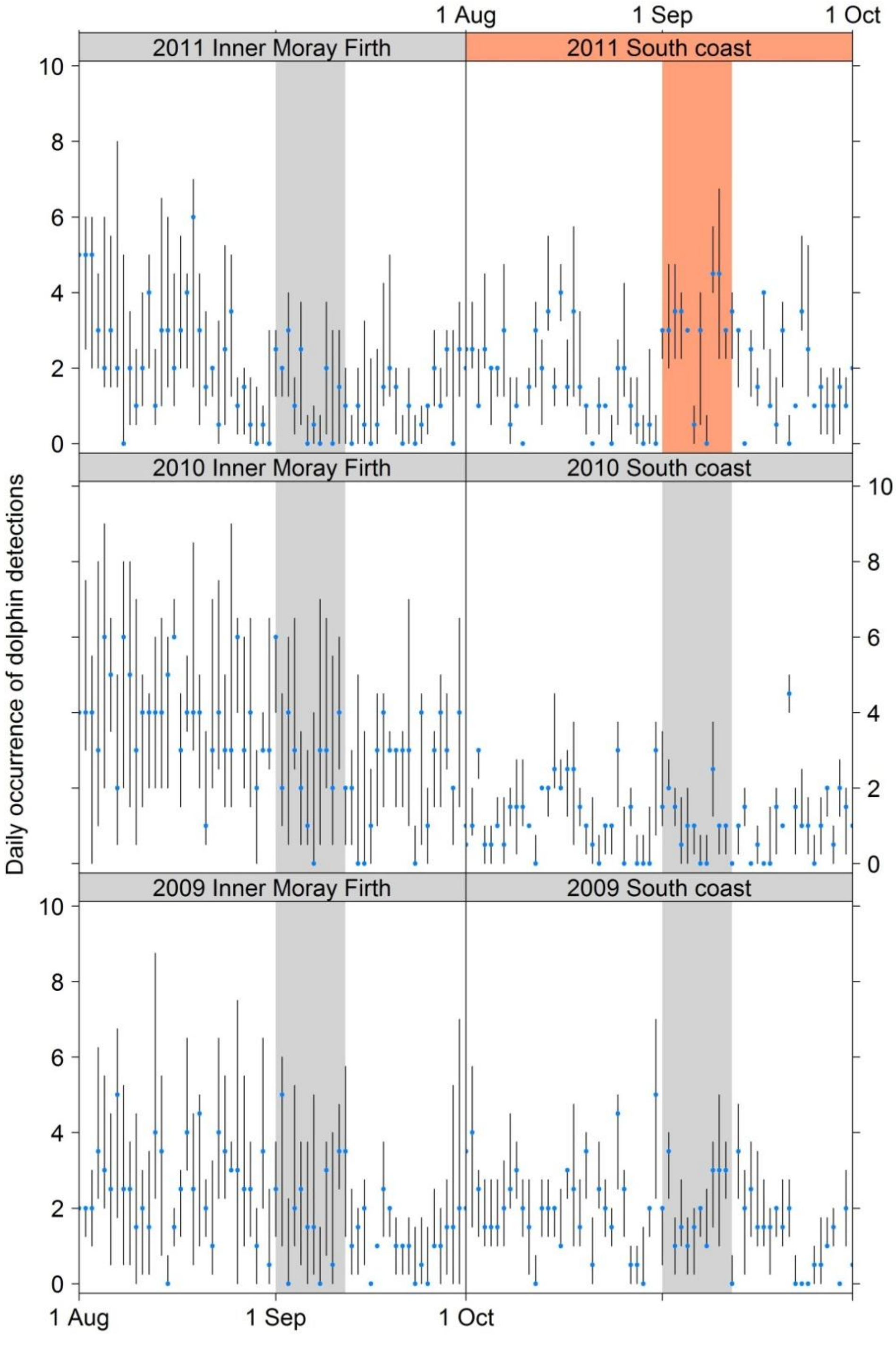


Figure 6. Seasonal variation in the occurrence of dolphins at PAM sites in the inner Moray Firth (n=7) and on the southern Moray Firth coast (n=6) in the year of the seismic survey (2011) and in the two previous years. The timing of the seismic survey is shaded in orange. Data are median detection positive hours with inter-quartile ranges.

Boat–based photo-identification surveys in the summers of 2009 to 2012 encountered groups of bottlenose dolphins both in the inner Moray Firth and along the southern Moray Firth coast (Figure 7; Table 5). Overall a total of 52 well-marked dolphins were identified during surveys along the southern Moray Firth coast. All but one of these individuals were also observed within the SAC in these years, and that single individual had been observed in the SAC in previous years.

Table 4. The results of a Poisson generalised linear mixed model used to investigate the effect of the seismic survey on acoustic detection of dolphins, before (1st – 31st August 2011) and during (2nd – 11th September 2011) the seismic survey at six sites on the southern Moray Firth coast (impact) and seven sites in the inner Moray Firth (control).

	Estimate	Standard Error	P value
Intercept	0.995	0.228	<0.001
Block	-0.394	0.337	0.243
Period	-0.526	0.106	<0.001
Block : Period interaction	0.926	0.139	<0.001

Table 5. Information on photo-identification survey sample sizes in different areas between May and September and the number of well-marked bottlenose dolphins photographed.

		2009	**2010**	**2011**	**2012**
No. of Surveys	Total	34	24	21	19
	South Coast	8	8	3	1
No. of Encounters	Total	107	121	107	119
	South Coast	12	12	3	5
No. of well-marked individuals observed	Total	53	60	55	59
	South Coast	32	30	13	28

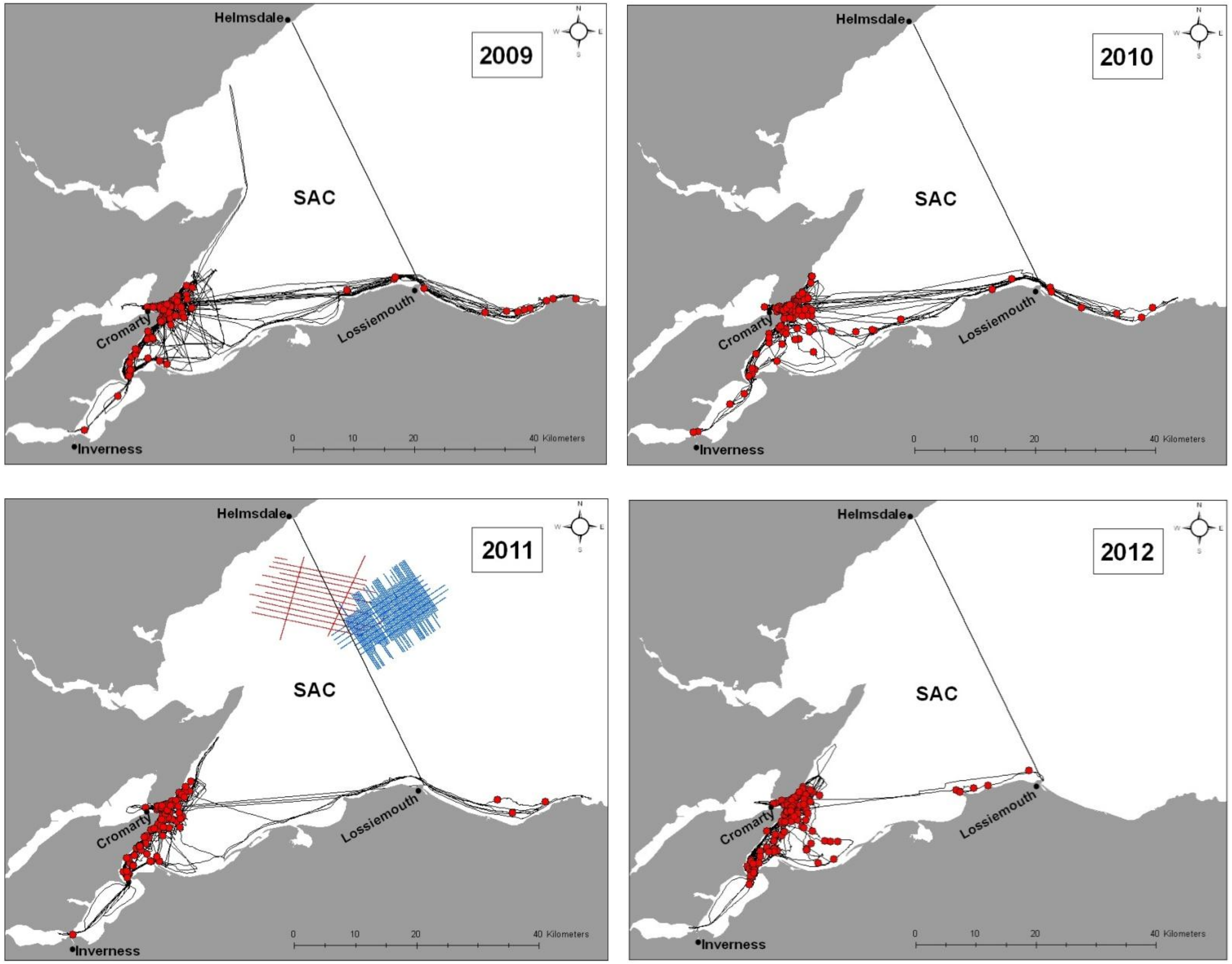


Figure 7. Map showing the photo-identification survey routes and locations of encounters with bottlenose dolphins within the SAC and along the southern Moray Firth coast between May and September 2009, 2010, 2011 and 2012. The seismic survey lines during full power surveys between the 1^{st} and 11^{th} September 2011 are shown as red and blue lines.

Four of these photo-identification surveys were conducted during September 2011, either during or soon after the seismic surveys, on the 1st, 5th, 15th and 29th. Bottlenose dolphins were seen on all surveys, and a total of 40 well-marked individuals were identified. The only survey to visit the south side of the Moray Firth was on 29th September, after the seismic survey had ended, when 10 well-marked individuals were encountered.

During our 5th September survey within the SAC, a group of 37 individuals was encountered south of the Cromarty Firth (57°38.569'N, 4°02.517'E) while the seismic survey was underway approximately 50 km to the NE. Hydrophone recordings made immediately after this encounter, at 12:57 GMT, recorded both the seismic air-gun and dolphin echolocation clicks and whistles. There was no discernible reaction to the seismic air-gun from this group, which contained 22 well-marked individuals that were regularly seen within the SAC, 15 of which had also been encountered on the south coast of the Moray Firth earlier in 2011.

Overall, estimates of the number of dolphins occurring within the Moray Firth SAC were similar in all four years, varying between 108 (84-138) and 121 (96-152) (Table 6).

Table 6. Capture-Mark-Recapture estimates of the number of well-marked individuals ($\hat{N}$) and the total number (N_{total}) of bottlenose dolphins (with 95% confidence intervals) present in the SAC during each summer between 2009 and 2012.

Year	$\hat{N}$	N_{total}	95% CI
2009	57	108	85-136
2010	64	121	96-152
2011	57	108	84-138
2012	63	119	94-150

5. Discussion

The potential impacts of air-gun noise from oil and gas exploration are widely recognised, but uncertainty over the nature and scale of these impacts currently constrains assessments of their ecological significance. These issues are highlighted in Thomsen *et al.*'s (2011) review, which included a detailed case study of the exploration and production industry on the UK's east coast. In that case study, Thomsen *et al.* (2011) focused on the potential impacts and data requirements for harbour porpoises and minke whales, the most widespread and abundant cetacean species in this area, and therefore those most likely to overlap with oil and gas activity. However, as illustrated in our study, limited data on more localised cetacean populations can also constrain environmental assessments for new developments, particularly where these occur in or near SACs that have been designated under the EU Habitat and Species Directive.

In the Moray Firth, concerns over potential impacts on the protected population of bottlenose dolphins required additional research and survey effort in the area to inform licencing decisions. Similarly, some of the most intensive studies of interactions between cetaceans and seismic survey activity have occurred where surveys have been planned near areas known to be regularly used by small populations of protected baleen whales (Blackwell et al., 2013, Johnson et al., 2007, Yazvenko et al., 2007). In our study, passive acoustics confirmed that dolphins occurred only rarely in the areas identified for oil and gas exploration (Figure 2). These acoustic data could not be used to determine the identity of those dolphins detected. However, directed aerial surveys and analyses of historic survey data (Reid et al., 2003, Robinson et al., 2007) indicate that those dolphins occasionally occurring in the proposed seismic survey area are most likely to be offshore species such as white-beaked dolphin and common dolphin (Figure 4), and not members of the bottlenose dolphin population that inhabit the Moray Firth SAC.

As a result of additional research in the outer Moray Firth, impact assessments for this development focused on potential far-field effects that might result in disturbance of bottlenose dolphins within core parts of their range. Although some of the planned seismic surveys were close to or within the eastern boundary of the SAC (Figure 1), our analyses of PAM and visual survey data suggested that bottlenose dolphins were most likely to be exposed to seismic noise when using waters along the southern Moray Firth coast (Chapter 2), at distances of 20-30 km from the seismic vessel. Previous studies have demonstrated that this area forms a corridor between the SAC in the inner Moray Firth and other key foraging areas around the east coast of Scotland (Cheney et al., 2013, Culloch and Robinson, 2008, Wilson et al., 2004). While serious disturbance effects were considered unlikely at this range, it was not possible to rule out changes in the occurrence of dolphins within that corridor, or even subsequent changes in the numbers of animals using the SAC.

We therefore used PAM to monitor patterns in the occurrence of dolphins, both at a series of sites within this corridor and at core sites within SAC. Year-round data from a subset of these sites highlighted consistent summer peaks in occurrence at all sites, as reported previously using boat-based survey data from within the Moray Firth SAC (Wilson et al., 1997). In general, detections were higher at sites within the inner Moray Firth but this appeared to vary between years and to a certain extent through the season (Figures 2 and 3). In Chapter 5, a BACI analysis identified a significant decrease in the occurrence of harbour porpoises within the seismic survey area compared to an offshore control area. Here, we used the same approach to determine whether the occurrence of dolphin detections changed significantly during the seismic survey period. Unexpectedly, we did identify a significant change in the occurrence of dolphin detections along the southern Moray Firth coast when compared to control sites within the inner Moray Firth. However, in this case, there was an observed increase in dolphin detections in the area closest to the seismic vessel during the seismic survey. This result could be due to an increase in vocalisation rates in this area, or an increase in the number of dolphins around these C-POD sites. Information on received levels of noise from this area were available from two recording sites (Chapter 4; sites 7 & 8), at distances of 23.8 and 21.3 km. Peak to peak levels at these sites averaged 156.9 and 155.7 dB re 1 µPa, and would be expected to be detectable above background noise for bottlenose dolphins. One possibility is that dolphins in this area altered their vocalisation rate, as reported for blue whales exposed to low level seismic survey noise (Di Iorio and Clark, 2010), or increased the amplitude of their calls during higher levels of background noise as observed in right whales (Parks et al., 2011). Alternatively, offshore seismic survey activity could have displaced dolphins into a narrower corridor along the coast, increasing detection rates at our near shore PAM sites. Future studies of far-field responses to impulsive noise from both seismic surveys and pile driving could explore these possible responses by conducting parallel visual and acoustic studies, or using broad band acoustic arrays to localise individuals and measure source levels.

Previously, information on the responses of small cetaceans to seismic survey activity has been based on observations directly around the survey vessel (Goold and Fish, 1998, Stone and Tasker, 2006, Weir, 2008). Our monitoring of far field responses by bottlenose dolphins, together with parallel near-field studies of harbour porpoises, provide additional evidence for short-term behavioural responses to noise as reported for baleen whales (Castellote et al., 2012). However, there was no evidence for an overall reduction in the occurrence of bottlenose dolphins in those parts of their core-range that were closest to the survey vessel. Annual abundance estimates of the number of bottlenose dolphins present in the Moray Firth SAC were also similar in all years. These findings support the Appropriate Assessment's conclusion that this relatively short seismic survey would not have a major impact on the number of animals using the SAC (DECC, 2011). However, our data do suggest that the survey was associated with a finer-scale re-distribution of individuals or change in behaviour that could incur some energetic costs. Where such changes occur during longer periods of disturbance, there could be potential impacts on individual vital rates (Currey et al., 2011, New et al., 2013). Further work is now required to determine the nature and magnitude of these impacts to support management frameworks that can be used to assess whether longer periods of disturbance influence population dynamics.

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