



Mapping widespread and increasing underwater noise pollution from acoustic deterrent devices

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ABSTRACT

Acoustic deterrent devices (ADDs) are used in attempts to mitigate pinniped depredation on aquaculture sites through the emission of loud and pervasive noise. This study quantified spatio-temporal changes in underwater ADD noise detections along western Scotland over 11 years. Acoustic point data ('listening events') collected during cetacean line-transect surveys were used to map ADD presence between 2006 and 2016. A total of 19,601 listening events occurred along the Scottish west coast, and ADD presence was recorded during 1371 listening events. Results indicated a steady increase in ADD detections from 2006 (0.05%) to 2016 (6.8%), with the highest number of detections in 2013 (12.6%), as well as substantial geographic expansion. This study demonstrates that ADDs are a significant and chronic source of underwater noise on the Scottish west coast with potential adverse impacts on target (pinniped) and non-target (e.g. cetaceans) species, which requires further study and improved monitoring and regulatory strategies.

1. Introduction

Over the past 30 years marine finfish aquaculture has expanded dramatically across the globe, and is projected to provide two thirds of global food fish by 2030 (FAO, 2017). This expansion has, however, resulted in increasing conflict with marine top predators such as cetaceans and birds, but particularly pinnipeds (Northridge et al., 2013; Quick et al., 2004). To reduce such interactions, various predator control methods have been tried, including targeted shooting of problem individuals, culling programmes to reduce populations, and different forms of non-lethal deterrence like physical barriers and animal relocation programmes (Quick et al., 2004). Of the non-lethal methods used, the emission of loud acoustic signals from Acoustic Deterrent Devices (ADDs, also known as Acoustic Harassment Devices [AHDs]) is often considered a comparatively benign solution to the problem of depredation at aquaculture facilities (Nash et al., 2000). However, their (long-term) effectiveness in preventing pinniped depredation has not been shown conclusively and remains a topic of considerable debate (reviewed by Götz and Janik, 2013).

Most commercially available ADDs are designed to produce intense

and aversive sounds within the hearing range of the target species (pinniped underwater hearing range 50 Hz to 86 kHz; National Marine Fisheries Service, 2016), aiming to deter them from approaching and damaging the pens or the fish themselves (Coram et al., 2014; Götz and Janik, 2013; Jacobs and Terhune, 2002; Quick et al., 2004). ADDs are deployed underwater, attached to aquaculture cages and can be set to run continuously (Northridge et al., 2013). A variety of ADD types exist which differ substantially in their acoustic characteristics (e.g. frequency range, amplitude, and duty cycle). The majority of these devices produce sounds in the range of 2 to 40 kHz, with source levels ≥ 185 dB re 1 μ Pa @ 1 m (RMS; Gordon and Northridge, 2003; Lepper et al., 2014; Reeves et al., 2001).

Given their frequency ranges and source levels, ADDs have the potential to cause physical and behavioural effects on both target and non-target species, including cetaceans. Physically, ADD noise may result in temporary or permanent reductions in hearing sensitivity (Temporary Threshold Shift [TTS] or Permanent Threshold Shift [PTS]) of marine mammals which use sound as their primary sense (Götz and Janik, 2013). ADD use can also lead to behavioural responses, and potential exclusion from key habitats used for foraging, resting and/or

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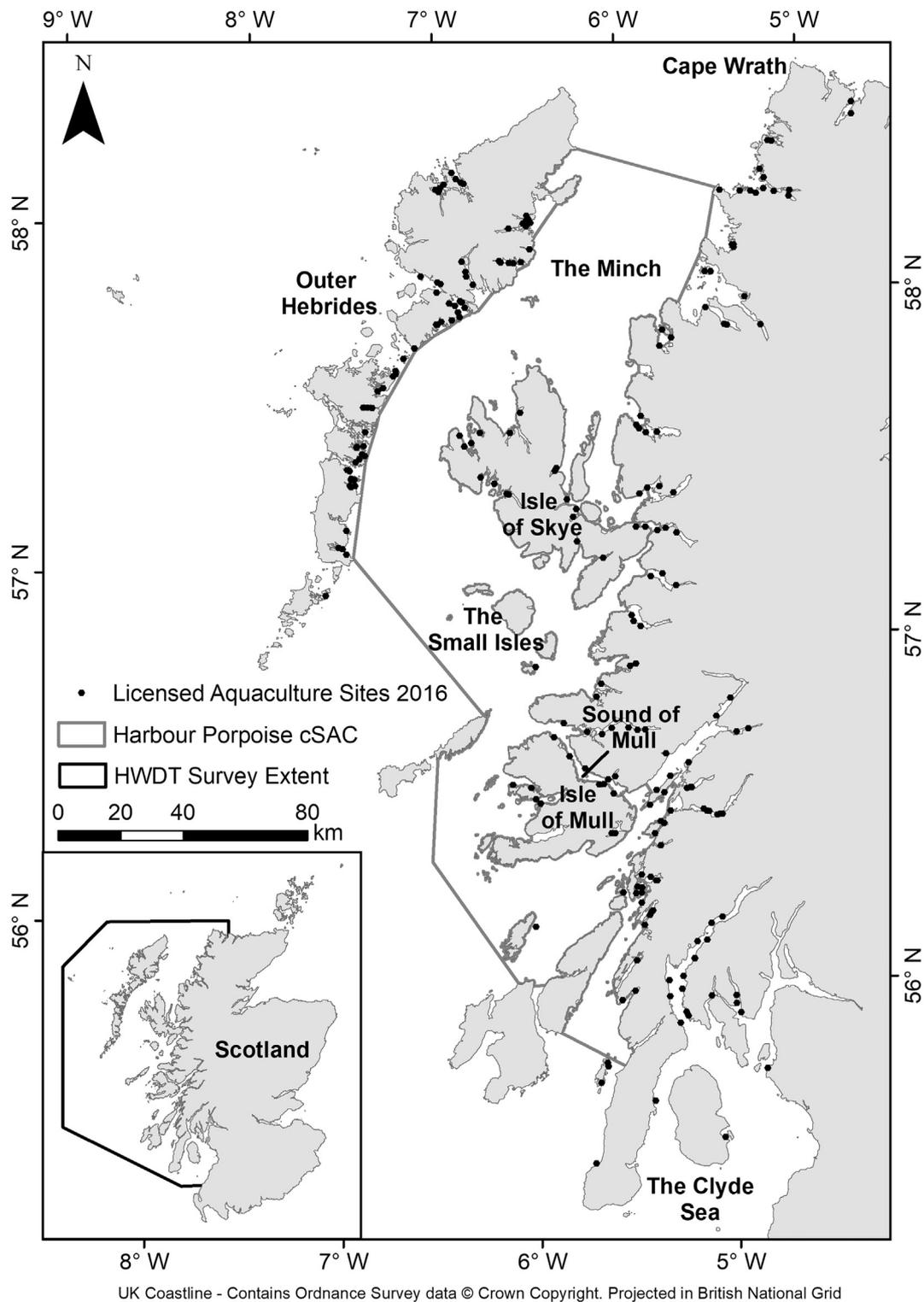


Fig. 1. Map of the west coast of Scotland, UK, illustrating overall Hebridean Whale and Dolphin Trust (HWDT) survey extent (bottom left), the locations of licensed salmon aquaculture sites (active and inactive) in 2016, and ‘the Inner Hebrides and the Minches’ candidate Special Area of Conservation (cSAC) for harbour porpoise (*Phocoena phocoena*).

reproducing (e.g. Brandt et al., 2013; Coram et al., 2014; Harris et al., 2014; Morton and Symonds, 2002). These issues are compounded when ADDs are used simultaneously on multiple cages within a single aquaculture site and among adjacent sites, which are often spread out to reduce cumulative negative impacts of localised eutrophication, chemical pollution, and disease outbreaks (Butler, 2002; Frid and Mercer, 1989). When used over large areas and extended time periods, ADDs

may therefore represent a source of chronic underwater noise pollution which may negatively affect animals’ individual fitness, potentially with long-term population consequences (King et al., 2015).

On the west coast of Scotland, cage-based finfish aquaculture (mainly involving Atlantic salmon, *Salmo salar*) is a rapidly expanding rural industry (The Scottish Government, 2015). Seal depredation has been reported by the sector (Harris et al., 2014; Northridge et al., 2013;

Table 1

Summary of survey and listening event effort carried out by the Hebridean Whale and Dolphin Trust (HWDT) for all years included in the present analysis (2006–2016), including the year of survey, distance surveyed in kilometres, total number of listening events, the number of ADD detections, ADD detection rate (%) and median across all years.

Year	Distance surveyed (km)	Total number of listening events	Total number of ADDs detected	ADD detection rate (%)
2006	8399.8	938	5	0.53
2007	8666.5	1878	55	2.93
2008	7956.5	547	29	5.30
2009	9846.4	2508	112	4.47
2010	8427.8	1963	92	4.69
2011	8678.1	2334	183	7.84
2012	5996.0	1500	145	9.67
2013	6123.0	1645	208	12.64
2014	8566.1	1737	122	7.02
2015	8886.2	2457	278	11.31
2016	9370.5	2094	142	6.78
Median	8566.1	1878	122	6.78

Table 2

Performance results for volunteer detections. True positive indicates the number of correctly identified acoustic deterrent devices (ADDs) as verified by independent sound analysis, false negative indicates the number of ADDs missed by volunteers, and false positive indicates the number of falsely identified ADDs. Missed detections represent the percentage of false negatives relative to all listening events, while false detections represent the percentage of false positives relative to all listening events.

Year	True positive	False negative	False positive	Total number of listening stations	Missed detections (%)	False detections (%)
2011	209	36	24	2334	1.5	1.0
2012	157	21	18	1500	1.4	1.2
2013	203	32	37	1645	1.9	2.2
2014	149	56	35	1737	3.2	2.0
2015	362	109	22	2457	4.4	0.9

Quick et al., 2004; The Scottish Government, 2016), involving both grey (*Halichoerus grypus*) and harbour (*Phoca vitulina*) seals which are widespread in Scottish west coast waters. ADDs were first introduced to the west coast of Scotland in the mid-1980s (Coram et al., 2014). Since then, their use in the Scottish aquaculture sector expanded quickly within the first few years of deployment (Ross, 1988). Following widespread uptake of ADDs in the 1990s, Quick et al. (2004) reported ADDs in use at 52% of 195 aquaculture sites interviewed in 2001. This figure is in broad agreement with the 49% of aquaculture sites reporting to use ADDs in a more recent study by Northridge et al. (2010). Although widely used in the Scottish salmon aquaculture sector, there are currently no formal statistics on numbers or types of ADDs used at aquaculture sites, and no license is required to use these devices (Coram et al., 2014). Additionally, there is a lack of consistent reporting on time periods within which ADDs are active at individual sites. ADD usage patterns appear to be varied; fish farms may use devices continuously, or only turn them on when fish become large enough to be considered at risk, when seals are close to nets, and/or when seal damage has occurred (Northridge et al., 2013). Thus, ADDs may represent a regionally important but often overlooked source of anthropogenic underwater noise pollution (Morton and Symonds, 2002).

This study aimed to address the gap in knowledge on the geographic and temporal extent of ADD use in the aquaculture industry on the west coast of Scotland, and to quantify the scale of their acoustic footprint. An 11-year dataset (2006–2016) of acoustic point data collected during cetacean line-transect surveys was used to determine the spatio-temporal changes in acoustic presence of ADDs, as well as to identify the

most commonly used ADD types deployed across the west coast of Scotland.

2. Materials and methods

2.1. Survey area and protocol

Acoustic point data were collected during dedicated visual and acoustic cetacean line transect surveys conducted by the Hebridean Whale and Dolphin Trust (HWDT) on board the 18 m motor-sailing vessel, *RV Silurian*. Surveys were conducted off the west coast of Scotland (Fig. 1; survey extent: 55.15°N to 58.7°N and 4.7°W to 8.7°W) from 2006 to 2016 between March and October. Survey effort varied between years, and acoustic data was collected each day typically between 09:00 to 17:00 UTC, however, the number of surveys and length of survey days varied seasonally with day lengths and variable weather conditions. For similar reasons, survey tracks were not identical each year, but attempted to broadly cover inshore and offshore waters to obtain wide-scale coverage across as much of the west coast of Scotland as possible. Visual and acoustic surveys were conducted by a team of trained volunteers and crew. Global Position System (GPS) data were automatically recorded every 10 s using Logger 2000 and 2010 software developed by the International Fund for Animal Welfare (IFAW) to promote benign and non-invasive research (Marine Conservation Research, 2016). In addition, data on survey effort and environmental conditions were manually entered into the same programme.

Every 15 min, while surveying in waters deeper than 20 m, the vessel slowed down to carry out a dedicated one-minute 'listening event'. During this time, HWDT volunteers listened to the hydrophone output to identify sources of audible sounds (i.e. ADDs, cetacean vocalizations, ship noise, etc.) and recorded these in the Logger database. As most ADDs transmit sounds in a frequency range of 2 to 40 kHz, with main energy at 10–15 kHz (Lepper et al., 2014), ADDs are audible to humans (nominal human hearing range: 20 Hz–20 kHz; Heffner and Heffner, 2007), allowing volunteers to score their presence by the intensity of the sound on a scale of 0 (inaudible) to 5 (loud). During each listening event, a one minute recording was made. The hydrophone array used for these recordings, consisted of two omni-directional high-frequency elements (HS150 elements – Sonar Research & Development Ltd.), with highest sensitivity at 150 kHz (–204 dB re 1 V/μPa) and an approximately flat frequency response between 2 and 140 kHz. Both hydrophone elements were connected to a pre-amplifier providing 29–35 dB of gain, and housed in a 35 mm diameter polyurethane tube filled with ISOPAR-M oil. Recordings were made at a sample rate of 96 kHz, resulting in an effective analysis bandwidth of 48 kHz.

2.2. Processing of listening event data

To gain a perspective on the spatial extent of ADD use across the west of Scotland, data on the presence or absence of audible ADD noise from each listening event logged on *Silurian*, were aggregated and plotted for all years using a 5 × 5 km European Environment Agency reference grid in ArcGIS 10.3.1. Grid cells indicated ADD presence for the year in question, if ADDs were detected during a minimum of one listening event within the extent of the cell. Yearly proportions of overall listening events where ADDs were audible were calculated and temporal changes analysed using a beta regression with log link function in R (Package: *betareg*; Cribari-Neto and Zeileis, 2010; version 3.3.3. R Core Team, 2017).

2.3. Verification of on-board database entries

To assess the validity of using the on-board database entries to estimate the spatio-temporal distribution of ADDs, a subset of 5 years of database entries (2011–2015) was manually validated post-hoc using the available, concurrently collected sound recordings. These data were

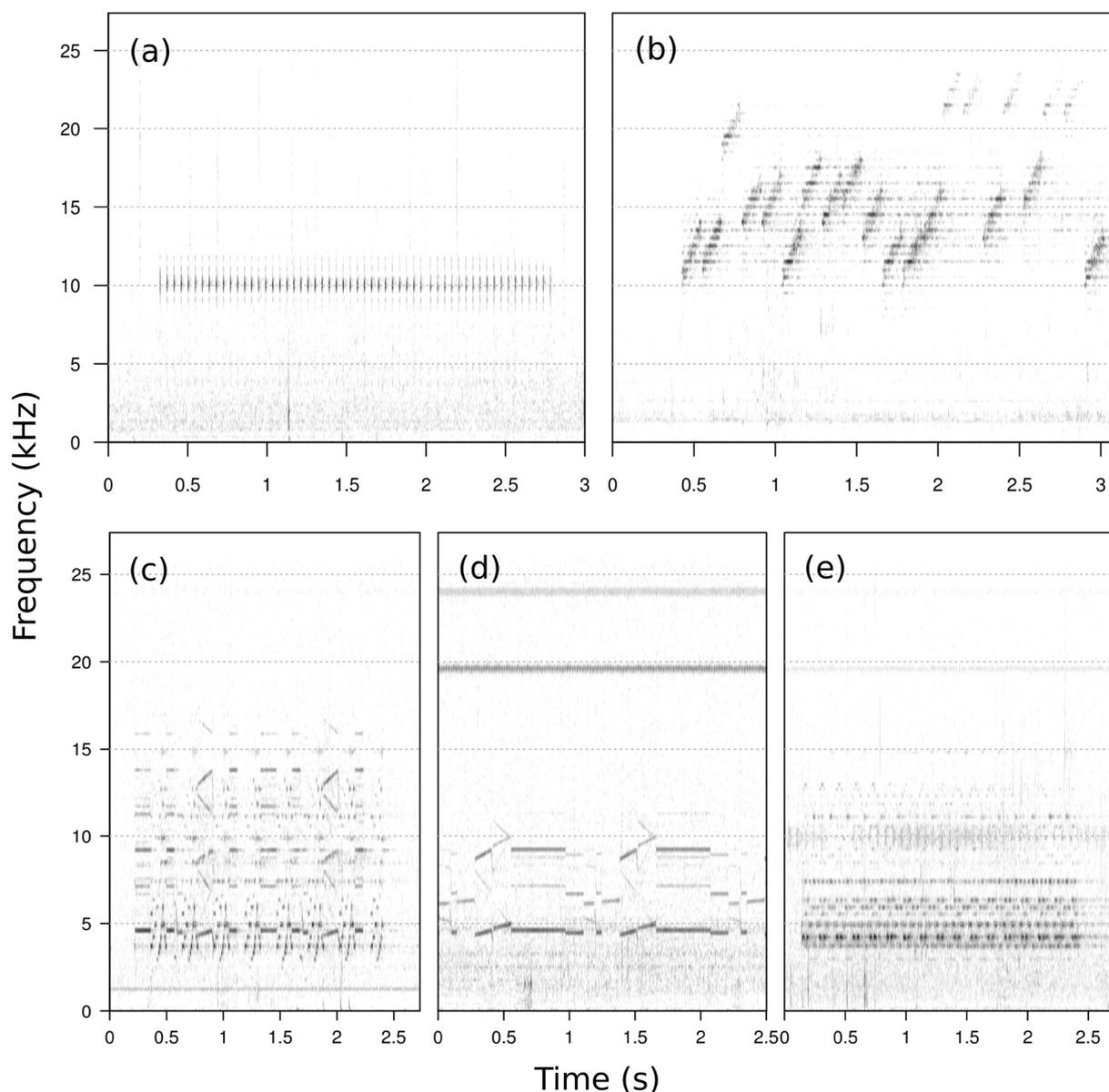


Fig. 2. Example spectrograms of acoustic deterrent device (ADD) types recorded on Hebridean Whale and Dolphin Trust cetacean surveys (2011–2015). Spectrogram parameters: FFT size = 1024 points, overlap = 50%, sample rate = 96 kHz; resulting in frequency and time resolution of 93.8 Hz and 10.67 ms, respectively. (a) Airmar™ (dB Plus II); (b) Ace Aquatec™ (US3); (c) Terecos™ (Type DSMS-4) Programme 4; (d) Terecos™ (Type DSMS-4) Programme 2; (e) Terecos™ (Type DSMS-4) Programme 3.

also used to determine which types of ADDs were being predominantly used by the aquaculture industry and whether any changes in ADD type could be observed over the 5 years analysed.

To visually and aurally determine ADD presence, spectrograms (60-s window, Fast Fourier Transformation (FFT) size = 1024 points, overlap = 50%, sampling rate = 96 kHz resulting in 93.8 kHz frequency and 10.7 ms temporal resolution) were created using PAMGuard software (version 1.15; Gillespie et al., 2008; <https://www.pamguard.org/>). Manually verified detections were then compared to volunteer database entries for the same listening events. Volunteer detection data quality was evaluated by comparing the percentage of false detections to the percentage of missed detections. ADDs were identified using information from existing literature (e.g. Brandt et al., 2013; Coram et al., 2014; Lepper et al., 2004, 2014), and online manufacturer specifications.

3. Results

A total of 90,917 km (yearly median: 8566.1 ± 709.3 km) of track line were surveyed by the HWDT between the years of 2006 and 2016 (Table 1). Over this time period, a total of 19,601 listening events were carried out across the west coast of Scotland from the Clyde Sea in the southern end of the survey region, to the eastern coastline of the Outer Hebrides and Cape Wrath in the north (Table 1; Fig. 1). ADDs were reported during a total of 1371 listening events, and their occurrence spanned the majority of the west coast of Scotland.

3.1. Verification of on-board database entries

Comparison of on-board database entries to spectrogram analyses of acoustic recordings showed that volunteers detected the presence of ADD signals with high levels of accuracy (Table 2). Overall, and in all years analysed, ADDs were missed < 5% of the time and they were

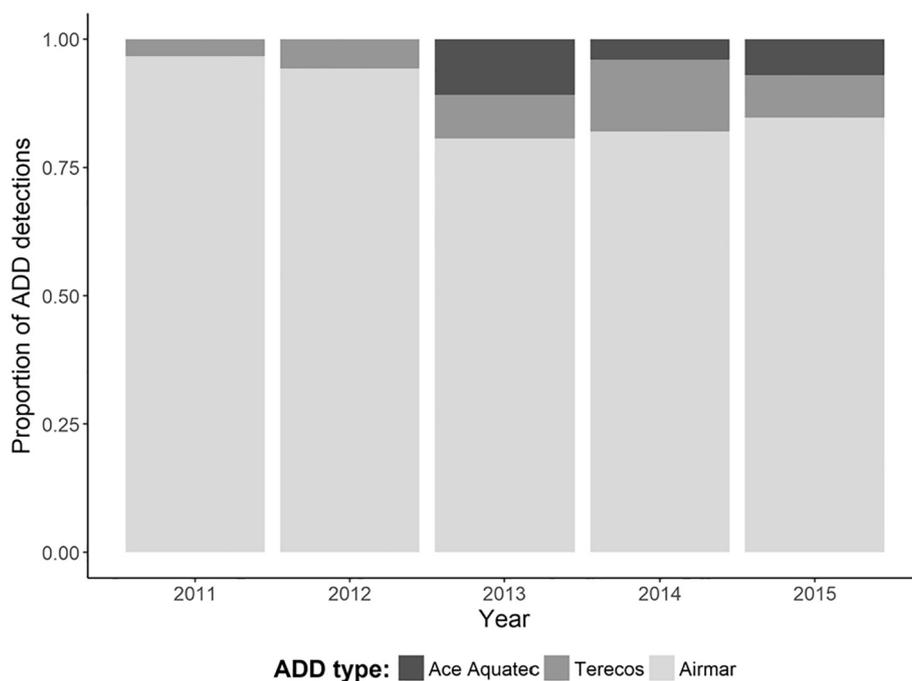


Fig. 3. Proportional change in detected acoustic deterrent device (ADD) types at acoustic listening stations (2011–2015) across the west coast of Scotland.

falsely detected even more rarely (< 3% of the time). Although not quantified systematically, visual observations during post-hoc analysis suggested that missed and false detection events occurred during periods of elevated ambient noise, or in instances where other anthropogenic noise sources were mistaken for ADDs. Based on these analyses, the volunteer data are therefore likely to give a reasonable indication of the presence of actively transmitting ADDs at sampling locations.

Spectrogram analyses of acoustic recordings (2011–2015) identified three different types of ADDs: Airmar™ (dB Plus II), Ace Aquatec™ (US3) and Terecos™ (Type DSMS-4; Fig. 2). Airmar signals consisted of a pulsed sinusoidal tonal burst at a peak frequency of 10 kHz, with each pulse lasting approximately 1.4 ms, and the entire transmission lasting for 2.5 s. Ace Aquatec showed peak frequencies between 10 and 25 kHz consisting of 19 sweeping tonal broadcasts with a period of 1 ms, the full duration of which lasted 2.4 s. Lastly, three Terecos programmes were detected all of which showed a complex series of multi-frequency components which varied in frequency (between 3 and 16 kHz) and temporal characteristics (Fig. 2; Lepper et al., 2014). Of these, the acoustic signals from Airmar devices were by far the most frequently detected in all assessed years (> 75%), whereas Terecos devices were detected in all years but at consistently low rates, and Ace Aquatec devices only started to be detected in 2013 (Fig. 3). At some listening stations multiple transducers and/or types of ADD were recorded, suggesting that some aquaculture sites use multiple units concurrently, and/or that acoustic footprints of ADDs deployed by different aquaculture sites overlap spatially.

3.2. Spatio-temporal distribution of ADD presence

Overall, the total acoustic presence and geographic distribution of ADDs along the west coast of Scotland has significantly increased over the 11-year period analysed (Figs. 4 & 5). In 2006, ADDs were detected at 5 out of a total of 938 listening stations (0.05%; Table 2), and all detections were localised within the Sound of Mull. Detections within this area subsequently increased and persisted throughout the 11-year period (Figs. 1 & 4). In later years ADDs were also detected in areas surrounding the Isle of Skye, the Small Isles, the Minch and in several north-western sea lochs extending up to Cape Wrath (Figs. 1 & 4). Starting in 2009, ADD presence was also identified on the eastern and

western coastlines of the islands of the Outer Hebrides (Figs. 1 & 4). ADD detection rates were highest in 2013 and 2015 (12.6% and 11.3%, respectively of all listening events recorded for these years; Table 2; Figs. 4 & 5). Despite inter-annual variability, the absolute number and ratio of listening events with ADD detections, compared to events without, increased consistently over the study period (Fig. 5). Results from the beta regression model indicated that year was a significant predictor of change in the detection of ADDs at listening events ($\beta = 0.132$, $p < 0.0009$, $R^2 = 0.563$).

4. Conclusions

Using an 11-year dataset of acoustic listening events from across the west coast of Scotland, this study shows that ADDs have become a chronic and widespread source of underwater noise pollution in this region. Areas containing multiple aquaculture sites that were regularly surveyed, for example the Sound of Mull (Fig. 1), exhibited persistent ADD detections throughout all years (Fig. 4). While generally increasing over time, the highest proportion of listening events with ADD detections was observed in 2013 (12.6%). These data were derived opportunistically from a boat-based study and were not specifically designed to map ADD noise, therefore there is some inter-annual variation in spatial coverage. However, the collection and scoring of a total of 19,601 (yearly median: 1878) listening events from a variety of habitats, distances from shore and over much of the west coast provides the first broad-scale measure of the acoustic footprint of ADDs used in the Scottish salmon aquaculture industry.

The use of volunteers for at-sea detection and logging of ADD signals was a pragmatic component of the survey, allowing for a systematic approach to assess broad-scale patterns in ADD presence, but raised the possibility of erroneous data collection. For example, ADD detections in two grid cells south of the Outer Hebrides in 2012 represent an example of false positive volunteer detections (Fig. 4). However, spectral analysis of a 5-year subset (2011–2015) of one-minute acoustic samples showed that ADD detections by volunteers were generally accurate, that this accuracy did not change substantially between years, and that any bias was likely to lead to a slight underestimate of the number of detections (Table 1). As the age range and experience of volunteers aiding surveys by the HWDT were comparable

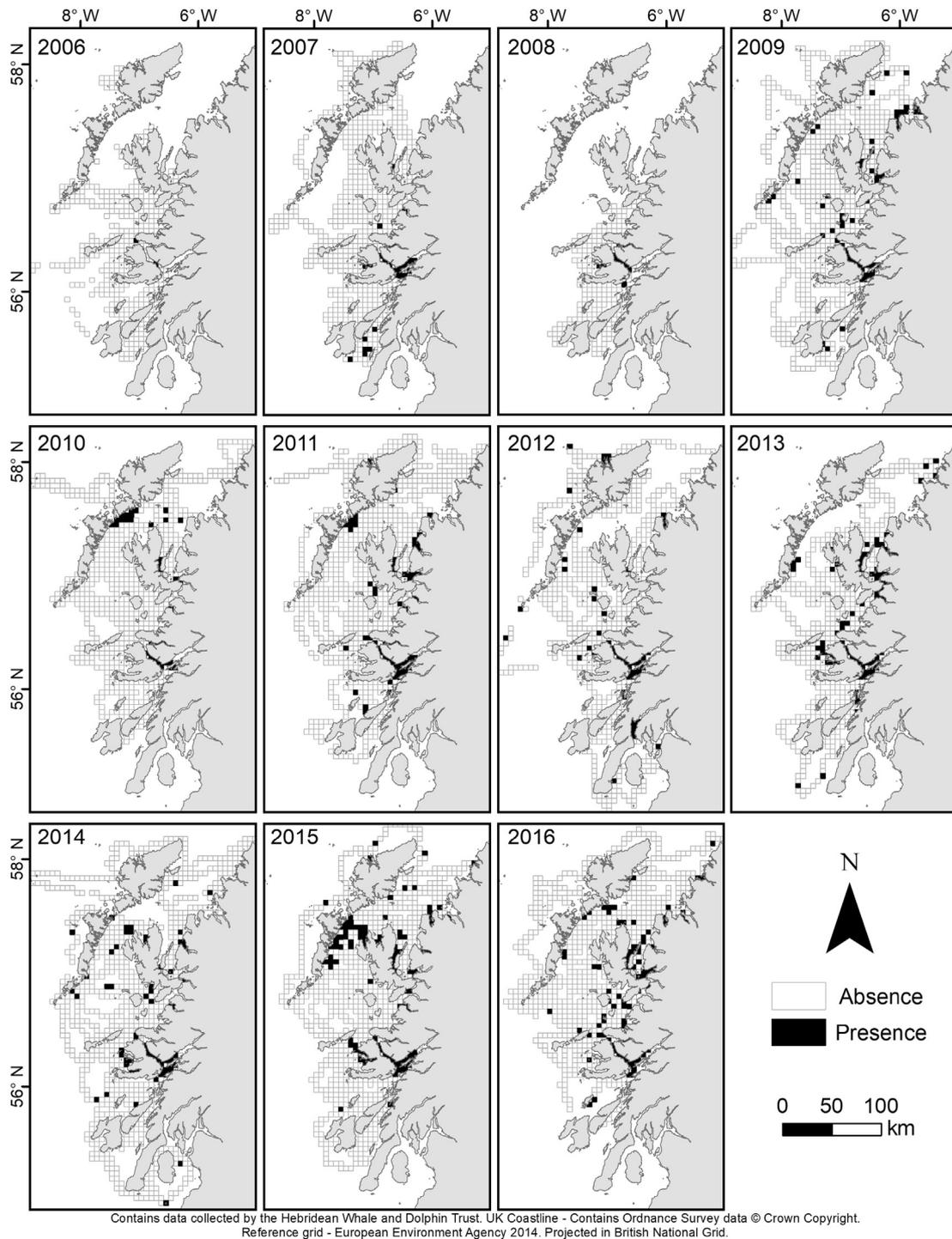


Fig. 4. Acoustic presence (solid black cells) and absence (clear cells) of acoustic deterrent device (ADD) detections on the west coast of Scotland, UK (2006–2016). Grid cell size = 5 × 5 km.

between years, it is unlikely that the data analysed for the 5-year subset would have differed substantially from any other years. Based on these data, it was decided to use all detections recorded by volunteers to map ADD acoustic presence for the full 11-year dataset, accepting a small number (< 5% in all years) of false and missed ADD detections.

Three types of ADDs were detected in the acoustically analysed subsample from 2011 to 2015: Airmar (dB Plus II), Terecos (Type DSMS-4), and Ace Aquatec (US3). Over these five years, Airmar signals were identified most frequently across the survey area, followed by Terecos (Fig. 3). This is in agreement with data from previous studies (Coram et al., 2014; Northridge et al., 2010). Having only become

commercially available in 2012 (pers comms. Pyne-Carter, 2016), Ace Aquatec devices were first recorded in 2013. Although this study was unable to accurately assess the ranges from fish farms at which ADDs could be detected above ambient noise, detections were made both inshore and offshore and at considerable distances from active fish farms (Figs. 1 and 4). Previous studies showed that, under certain ambient noise conditions Airmar devices can be detected up to 20 km from the source (Jacobs and Terhune, 2002), while Olesiuk et al. (2002) suggested that in some instances Airmar signals could even be heard up to 50 km from the source.

The overall increase in ADD acoustic detection rates across the west

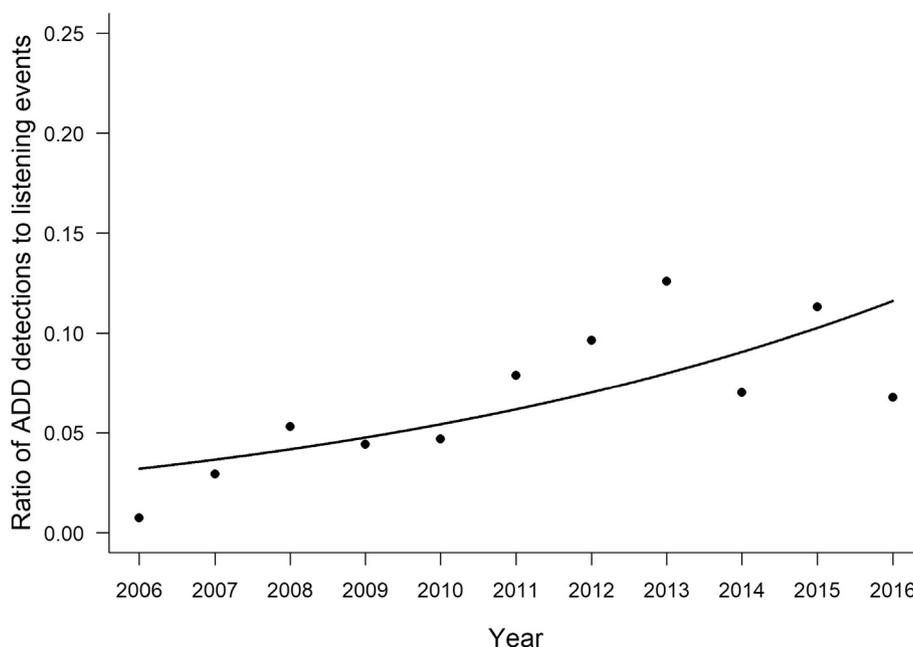


Fig. 5. Relationship between the ratio of listening events with acoustic deterrent device (ADD) detections as a function of year (2006–2016).

coast of Scotland over the last decade, as observed in this study, suggests that these devices have increasingly been implemented as a method of predator deterrence by aquaculture companies in recent years. Indeed, the Scottish Government has recommended the use of non-lethal alternatives, such as ADDs, to shooting seals, which historically was commonly practiced (United Kingdom Parliament, 2010). Currently, licenses to shoot ‘problem seals’ may still be granted under the Marine Scotland Act 2010 (Part 6, section 110) but it is understood that shooting “... should ... be undertaken as a last resort.” (United Kingdom Parliament, 2010). However, despite being widely used as mitigation to seal depredation at aquaculture facilities, consistent long-term effectiveness of ADDs in reducing depredation has yet to be conclusively proven. For example, Yurk and Trites (2000) found that harbour seal depredation was significantly reduced by the presence of an Airmar transducer in British Columbia, Canada, while Jacobs and Terhune (2002) found harbour seals showed no change in behaviour in response to the same ADD type deployed for 8 months in the Bay of Fundy, Canada.

In contrast, there is considerable evidence for the unintentional effects of ADDs on non-target species (summarised in Götz and Janik, 2013). Several authors have shown avoidance behaviour of harbour porpoises (*Phocoena phocoena*) at ranges from a few hundred meters up to 12 km to actual and simulated ADD signals (Brandt et al., 2013; Dähne et al., 2017; Johnston, 2002; Mikkelsen et al., 2017; Olesiuk et al., 2002). These effects have recently been exploited in other applications such as pile driving in offshore construction, to avoid the potential for hearing damage from these loud, short-term noise emissions (Brandt et al., 2013). However, depending on context and time of exposure, ADDs may also cause temporary (TTS) or permanent (PTS) hearing loss in target (pinnipeds) and non-target (e.g. cetaceans) species. Theoretical calculations show that if exposed to about 15 min of an Airmar transducer with a 50% duty cycle, harbour porpoises could experience PTS up to 295 m away from the source (Götz and Janik, 2013). In Scotland, the deployment of multiple ADD transducers per fish farm (e.g. one per cage) is common (Northridge et al., 2010), and supports observations of overlapping signals made during analysis of the acoustic data in this study. This practice poses additional risk to marine fauna as it alters the original duty cycle of ADDs by reducing silent periods between pulses, which ultimately increases the time over which animals are exposed to ADD noise (Götz and Janik, 2013; Harris

et al., 2014). The effects of multiple transducers used by one fish farm may further be heightened in areas where different ADD types are used at adjacent sites, which was also observed in this study, as this further increases and complicates the overall ambient noise field produced by the widespread use of these devices (Götz and Janik, 2013). Various non-lethal depredation methods have been developed including improved cage tensioning, diligent removal of dead or dying fish, and reducing fish visibility to seals through seal blinds (Northridge et al., 2010, 2013; Quick et al., 2004; Ross, 1988). However, further work is required to accurately evaluate the relative effectiveness of these methods.

On the Scottish west coast, both seals and cetaceans such as harbour porpoises are observed in high densities (Embling et al., 2010; Hammond et al., 2013; Jones et al., 2017; MacLeod et al., 2008). For both seals and cetaceans, various established (and proposed) protected sites (SNH, 2014, 2016; United Kingdom Parliament, 2010), across the Scottish west coast are within close proximity to numerous aquaculture facilities. Given present knowledge of ADD signals' effects on species such as harbour porpoises, the widespread and increasing use of ADDs in Scottish waters could therefore have a range of negative impacts including causing chronic reductions in hearing thresholds (Götz and Janik, 2013; Lepper et al., 2014), and/or the potential for exclusion from key habitats, risking creating barriers to their movement (Johnston, 2002), all of which can have long-term fitness and population-level consequences (Coram et al., 2014; King et al., 2015). Further work is required to accurately assess the magnitude and extent of such impacts on species such as harbour porpoises across different spatio-temporal scales.

Although it is evident from this study that ADD use is widespread and increasing on the west coast of Scotland, the precise nature of the use of ADDs at individual aquaculture sites remains poorly understood (a problem already identified by Coram et al., 2014). Currently aquaculture sites in Scottish waters seeking planning permission to expand or amend site operations (e.g. increase fish biomass) require the consent of the relevant local authority, and it is at this stage that predator control plans are reviewed (Henderson and Davies, 2000). However, these plans often only provide limited details beyond the general intent to deploy ADDs in terms of number and type, making it difficult to adequately assess likely environmental impact of such deployments at individual fish farms, let alone cumulative effects across a wider area.

Given the evident pervasive presence of ADD noise along much of the west coast of Scotland, there is a clear need to improve the reporting of ADD usage, including information on ADD types, numbers, and operation schedules. This information could subsequently be used to fulfil requirements under the Marine Strategy Framework Directive (MSFD) Criterion 11.1 (2008/56/EC) to record loud, low- to mid-frequency impulsive noise. ADDs are explicitly mentioned in this legislation and in the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR, 2014) but have so far not been recorded in any of the national marine registries presently under development (Dekeling et al., 2014; Merchant et al., 2016). This omission risks ignoring a regionally significant source of chronic anthropogenic underwater noise pollution with potentially widespread negative consequences for marine wildlife.

To conclude, this study has quantified the increasing acoustic footprint of ADDs on the west coast of Scotland, which were found to constitute a significant source of underwater noise pollution in this region. As large-scale and long-term noise pollution may have detrimental impacts on target and non-target species within the vicinity of such sites, improved monitoring and documentation of current ADD usage in the Scottish salmon aquaculture sector would be useful in assessing the wider environmental impact of this industry.

Declarations of interest

None.

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