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RESEARCH ARTICLE

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Exposure of individual harbour seals (*Phoca vitulina*) and waters surrounding protected habitats to acoustic deterrent noise from aquaculture

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Abstract

1. Pinniped depredation at aquaculture sites is a globally recognized problem. To mitigate depredation, the aquaculture sector uses acoustic deterrent devices (ADDs) as a non-lethal alternative to shooting pinnipeds interacting with caged finfish. However, it is unclear whether sound emissions from ADDs have the potential to also impact non-target pinnipeds at spatial scales relevant to populations.
2. Global Positioning System (GPS) tracking data from seven harbour seals tagged in a non-aquaculture context, on the west coast of Scotland, in 2017 were combined with modelled maps of ADD noise to quantify sound exposure and estimate the potential for auditory impairment. The acoustic model applied an energy flux approach across the main frequency range of ADDs (2–40 kHz). Predictions of temporary and permanent auditory threshold shifts were made using seal location data and published noise exposure criteria. The acoustic exposure of waters (10-km buffers) surrounding protected habitats (i.e. designated haul outs and Special Areas of Conservation (SACs)) on the west coast of Scotland was also assessed.
3. All tagged seals and waters surrounding 51 of 56 protected sites were predicted to be exposed to ADD noise exceeding median ambient sound levels. Temporary auditory impairment was predicted to occur in one of the seven tagged harbour seals and across 1.7% of waters surrounding protected habitats over a 24-hour period, when assuming a 100% ADD duty cycle.
4. Although the predicted risk of auditory impairment appears to be relatively low, these findings suggest that harbour seals inhabiting inshore waters off western Scotland are routinely exposed to ADD noise that exceeds median ambient sound levels. This chronic exposure risks negative consequences for individual harbour seals among the wider population in this region. The use of ADDs to mitigate pinniped depredation should be carefully considered to reduce unintended habitat-wide impacts on non-target species, including pinnipeds that are not specifically interacting with aquaculture.

KEYWORDS
acoustic deterrent device (ADD), aquaculture, depredation, harbour seals, marine protected areas, noise pollution, pinnipeds

1 | INTRODUCTION

Depredation, the act of predation upon or damage to captive prey by pinnipeds (phocids and otariids) at aquaculture and fishery sites, is a globally recognized problem. Pinniped depredation has been reported in numerous countries, including Australia (Pemberton & Shaughnessy, 1993), Canada (Jacobs & Terhune, 2002), Chile (Vilata, Oliva & Sepulveda, 2010), New Zealand (Kemper et al., 2003), Norway (Fjalling, Wahlberg & Westerberg, 2006), Turkey (Güçlüsoy & Savas, 2003), the USA (Nelson, Gilbert & Boyle, 2006), and Scotland (Northridge, Coram & Gordon, 2013). In the context of aquaculture, the presence of interacting pinnipeds around sites may have a number of detrimental effects on finfish production (Northridge, Coram & Gordon, 2013). Potentially, pinnipeds can: (i) stress fish, thus reducing feeding and growth; (ii) attack fish through the netting, causing injury or death; and (iii) breach containing nets, damaging the cages and allowing fish to escape (Northridge, Coram & Gordon, 2013). To limit such interactions, various predator control methods have been used, including the targeted shooting of 'problem' individuals (Nunny, Langford & Simmonds, 2016; Nunny, Simmonds & Butterworth, 2018), culling programmes to reduce populations (Nunny, Simmonds & Butterworth, 2018), and different forms of non-lethal deterrence. These include: anti-predator nets; tensioned netting; stronger and stiffer netting materials; seal blinds; animal relocation programmes; visual deterrents, such as lights; chasing by boats; conditioned taste aversion; electric fields; and acoustic deterrents (Coram et al., 2014; Thompson et al., 2020b).

In Scotland, finfish aquaculture for Atlantic salmon (*Salmo salar*) is a rapidly expanding rural industry, and Scotland is now the third largest finfish producer globally, behind Norway and Chile (Kenyon & Davies, 2018). On the west coast of Scotland, where most aquaculture production occurs, individual sites are widely distributed to reduce the cumulative negative impacts of localized eutrophication, chemical pollution, and disease outbreaks (Frid & Mercer, 1989; Butler, 2002). This coastline is also an important habitat for several marine mammal species, and depredation events by harbour seals (*Phoca vitulina*) and grey seals (*Halichoerus grypus*) are frequently reported by the local aquaculture sector (Coram et al., 2014). For a number of years the use of non-lethal mitigation, such as acoustic deterrent devices (ADDs, also known as acoustic harassment devices (AHDs)), has been recommended as an alternative to the licensed shooting of 'problem' seals at aquaculture sites (RSPCA, 2018). However, the shooting of seals to protect farmed fish, which was common practice in Scotland, has recently been banned (1 February 2021; Marine (Scotland) Act 2010, Part 6, Section 110; United Kingdom Parliament, 2010).

As a result of the impacts of seals, ADDs are currently in wide use around the Scottish coastline (The Scottish Government, 2021). They are designed to produce loud sounds (source levels in excess of 185 dB re 1 μPa root-mean-square pressure (RMS)), within the mid- to high-frequency range (0.5–40 kHz; Lepper et al., 2014; Todd et al., 2021) and are within the hearing ranges of most marine mammals (pinnipeds, 50–86 kHz; small cetaceans, 150–160 kHz) (National Marine and Fisheries Service (NMFS), 2018). Consequently, the acoustic emissions produced by these devices have the potential to cause auditory impairment and/or changes in behaviour (Götz & Janik, 2013). Several studies have examined the potential effects of noise from ADDs on non-target cetacean species, such as killer whales (*Orcinus orca*), minke whales (*Balaenoptera acutorostrata*), and harbour porpoises (*Phocoena phocoena*). Reported effects include temporary reductions in hearing sensitivity, disruption and changes to behaviour, and displacement from habitats (Morton & Symonds, 2002; Northridge et al., 2010; Brandt et al., 2013; Lepper et al., 2014; McGarry et al., 2017; Mikkelsen et al., 2017; Schaffeld et al., 2019; Thompson et al., 2020a; Boisseau et al., 2021; Todd et al., 2021). Studies have also assessed potential effects of noise from ADDs on seals (Jacobs & Terhune, 2002; Graham et al., 2009; Harris et al., 2014; Lepper et al., 2014; Mikkelsen et al., 2017; Gordon et al., 2019; Todd et al., 2021), noting effects including auditory impairment, changes in swimming speed, and avoidance of or attraction to the sound source. However, for both cetaceans and seals, studies have tended to focus on the short-term deterrence effects of ADD noise, limiting our ability to understand the impacts of ADDs that have been used for considerable periods of time and over large spatial scales, such as on the west coast of Scotland (Findlay et al., 2018).

Harbour seals occur in high densities on the west coast of Scotland, with 49% of the entire UK population having been recorded in this region in 2016 (Thompson et al., 2019). The species is listed in Annex II of the European Union (EU) Habitats Directive (92/43/EEC) and is protected in Scotland under Part 6 of the Marine (Scotland) Act 2010 (Thompson et al., 2019). Accordingly, on this coastline, three harbour seal Special Areas of Conservation (SACs), one candidate SAC where the species is a 'feature of qualifying interest', and 129 haul-out sites have been designated (The Scottish Government, 2014; SCOS, 2017), to help monitor and maintain the favourable conservation status of the harbour seal population (SCOS, 2017; Thompson et al., 2019). These SACs and haul-out sites are adjacent to aquaculture production (Figure 1), which has led to concerns over whether harbour seals are repeatedly exposed to ADD noise when transiting and foraging in waters around the west coast of Scotland (Findlay et al., 2018).

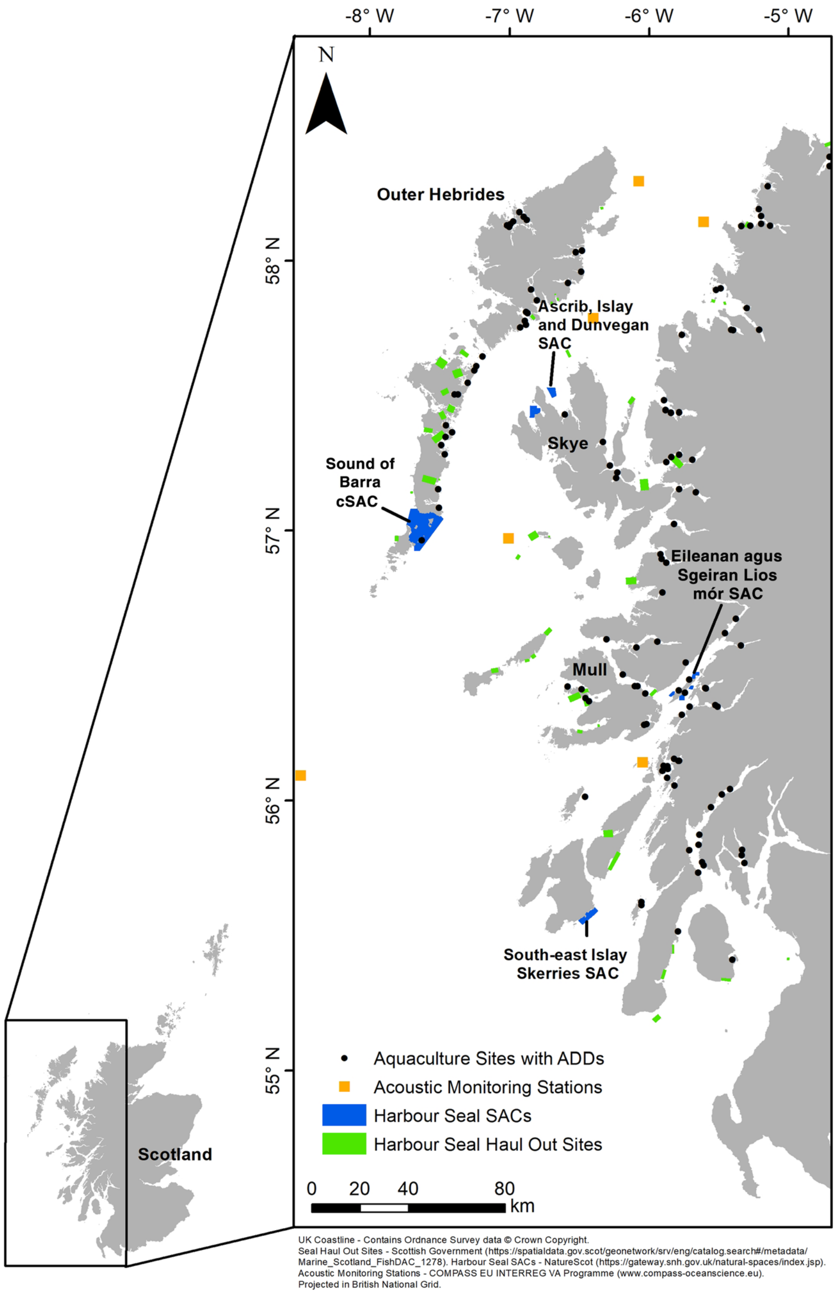

FIGURE 1 Map of the west coast of Scotland, including: the locations of aquaculture sites using acoustic deterrent devices (ADDs; black dots) from 1 February 2017 to 31 January 2018 (NatureScot, 2018); locations of long-term acoustic monitoring stations in 2018 (COMPASS EU INTERREG VA Programme; www.compass-oceanscience.eu); protected haul-out sites (Scottish Government: https://tinyurl.com/yc6g9759); and Special Areas of Conservation (SACs) designated for harbour seals or where harbour seals are a priority feature (i.e. Sound of Barra candidate SAC) (NatureScot: https://tinyurl.com/atm2psrv)

Observations often describe close approaches of individual seals to or past aquaculture sites with active ADDs (Jacobs & Terhune, 2002; Northridge et al., 2010; Lepper et al., 2014). Repeated exposure to ADD noise at close range thus has the potential to cause auditory impairment in seals through the elevation of hearing thresholds (Götz & Janik, 2013). Such threshold shifts can be described as either temporary (TTS) or permanent (PTS), depending on auditory recovery after exposure (Southall et al., 2019). Measurements of the auditory systems of harbour seals have noted that their highest underwater hearing sensitivity occurs between 50 Hz and 86 kHz (Mohl, 1968; Terhune, 1988; Kastelein et al., 2009a; Kastelein et al., 2009b; Cunningham & Reichmuth, 2016), encompassing the frequency ranges at which the majority of ADDs operate (0.5–40 kHz) (Lepper et al., 2014; Todd et al., 2021). A number of captive studies have documented both TTS and PTS from exposures to noise between these frequencies (0.5–40 kHz) (Kastak et al., 2005; Kastelein et al., 2012; Kastelein et al., 2013b; Kastelein, Helder-Hoek & Gransier, 2019; Reichmuth et al., 2019; Kastelein et al., 2020a; Kastelein et al., 2020b). However, although models have predicted this noise source as a risk of auditory impairment to seals (Götz & Janik, 2013; Lepper et al., 2014), the potential for auditory impairment in non-target seals at sea and in waters around protected sites has yet to be quantified.

In the current study, tracking data for seven harbour seals and locations of protected habitats (designated haul outs and SACs plus a 10-km buffer) for this species on the west coast of Scotland were combined with modelled maps of ADD noise from 2017, to quantify sound exposure and estimate the potential for auditory impairment.

2 | METHODS

2.1 | The west coast of Scotland and acoustic deterrent devices (ADDs)

In this study, the west coast of Scotland is denoted as the area that extends from the Scottish mainland to beyond the Outer Hebrides archipelago (from 55°N to 59°N and from 4°W to 9°W). This area is representative of a typical temperate, shallow (<300 m) coastal shelf environment. The region is also topographically complex, with numerous islands, sea lochs, and inlets (Figure 1) (Mcintyre & Howe, 2010). In 2017, a total of 120 aquaculture sites in this region were equipped with ADDs to mitigate seal depredation events (NatureScot, 2018); for more details on aquaculture sites using ADDs, the types of devices deployed, and the signal characteristics of these devices, see Findlay et al. (2021)).

2.2 | Telemetry

Data from the Global Positioning System (GPS), obtained with Global System for Mobile Communication (GSM) tags (SMRU Instrumentation, University of St Andrews, Fife, UK) (McConnell et al., 2010) deployed on seven adult female harbour seals on the Isle of Skye, in March 2017 (Arso et al., 2018), were used to measure the movements and exposure of seals at sea to ADD noise produced at aquaculture sites. These seals were not tagged to study their association with aquaculture facilities, but their movement data were used in this study as the period of the tagging data (from 16 March 2017 to 29 July 2017) co-occurred with the time period for which information on the location of aquaculture sites using ADDs was available (from 1 February 2017 to 31 January 2018) (NatureScot, 2018). This allowed for an assessment of the overall exposure to ADD noise by seals that were not actively targeting aquaculture sites.

Seals were captured whilst hauled out on land and were anaesthetized with Zoletil® (Virbac, Hamilton, New Zealand) and Ketaset® (Zoetis, Parsippany, NJ, USA) in combination with Hypnovel®. GPS/GSM tags were attached to the fur at the back of the neck using Loctite® 422 Instant Adhesive (Henkel Corp., Bridgewater, NJ, USA). Capture and handling procedures are described in more detail by Sharples et al. (2012). All capture and handling protocols were carried out under the UK Home Office licence #70/7806, in accordance with the Animals (Scientific Procedures) Act 1986 Amendment Regulations (SI 2012/3039), and under licence from Marine Scotland.

The GPS/GSM tags aim to record the location of surfacing seals at regular intervals using a hybrid GPS system (Fastloc®, Wildtrack Telemetry Systems Limited, Leeds, UK). Stored locations are relayed ashore through an embedded mobile phone (GSM) modem, approximately every 15 minutes. Of the seven tags, six collected data for 100–130 days, whereas one tag had a short transmission duration of just 18 days. All tag data, where possible, were included in the analysis regardless of duration (Table 1). Data were cleaned and erroneous locations were removed using thresholds of residual error and the number of satellites, based on assumptions from land tests, which showed that 95% of locations had a distance error of <50 m (Russell et al., 2015). Tracks of seals were linearly interpolated between successive GPS locations (where these were less than 30 minutes to minimize data loss and maintain reasonable representations of true tracks) to provide estimated locations at one-second intervals using the ADEHABITATLT package in R (Calenge, 2006).

2.3 | Acoustic propagation model

To predict the sound levels of the ADDs used at aquaculture sites within the study area in 2017, a validated energy flux acoustic propagation model (Weston, 1971), written and applied in MATLAB 2018b (MathWorks, Natick, MA, USA) was used to estimate propagation loss. Energy flux models are two-dimensional, range-dependent models that account for bathymetry, sound speed, and seabed reflectivity, and are widely used for higher frequency sources (>1 kHz) located in shallow waters (Sertlek & Ainslie, 2014). Propagation loss from each aquaculture site using ADDs was calculated for all one-third-octave frequency bands (TOBs) centred between 2 and 40 kHz (Lepper et al., 2014). Additional details on the acoustic propagation modelling and the model validation are described by Findlay et al. (2021).

TABLE 1 Summary of harbour seal (*Phoca vitulina*) GPS/GSM telemetry data from the Isle of Skye, 2017. All tagged individuals were pregnant adult females. Table includes the seal reference number, tag deployment date, tag duration (days), and median and closest proximity to an aquaculture site using ADDs (km)

Seal reference number	Tag deployment date	Tag duration (days)	Median proximity to ADD (km)	Closest proximity to ADD (km)
vf02–152-17	22/03/2017	100	106.5	7.5
vf02–211-17	22/03/2017	127	103.6	0.98
vf02–362-17	16/03/2017	18	114.9	2.6
vf02–497-17	18/03/2017	102	103.1	4.1
vf02–498-17	19/03/2017	130	102	<0.1
vf02–506-17	17/03/2017	131	104	8.5
vf02–507-17	19/03/2017	119	106.2	4.7

Energy source levels (dB re 1 μPa^{2}s·m^2) expressed in TOBs between 2 and 40 kHz for Airmar dB Plus II, Terecos Type DSMS-4, and Ace Aquatec US2 ADDs were taken from the literature (for more details on ADD source characteristics, see Lepper et al. (2014) and Findlay et al. (2021)). Phocid pinniped auditory weighting (PW), as recommended by the NMFS (2018), which was largely duplicated by Southall et al. (2019), was applied to TOB received sound pressure levels (SPL_w; dB re 1 μPa). PW SPL_w and 24-hour cumulative sound exposure levels ($SEL_{w,24h}$, dB re 1 μPa^{2}s) (ISO, 2017) at each TOB centre frequency were computed as follows:

$$SPL_w(f) = ESL(f) - PL(f), \quad (1)$$

$$SEL_{w,24h}(f) = SPL_w(f) + 10\log_{10}(T), \quad (2)$$

where $ESL_w(f)$ is the one-second energy source level (ISO, 2017) at a specific TOB centre frequency f, $PL(f)$ is the associated propagation loss, and T is the time over 24 hours in seconds. Broadband (2–40 kHz) SPL_w and $SEL_{w,24h}$ values were then computed via an energy summation across all frequencies.

2.4 | Ambient sound

Ambient sound (ISO, 2017) data were collected over a period of 1 year (2018) at six acoustic monitoring stations within the study area (Figure 1; The COMPASS Project, www.compass-oceanscience.eu). As ambient sound data were not available for 2017, data from 2018 were used to provide an approximate level for the west coast of Scotland. SoundTrap 300 HF acoustic recorders (end-to-end factory calibration in the range of 172.3–176.2 dB re 1 μPa; Ocean Instruments, Warkworth, Auckland, New Zealand) were deployed for up to 4 months, moored approximately 3 m above the sea floor in depths ranging from 45 to 110 m, and programmed to record on a 20/40-minute on/off duty cycle at a sampling rate of 96 kHz.

PAMGUIDE (Merchant et al., 2015) was used to calculate median TOB sound pressure levels (SPLs; dB re 1 μPa) for each site. Median TOB SPLs for each site were then weighted for PW (NMFS, 2018; Southall et al., 2019) and accumulated over a 24-hour period ($SEL_{w,24h}$; equation 2). The median broadband (2–40 kHz) SPL_w and $SEL_{w,24h}$ for each site were then computed via an energy summation across all frequencies, and the median SPL_w and $SEL_{w,24h}$ for all sites combined was calculated and used in ADD noise maps to represent ambient sound levels (for ambient noise SPL_w across all months in 2018, see Figure S1). A signal-to-noise ratio (SNR) of 0 dB was used for mapping the extent of ADD signal propagation and exposure.

2.5 | Predictions of acoustic exposure and auditory impairment in harbour seals

For the tagged seals, predictions of acoustic exposure and potential auditory impairment were made by matching the mapped outputs of SPL_w for ADD noise produced using the acoustic propagation model described by Findlay et al. (2021) at the one-second interpolated locations of each of the seals using the RASTER package in R (Hijmans, 2018). $SEL_{w,24h}$ values were calculated for each individual seal over consecutive 24-hour windows starting at the beginning of each tag deployment, adopting the consistent accumulation period recommended by the NMFS (2018). $SEL_{w,24h}$ values for the rolling windows were compared with non-impulsive TTS and PTS values (TTS, 181 dB re 1 μPa^{2}s; PTS, 201 dB re 1 μPa^{2}s) defined for phocid pinnipeds by the NMFS (2018) and by Southall et al. (2019). Non-impulsive thresholds were used following recommendations made by Southall et al. (2007), which state that although these devices can produce impulsive signals, they are emitted in such a rapid fashion that some mammalian auditory systems are likely to perceive them as continuous. Non-impulsive thresholds were also used to reflect the continuous use of these devices during finfish production in Scotland, which can result in a sustained source of noise around aquaculture sites (The Scottish Government, 2021). Although there are no internationally harmonized noise impact criteria, these TTS and PTS values are often used by regulators to assess zones of potential auditory impairment (Lucke, Martin & Racca, 2020), including in Scotland. Results were used to determine the potential for ADD noise to exceed thresholds of TTS and PTS in hearing sensitivity for the main frequencies of ADDs included in this study (2–40 kHz), in individual seals.

To predict ADD noise exposure within waters surrounding protected habitats, data on the locations of designated seal haul-out sites (Morris et al., 2014) and SACs designated for harbour seals within this region were obtained from the Scottish Government (https://tinyurl.com/yc6g9759) and from NatureScot (https://tinyurl.com/atm2psrv). Waters surrounding these protected sites were chosen for assessing acoustic exposure to the wider harbour seal population on the west coast of Scotland, as they represent sites where 50% of the harbour seal population in each seal management unit are likely to be found (Morris et al., 2014) and sites of community importance (SCIs) within the wider Natura 2000 network (EU Habitats Directive; 92/43/EEC). Of the eight SACs designated for harbour seals in the UK, three are located in this region: (i) Ascrib, Isay, and Dunvegan (comprising two haul-out sites); (2) Eileanan agus Sgeiran Lios mór (comprising five haul-out sites); and (3) South-East Islay Skerries (comprising one haul-out site; Figure 1). The Sound of Barra candidate SAC (cSAC, comprising three haul-out sites) was also included in the analysis as harbour seals are a qualifying feature but not the primary reason for the designation (Figure 1). A total of 129 harbour seal haul-out sites have been identified and protected in Scottish waters (The Scottish Government, 2014; SCOS, 2017); 45 of these are located within the study area (Figure 1), with 34 recording the presence of only harbour seals and 11 recording the presence of harbour seals and grey seals. Exposure was assessed within 10-km buffers around the centroid of each protected site (land was excluded from 10-km buffers). Buffers were created in ARCGIS 10.6.1 and compared with $SEL_{w,24h}$ maps of ADD noise. Each aquaculture site was assumed to deploy: (i) a single device (Airmar, 52.4% duty cycle; Terecos, 6.7% duty cycle (Lepper et al., 2014); and Ace Aquatec, 5% duty cycle (Pyne-Carter, 2019, unpublished data)); or (ii) multiple devices. There is a lack of information on the aggregate duty cycles of sites with multiple temporally overlapping devices (for example over 20 per site), which is common practice in this area (Northridge et al., 2010; The Scottish Government, 2021). As a proxy for multiple overlapping devices, the assumed aggregate duty cycles of either 75% or 100% were used in estimations. Duty cycles were calculated as the percentage of time a device was 'on' in seconds over a 24-hour period (equation 2). A 10-km buffer around each protected site location was chosen based on approximately 50% of the at-sea usage by tagged harbour seals presented in this study being recorded within 10 km of the initial tagging site. The $SEL_{w,24h}$ and the area of potential auditory impairment to seals across the ADD frequency range, within each 10-km buffer around protected sites, were determined using ARCGIS and the RASTER package in R (Hijmans, 2018).

3 | RESULTS

3.1 | Telemetry

The GPS/GSM tag deployment resulted in a total of 726 days of data collected from seven adult female harbour seals. When considering all individuals and GPS locations, the seals travelled a mean Euclidean distance of 17.7 km from the haul-out site (range: 4.3–132.9 km). Six of the seven seals remained around the Isle of Skye throughout the deployments, travelling across the Minch and towards the eastern edge of the Outer Hebrides archipelago (Figure 2). However, one seal ('vf02–498-17') travelled 132.9 km away from the tagging site, travelling through the Sound of Mull and into Loch Linnhe, where it remained for a period of 36 days before travelling back towards the Isle of Skye (Figure 2). The closest Euclidean distance to aquaculture sites using ADDs varied between individuals, ranging from <0.1 to 8.5 km (Table 1).

3.2 | Predictions of acoustic exposure and auditory impairment in harbour seals

During the seal tag deployment, all individuals moved within areas where predicted ADD noise was above the median ambient SPL_w (93 dB re 1 μPa, over 2–40 kHz), and this was equivalent to 81.7% of the total water tag time of all seals combined. The maximum SPL_w predicted at the locations of individual seals varied from 123 to 146 dB re 1 μPa (median of all individuals, 114 dB re 1 μPa; Figures 2 and S2; Table 2).

Over 24-hour periods, all tagged seals were predicted to be exposed to cumulative ADD noise levels ranging from 142 (the median ambient $SEL_{w,24h}$) to 185 dB re 1 $\mu Pa^2 s$ $SEL_{w,24h}$ (Figure S2). The median $SEL_{w,24h}$ across all individuals (165 dB re 1 $\mu Pa^2 s$) exceeded the median ambient sound level by more than 22 dB (Figure 3; Table 2). Predicted $SEL_{w,24h}$ from ADD noise varied between individual seals: seal 'vf02–506-17' was exposed to the lowest median $SEL_{w,24h}$ at 162 dB re 1 $\mu Pa^2 s$, whereas seal 'vf02–497-17' had the highest median $SEL_{w,24h}$ at 166 dB re 1 $\mu Pa^2 s$ (Figure 3). Seal 'vf02–498-17' had the highest maximum $SEL_{w,24h}$ at 185 dB re 1 $\mu Pa^2 s$ (Table 2; Figure 3). This seal was the only seal predicted to be exposed to levels of ADD noise that exceeded the PW TTS threshold of 181 dB re 1 $\mu Pa^2 s$ (Figures 3 and S2) (NMFS, 2018; Southall et al., 2019), and this continuous exposure remained above the TTS threshold for a period of 14 consecutive days.

Of the waters surrounding the 56 protected sites designated for harbour seals on the west coast of Scotland (where the combined at-sea area within all 10-km buffers was equal to 7,069.2 km^2), the waterways surrounding 51 sites (area: 48.7% or 3,442.7 km^2; Table 3) were predicted to be exposed to noise from ADDs (within their 10-km buffer) exceeding the median ambient $SEL_{w,24h}$ (142 dB re 1 $\mu Pa^2 s$; over 2–40 kHz), based on model predictions assuming a single ADD at each aquaculture site (Figure 4; Table 3). Of these, 41 surrounded designated haul-out sites, seven surrounded haul-out sites that formed two of the SACs (Ascrib, Isay, and Dunvegan and Eileanan agus Sgeiran Lios mór), and three surrounded haul-out sites that formed the cSAC (Sound of Barra). At higher aggregate duty cycles (75% and 100%), more waters around protected sites (within their 10-km buffer) were predicted to be exposed to noise from ADDs exceeding the median ambient $SEL_{w,24h}$ (75% duty cycle, 54/56 sites; area, 57.1% or 4,036.5 km^2; 100% duty cycle, 54/56; area, 58% or 4,100.1 km^2; Figure 4; Table 3), including the South-East Islay Skerries SAC. Within the 10-km buffer zones around these protected sites, received $SEL_{w,24h}$ values were predicted to range from 142 to 225 dB re 1 $\mu Pa^2 s$ (median: 142 dB re 1 $\mu Pa^2 s$) when assuming a single device, and these values increased at higher aggregate duty cycles (75% duty cycle, 142–228 dB re 1 $\mu Pa^2 s$, median 149 dB re 1 $\mu Pa^2 s$; 100% duty cycle, 142–229 dB re 1 $\mu Pa^2 s$, median 150 dB re 1 $\mu Pa^2 s$).

Based on predictions for a single device at each aquaculture site, less than 1% (53.7 km^2; Figure 4) of the waters around all protected sites would be exposed to ADD noise exceeding the TTS thresholds (≥181 dB re 1 $\mu Pa^2 s$) over a 24-hour period. Of these, waters surrounding the Eileanan agus Sgeiran Lios mór SAC (Figure 5) and Sound of Barra cSAC were predicted to be exposed to ADD noise exceeding TTS thresholds (within their 10-km buffer). The at-sea areas affected by ADD noise levels exceeding TTS thresholds increased at higher duty cycles (75% duty cycle, 1.3% or 92 km^2; 100% duty cycle, 1.7% or 120.2 km^2; Figure 4; Table 3). The area within all 10-km buffers of protected sites predicted to exceed PTS thresholds (≥201 dB re 1 $\mu Pa^2 s$) was small, ranging between 150 and 400 m^2 (single device, 0.003% or 176.7 m^2; 75% duty cycle, 0.004% or 282.8 m^2; 100% duty cycle, 0.005% or 353.5 m^2; Figure 4; Table 3). Most at-sea areas where noise levels did exceed PTS thresholds surrounded designated haul-out sites, and three areas surrounded haul-out sites that formed part of the Eileanan agus Sgeiran Lios mór SAC (Figure 5).

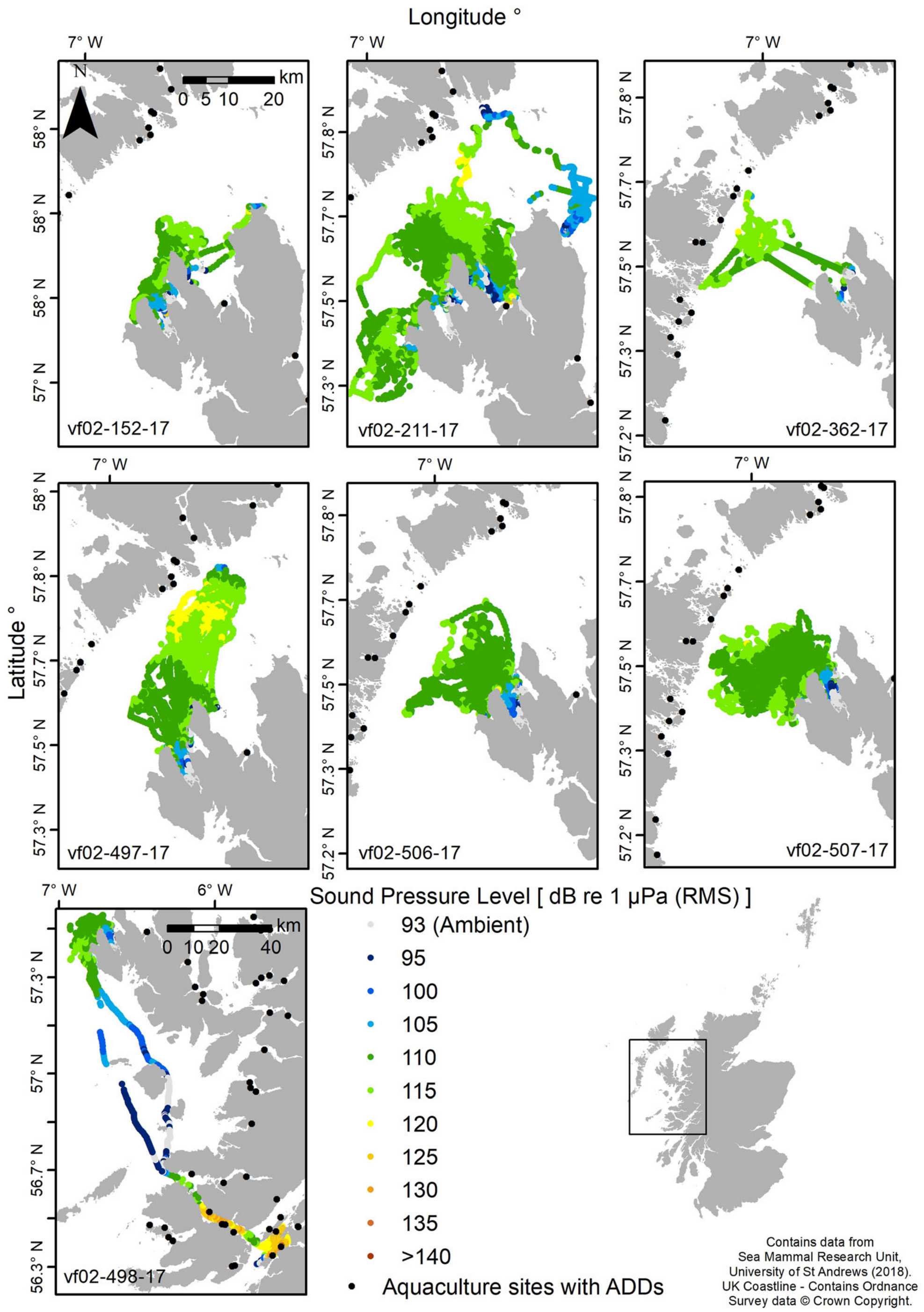

FIGURE 2 Phocid pinniped weighted sound pressure levels (SPL_w; dB re 1 μPa) predicted for seven individual harbour seals (indicated by seal reference number) tagged on the Isle of Skye in 2017 with GPS/GSM tags. SPL_w values for each seal are presented at 10-minute intervals and, unless specified, the scale of each map is the same as the previous map

4 | DISCUSSION

The inshore waters of the west coast of Scotland are an important habitat for harbour seals, evident from the continual and increasing presence of this species at designated haul-out sites during aerial counts, conducted every 5 years, and the designation of three SACs (SCOS, 2017; Thompson et al., 2019). Harbour seals on the west coast of Scotland and in the Outer Hebrides have been shown in this study and others (e.g. Cunningham et al., 2009; Sharples et al., 2012; Jones et al., 2015) to remain within close proximity to the coast during foraging trips (approx. 10 km). However, these coastal areas overlap significantly with the areas predicted to be ensonified by ADD noise from the aquaculture sector (Findlay et al., 2021). Results from this study indicated that all individual free-ranging harbour seals and waters surrounding 51 of the 56 protected sites were predicted to be exposed to ADD noise above median ambient sound levels. With the chronic and widespread use of ADDs by the Scottish aquaculture industry (Findlay et al., 2018), it is possible that individual

TABLE 2 Summary of individual seal exposure to ADD noise from aquaculture sites. Table includes the percentage of in-water tag time where seals were exposed to ADD noise above the ambient sound level, the predicted median and maximum phocid pinniped weighted sound pressure level (SPL_w, dB re 1 μPa), and the 24-hour cumulative sound exposure level ($SEL_{w,24h}$, dB re 1 $μPa^2s$) for each tagged seal

Seal reference number	Percentage in-water tag time exposed to ADD noise (%)	Median SPL_w(dB re 1 μPa)	Maximum SPL_w(dB re 1 μPa)	Maximum $SEL_{w,24h}$(dB re 1 $μPa^2s$)
vf02–152-17	90	115	129	168
vf02–211-17	91.1	115	134	172
vf02–362-17	82.7	113	123	168
vf02–497-17	80.3	115	129	170
vf02–498-17	87.6	115	146	185
vf02–506-17	81.3	113	129	168
vf02–507-17	61.8	112	129	166

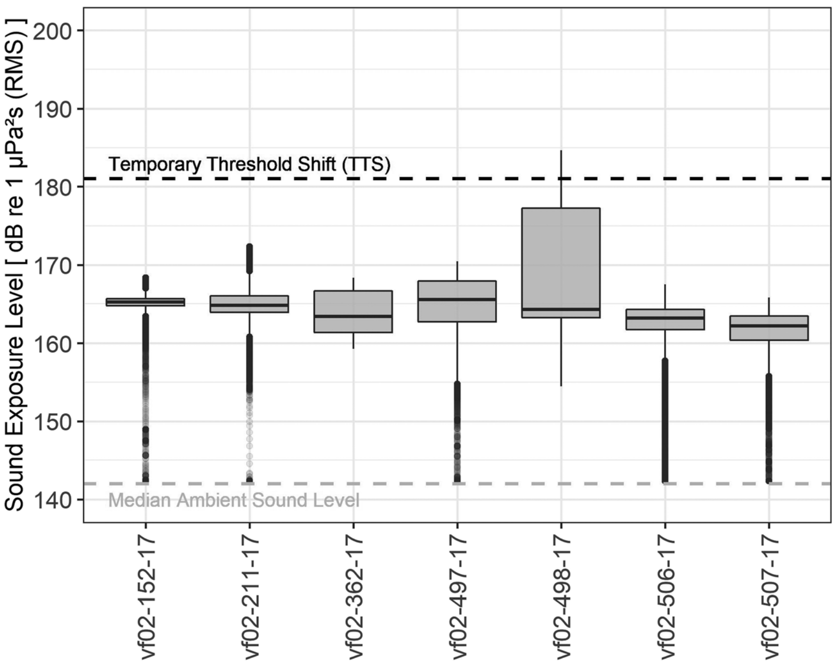

FIGURE 3 Summary of phocid pinniped weighted 24-hour sound exposure levels ($SEL_{w,24h}$, dB re 1 $μPa^2s$) for individual harbour seals (indicated by seal reference number). The figure shows median value (solid line), the 25th and 75th percentiles (grey boxes), the range without outliers (whiskers), and the outliers (black circles). The grey dashed line indicates 142 dB re 1 $μPa^2s$, which is the median ambient sound level, and the black dashed line indicates 181 dB re 1 $μPa^2s$, which is the temporary threshold shift (TTS) level for phocid carnivores in water over a 24-hour period as defined by the National Marine and Fisheries Service (NMFS, 2018) and Southall et al. (2019)

TABLE 3 Percentage area (%) within all 10-km buffers of at-sea areas surrounding protected sites exposed to phocid pinniped weighted 24-hour sound exposure levels (dB re 1 $μPa^2s$) exceeding ambient sound, temporary threshold shift (TTS), and permanent threshold shift (PTS) levels. Results illustrate variable duty cycles (single device: 5%, 6.7%, or 52.4%, and 75%, or 100%)

	Percentage area (%)		
Sound exposure level (dB re 1 $μPa^2s$)	Single-device duty cycle	75% duty cycle	100% duty cycle
>142 (ambient sound level)	48.7	57.1	58
≥181 (TTS)	0.76	1.3	1.7
≥201 (PTS)	0.003	0.004	0.005

seals are routinely exposed to ADD noise over long time periods, as shown by this case study, which may have negative consequences for these individuals.

Only one tagged seal (‘vf02–498-17’) and an area of less than 2% (between 53.7 and 120.2 km^2) around protected sites were predicted to be exposed to ADD noise exceeding the TTS threshold for seals (>181 dB re 1 $μPa^2s$). This area further decreased (0.003% to 0.005%) for levels exceeding the PTS threshold (>201 dB re 1 $μPa^2s$). Nonetheless, the evidence presented here of the potential exceedance of both temporary and permanent auditory impairment thresholds, especially within waters surrounding the Eileanan agus Sgeiran Lios mór SAC (Figure 5), highlights a potential auditory risk for individuals that frequently travel and/or forage within close vicinity of aquaculture sites using ADDs or routinely use these loud waterways

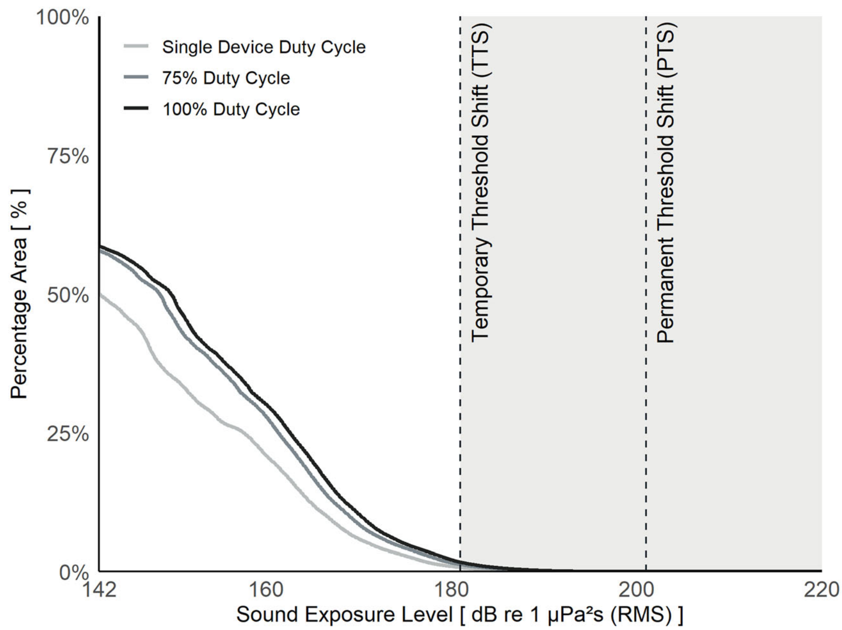

FIGURE 4 Percentage area (within 10-km buffers) of harbour seal protected sites exceeding 24-hour phocid pinniped weighted sound exposure levels ($SEL_{w,24h}$, dB re 1 μPa^2s), which are predicted to be above median ambient sound levels (<142 dB re 1 μPa^2s) and temporary or permanent threshold shift (TTS/PTS) levels (181 and 201 dB re 1 μPa^2s, respectively). Results illustrate variable duty cycles (single device: 5%, 6.7%, or 52.4%, and 75%, or 100%)

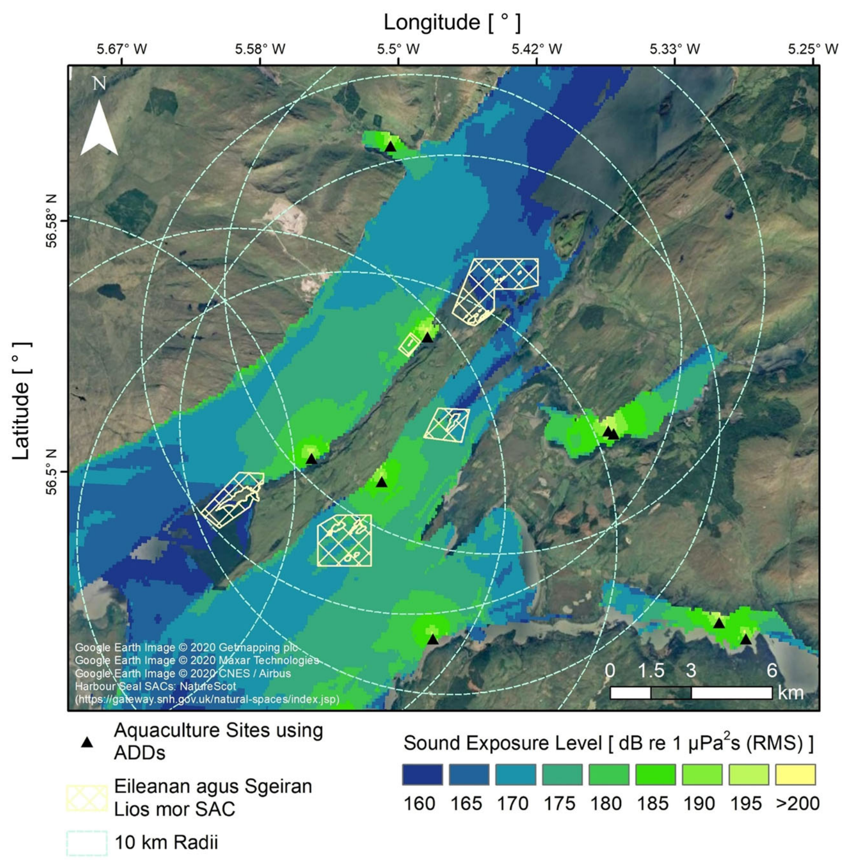

FIGURE 5 Example of phocid pinnipeds weighted 24-hour sound exposure levels ($SEL_{w,24h}$, dB re 1 μPa^2s) within 10 km of the centroid (indicated by circles) of five Eileanan agus Sgeiran Lios mór Special Area of Conservation (SAC) sites (yellow checked boxes), assuming multiple ADDs at aquaculture sites (black triangles) equating to an aggregated duty cycle of 100%

to gain access to protected haul-out sites. It should be noted that the threshold for TTS presently defined by the NMFS (2018) indicates the $SEL_{w,24h}$ at which an animal will have already experienced a 6-dB TTS in its hearing. As a result, the number of individuals and area of TTS exceedance over a 24-hour period around protected sites predicted in this study may be conservative given that seals could experience low levels of TTS at a predicted $SEL_{w,24h}$ of 175 dB re 1 μPa^2s. Furthermore, recent evidence from the Scottish Government suggests that ADDs are often deployed continuously at aquaculture sites during finfish production cycles, which can last up to 2 years (The Scottish Government, 2021). As such, it is highly likely that seals inhabiting this coastline will be repeatedly exposed to chronic ADD noise, which in turn increases the possibility of auditory impairment in individuals over time.

It is unknown how a reduction in hearing sensitivity at frequencies between 2 and 40 kHz (the frequency ranges assumed for ADDs in this study) might affect the ecology of harbour seals, given the broad range of frequencies at which they are capable of hearing (Mohl, 1968; Terhune, 1988; Kastelein et al., 2009a; Kastelein et al., 2009b; Cunningham & Reichmuth, 2016). However, auditory impairment at these frequencies could reduce dynamic range, frequency discrimination, and passive listening space, with implications for predator/prey detection and conspecific communication, such as male–male competition and breeding advertisement (Hanggi & Schusterman, 1994; Van Parijs, Hastie & Thompson, 1999; Götz & Janik, 2013; Kastelein, Gransier & Hoek, 2013a; Pine et al., 2019). Furthermore, although it is clear that PTS constitutes an injury in marine mammals, the situation is less clear for TTS (Tougaard, Wright & Madsen, 2015). Increasingly, studies of terrestrial mammals note the inability of auditory systems to recover fully from TTS and the potential for repeated TTS-inducing noise exposures to have cumulative effects on hearing, leading to permanent auditory impairment (Kujawa & Liberman, 2009; Wang & Ren, 2012; Luo et al., 2020). For example, Kujawa & Liberman (2009) measured a 40-dB TTS in mice 24 hours after a 2-hour exposure to octave band noise (8–16 kHz) at a sound pressure level of 100 dB re 20 μPa. This exposure resulted in an acute loss of afferent nerve terminals and permanent neurological degeneration of the cochlear nerve over the course of 1–2 years post exposure; however, cochlear sensory (hair) cells appeared to remain intact. Although hair cells may remain intact, this neurological degeneration may compromise auditory processing and lead to a reduction of stimulus encoding under noisy conditions, tinnitus (perception of phantom sounds), and hyperacusis (intolerance of moderately intense stimuli) (Kujawa & Liberman, 2009). Although this has not been studied in marine mammals, given similarities in mammal auditory structures, it is possible that repeated exposed to very loud ADD noise could, in the long term, lead to neurologically based PTS in harbour seals.

Repeated exposure to ADD noise has the potential to impact the individual fitness of harbour seals through subtle changes in their behaviour. It has been shown that this species will cease foraging and show directed movements away from ADDs when situated within 1 km of these devices at predicted received levels of 134.6 dB re 1 μPa (RMS) (Gordon et al., 2019), and observations in the field have documented seals lifting their heads out of the water, potentially to decrease their acoustic load, when in close proximity to ADDs, and consequently reducing their underwater foraging time (Fjalling, Wahlberg & Westerberg, 2006). Broadband signals produced by ADDs have the potential to mask the higher-frequency components of male harbour seal vocalizations produced during breeding advertisement (Van Parijs et al., 1997), which may have implications for reproductive success. Male seals may therefore avoid 'loud' areas (Yurk & Trites, 2000), and in turn increase intraspecific competition for quieter at-sea display areas, suggested to be used by males when attracting females for mating purposes (Van Parijs, Janik & Thompson, 2000). Behavioural changes such as these could lead to individuals dedicating less time to biologically important behaviours such as foraging, reproducing, and resting. Additionally, studies on humans have reported that persistent low-level noise exposure has the potential to increase stress hormone levels, blood pressure, and heart rate, leading to hypertension, arrhythmia, dyslipidemia, increased blood viscosity and blood glucose, and the activation of blood clotting factors, consequently increasing the risk of cerebrocardiovascular diseases such as stroke, ischaemic heart disease, acute myocardial infarction, heart failure, and arterial hypertension (Hahad et al., 2019). In marine mammals, it has been shown that, similar to results found from human studies, chronic noise can increase physiological stress levels (Thomas, Kastelein & Awbrey, 1990; Wright et al., 2007; Rolland et al., 2012). Exposure to chronic ADD noise may therefore have similar longer-term impacts such as those shown for humans, and this may be detrimental for the health of individual harbour seals in areas also used for aquaculture production.

Fifty-one protected sites, including two SACs (Ascrib, Isay, and Dunvegan and Eileanan agus Sgeiran Lios mór), comprising seven haul-out sites, and the cSAC Sound of Barra, comprising three haul-out sites, were within 10 km of ADD noise predicted to exceed median ambient sound levels (Figures 4 and 5). It is important to highlight that all these protected sites are on land, so there is little risk of acoustic exposure to animals within the sites themselves. However, these sites have been designated as they either represent significant concentrations of seals hauled out on land (50% of the harbour seal population in each seal management unit at any one time; Morris et al., 2014) or are important for species conservation as they form SCIs within the wider Natura 2000 network (EU Habitats Directive, 92/43/EEC). High levels of underwater noise in the waters immediately surrounding these sites could result in seals reducing their use of these protected sites, moving to alternative, less desirable haul outs, or becoming increasingly sensitized to noise disturbances, even when on land at the sites (Bejder et al., 2009). As such, exposure to ADD noise in waters surrounding these protected sites may have implications for the conservation of harbour seals as it may result in the deterioration of habitats and/or significant disturbance to individuals within the immediate vicinity of these sites, which in turn may alter the numbers of seals using areas designated for their protection and conservation.

Further, at the time of tagging, all seven harbour seals in this study were pregnant (Table 1). Harbour seal parturition occurs in Scotland from June to early July (Van Parijs et al., 1997), encompassing the duration of tag data for six of the seals (Table 1). During the maternal period, female harbour seals will make regular foraging trips but are constrained to areas close to the pupping sites (Bailey, Hammond & Thompson, 2014). As such, these individuals may be increasingly susceptible to ADD noise exposure if it is within the vicinity of the pupping site and may be limited in their capacity to disperse to alternative, potentially quieter areas. Furthermore, little is known about how repeated exposure may impact the hearing of very young pups around these sites (Finneran, 2015; Southall et al., 2019), as they are able to swim almost immediately from birth, or the potential for these sounds to mask communication between mothers and pups, as harbour seals have been show to produce mother attraction calls both in air and underwater (Sauvé et al., 2015). Additionally, how exposure may impact the neurological and/or physiological development of seal foetuses is unknown. Impacts to foetuses from exposure to chronic noise have been suggested to occur in terrestrial mammals, birds, fish, and humans (Kight & Swaddle, 2011), and as such this raises specific questions with regards to effects on foetal development in marine mammals. Chronic noise could therefore have consequences for individual harbour seals at different life-history stages in Scottish inshore waters.

It is important to highlight that the results presented here are based on an acoustic model, which is subject to limitations and uncertainties that may lead to over- or underestimations of exposure. The energy flux acoustic modelling approach used in this study is a computationally efficient range-dependent model capable of accounting for variables including bathymetry, sound speed, seabed reflectivity, and acoustic frequency (Weston, 1971). Although this modelling approach is relatively simple compared with other more sophisticated approaches, such as ray tracing (Porter & Liu, 1994), validation of this approach in the field has shown good agreement with measurements of peak ADD frequencies out to 5 km from the source (Findlay et al., 2021). Although this reduces uncertainty in the model predictions, accurately modelling the acoustic output of individual aquaculture sites with ADDs is challenging because of a lack of licensing required to deploy these devices, leading to data gaps in our understanding of their daily usage, number of active devices, and aggregate duty cycles (The Scottish Government, 2021). More recent data, which were not available when this study was conceived and carried out, suggest that in 2017 aquaculture sites often deployed multiple ADDs, which were run continuously for 89% of stocked days per year (The Scottish Government, 2021). Consequently, the estimated noise levels for higher aggregate duty cycles (i.e. 75% and 100%) may be a realistic approximation for 2017. Addressing these uncertainties in the use of ADDs at aquaculture sites could further refine the overall results of exposure presented.

Within this study, all seven seals were pregnant females and were tagged at haul-out sites on the Isle of Skye (Arso et al., 2018), an area with limited nearby ADD use (Figure 3). Consequently, the results of exposure and auditory impairment presented may not be representative of the wider non-target harbour seal population on the west coast of Scotland. Studies suggest that female and male harbour seals will alter their distribution and movement patterns depending on the time of year and their reproductive cycles (Van Parijs et al., 1997). For example, during early lactation females may spend more time on land, whereas their male counterparts will continue to spend similar periods of time in the water, and as a result exposure may vary between the sexes depending on the time of year (Van Parijs et al., 1997). Future studies addressing ADD noise exposure may wish to better consider the sexes, age groups, time of year, and locations where seals are tagged. For example, if harbour seals had been tagged at the Eileanan agus Sgeiran Lios mór SAC, which is in close proximity to multiple aquaculture sites using ADDs (Figure 5), the predictions of $SEL_{w,24h}$ in tagged individuals based on this simple summation approach would have been higher. This is evident from seal 'vf02–498-17' that travelled towards the Eileanan agus Sgeiran Lios mór SAC and was exposed to ADD noise levels predicted to exceed the TTS threshold of 181 dB re 1 $\mu Pa^2 s$ over a 24-hour period.

The NMFS (2018) noise exposure criteria recommend a 24-hour consistent accumulation period for predicting auditory impairment and the equal energy hypothesis (EEH), where fatiguing sounds with equal SELs induce the same TTS (Finneran & Branstetter, 2013). These approaches are used here when accumulating the exposure of tagged seals to assess the potential for auditory impairment. However, discussions are continuing with regards to what constitutes a biologically relevant window over which to accumulate sound and assess auditory impairment, as the predicted sound exposure level will vary depending on the time over which the sound is accumulated; so, for example, a doubling (48 hours) or halving (12 hours) of the exposure time will result in an increase or decrease of 3 dB (Finneran, 2015; Tougaard & Beedholm, 2019). Additionally, the EEH is often criticized for overestimating the effect of intermittent signals, where recovery may be possible between exposures within the total accumulation period (Ward, Cushing & Burns, 1976; Finneran, 2015). The ADDs used by the Scottish aquaculture sector produce intermittent signals and therefore some auditory recovery is likely to occur between signal pulse trains or sweeps (for more details on ADD source characteristics, see Findlay et al., 2021). However, during the deployment of multiple devices (Northridge et al., 2010; The Scottish Government, 2021), where higher aggregate duty cycles are expected (75% and 100%), periods in which auditory recovery could occur are likely to be significantly reduced. Hearing loss is therefore dependent on several interacting factors, including exposure level, duration, and repetition rate (Kastelein et al., 2012; Kastelein, Gransier & Hoek, 2013a), as well as directionality of hearing, changes in vertical dive behaviour, and hauling out, all of which may influence auditory recovery time or the overall acoustic load (Fjalling, Wahlberg & Westerberg, 2006; Chen et al., 2017; Kastelein, Helder-Hoek & Terhune, 2018; Gordon et al., 2019; Trigg et al., 2020). Hence, the results of ADD exposure and TTS presented here, even at higher aggregate duty cycles, may potentially overestimate exposure levels for the tagged seals.

Effective quiet, the maximum SPL that will fail to produce a significant threshold shift regardless of exposure duration and level of accumulation (Ward, Cushing & Burns, 1976), is often assumed in modelling exercises when assessing exposure to anthropogenic noises (Trigg et al., 2020; Whyte et al., 2020). However, in this study it was not accounted for when calculating the rolling $SEL_{w,24h}$. To date, no studies have explicitly measured effective quiet in marine mammals (Finneran, 2015), and the level estimated for harbour seals (≤124 dB re 1 μPa) can only be applied with confidence up to 4 kHz (Kastelein et al., 2012). Given that the main frequencies of ADDs used by the Scottish aquaculture sector at the time of this study occurred between 2 and 40 kHz (Lepper et al., 2014), the inclusion of effective quiet in this study was deemed inappropriate. As a result, the $SEL_{w,24h}$ presented may provide an inflated impression of sound levels

(Finneran & Branstetter, 2013). Future measurements of effective quiet at frequencies in excess of 4 kHz could further improve confidence in predictions of $SEL_{w,24h}$ in tagged individuals from exposure to mid- to high-frequency anthropogenic sound sources, such as ADDs.

This study provides evidence of an individual harbour seal using waters within close proximity of high levels of predicted ADD noise. Seal 'vf02–498-17' moved in close proximity (<100 m) to an aquaculture site using ADDs. The likelihood of an individual seal remaining within a high noise environment will be strongly dependent on the individual's motivation to remain because of the presence of a valued resource, such as prey and available haul-out sites, or whether they have encountered the noise before (Ellison et al., 2012; Gomez et al., 2016). Indeed, the responses of individual seals to ADD noise have previously been shown to vary. For example, harbour seal numbers have either significantly reduced or showed no change in response to Airmar dB Plus II ADDs when used at aquaculture and fisheries sites in Canada (Yurk & Trites, 2000; Jacobs & Terhune, 2002). Seals have also been shown to remain in the presence of loud ADD noise or be attracted to these sites when there is a continual presence of food (Geiger & Jefferies, 1987; Götz & Janik, 2010). It is also possible that deterrence is reduced as a result of impaired hearing at the peak frequencies of ADDs (Götz & Janik, 2013), in turn limiting the effectiveness of these devices at reducing depredation. It is therefore recommended that before deploying ADDs as a mitigation intervention at aquaculture and fisheries sites, robust empirical evidence of their long-term effectiveness at deterring seals should be assessed.

At the planning stages for new aquaculture sites it may also be useful to formally consider the size and proximity of seal haul outs at the proposed fish farm location, in order to reduce the likelihood of depredation events and noise exposure from ADDs for seals; this could be informed by sound propagation modelling approaches like the one used in the current study. For existing aquaculture sites, temporal management of ADDs at fish farms in close proximity to protected sites could be considered to help reduce noise exposure to non-target individuals. For example, limits on the duration of ADD use at times of particular sensitivity (e.g. mating and pupping seasons) may be a useful approach to reducing potential impacts on local populations. Alternatively, aquaculture sites could consider using non-acoustic mitigation options to reduce pinniped depredation. These include improving animal husbandry, reducing stock density, seal blinds, anti-predator nets, maintaining correct net tensioning, and using stronger and stiffer net materials (e.g. high-density polyethylene netting) (Thompson et al., 2020b). These approaches, if effective, could reduce overall ADD use, resulting in non-target individuals being less frequently exposed to noise and decreasing potential risks to species, such as harbour seals, using areas in close proximity to aquaculture sites.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with this work.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available from the first author upon reasonable request.

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