Marine Scotland

Use and efficacy of Acoustic Deterrent Devices (ADDs) in Aquaculture

April 2022

Scottish Government
Riaghaltas na h-Alba
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Use and efficacy of Acoustic Deterrent Devices (ADDs) in Aquaculture

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This report presents the results of work commissioned by Scottish Government.

1 Executive Summary

The aim of this study was to collate and review data on the use of Acoustic Deterrent Devices (ADDs) in the aquaculture sector to provide a better understanding of how they are being used, their efficacy and any potential for impact on sensitive non-target species. Records were provided by a range of industry sources and regulators, and a dataset developed which describes the extent of ADD use in Scotland from 2014 to 2020.

This report describes changes in ADD use across Scottish finfish farms over the period from 2014 to 2019 as well as providing a more detailed snapshot from the winter of 2019/2020. The use of ADD systems is dynamic, with changes made by finfish farm operators and manufacturers continuously. Patterns of use and device types are evolving as new technologies are developed to meet the regulatory framework and new scientific understanding. Lower frequency and lower amplitude ADDs, which potentially have a lower impact on sensitive non-target species, are now reportedly being used at an increasing proportion of farms.

Quantitative analysis was conducted to examine evidence of the efficacy of ADDs. Overall, there was a positive association between ADD use and seal depredation, with more frequent depredation and higher resulting mortality of fish on farms where ADDs were used, compared to where they were not used. This is likely to be a consequence of fish farms which experience high levels of seal depredation being more likely to use ADDs. However, despite an extensive modelling exercise designed to remove the effect of confounding variables, it was not possible to differentiate between any effect of ADDs in reducing depredation and the underlying factors that link ADD use with increased depredation. A small number of sites were identified where the use of ADDs is not permitted and depredation was found to be higher on average at these sites than sites where ADD use is permitted. If these sites could be considered representative of average background depredation levels, then this finding may indicate effectiveness of acoustic deterrence measures, but this assumption is difficult to test. Our findings illustrate the limitations of current observational data and demonstrate the importance of undertaking further experimental work to understand ADD effectiveness.

This work highlights the paucity of evidence and available data, particularly for assessment of ADD efficacy in preventing seal depredation. Systematic data collection on the extent and nature of ADD use across Scottish aquaculture sites is therefore urgently required.

Research priorities are provided based on the key knowledge gaps in relation to depredation by seals in aquaculture. Controlled experimental trials are required to understand the efficacy of ADDs in reducing depredation and to understand any effects on non-target species. This is particularly important in the context of the changing scientific understanding of the potential impacts on non-target species, and current regulatory frameworks. Research is also required to better understand the efficacy of alternative management measures, and recommendations are provided in Thompson et al. (2021), which considers the management options for pinniped predators at finfish farms in a broader context.

2 Introduction

2.1 Depredation in aquaculture

Farming of Atlantic salmon *(Salmo salar)* in Scotland is an important and growing industry. Production has increased from less than 40,000 tonnes of production in 1990 to over 200,000 tonnes in 2019. Farmed salmon is currently the UK's largest food export product by value. It directly employs around 2,400 people, with a further 8-10,000 jobs in downstream processing and associated roles. It has particular economic importance in coastal and rural areas, where few employment opportunities exist. Furthermore, the Scottish Government has a stated ambition to increase salmon production, to double the economic contribution of the sector from £1.8 billion in 2016, to £3.6 billion by 2030, and to double the number of jobs to 18,000 by 2030 (Scottish Government, 2020a). As of December 2020, there were around 220 active finfish farm sites in Scotland (Scotland's Aquaculture, 2020).

The seas around Scotland are important for marine wildlife, supporting at least 22 species of marine mammals, including seven relatively common species of cetacean (bottlenose dolphin - *Tursiops truncatus*, harbour porpoise – *Phocoena phocoena*, minke whale – *Balaenoptera acutorostrata*, white-beaked dolphin – *Lagenorhynchus albirostris*, Risso's dolphin – *Grampus griseus*, common dolphin – *Delphinus delphis* and killer whale – *Orcinus orca*) as well as large numbers of two species of pinnipeds (grey and harbour seals - *Halichoerus grypus* and *Phoca vitulina*, respectively). Marine mammal populations around Scotland inevitably interact with finfish farms to some extent, and these interactions can be negative to both the wild animals and the aquaculture industry. The most significant and problematic of these interactions occur between finfish farms and seals. Scotland has a population of around 122,500 grey seals representing around 83% of the UK population, and a minimum population of 26,900 harbour seals representing around 82% of the UK population (SCOS, 2019).

Depredation by seals at finfish farms is a serious welfare and economic concern for the Scottish aquaculture industry, occurring at around 73% of finfish farms (Northridge et al., 2013). The precise mechanism of predatory attacks is not well understood, but seals are known to manipulate finfish farm nets in order to attack and kill fish from the outside (Coram et al., 2016). As well as injury and mortality of stocked fish, predators can cause stress to stocked fish (Barcellos et al., 2007), potentially reducing growth rate and tolerance to disease (although this has not been studied in the context of seal depredation). Seals can also cause damage to fish farm infrastructure. Damage by predators to nets has been reported as one of the largest causes of fish escapes in European aquaculture (Jackson et al., 2015).

A combination of lethal and non-lethal management and mitigation options have been used by managers to reduce the impact of predators in aquaculture. Until 2011, the lethal removal of seals to alleviate depredation was largely unlicensed. However, since the introduction of the seal licensing system in 2011 through the Marine (Scotland) Act 2010, there has been an overall reduction in the numbers of seals targeted and subsequently shot under license as a last resort (Scottish Government, 2020b). Throughout the period of licensed lethal removal, the aquaculture industry maintained an ambition to reduce the number of seals killed under licence for the protection of stocked fish to zero (RECC, 2018), Changes to the Marine (Scotland) Act 2010[1] which came into force on 1 February 2021 mean that licences can no longer be granted authorising the taking or killing of seals for the purpose of preventing serious damage to fisheries or fish farms, or to protect the health and welfare of farmed fish. There is therefore a requirement to find additional options for reducing the occurrence of depredation caused by seals.

One of the most regularly used methods to address seal-aquaculture interactions is the use of Acoustic Deterrent Devices (ADDs), which has increased substantially on the west coast of Scotland from 2006 to 2016 (Findlay et al., 2018). These devices produce underwater sounds which aim to deter seals in order to reduce the risk of depredation or stress caused to fish by predatory behaviour. However, their use in aquaculture to deter seals may cause disturbance to cetaceans under certain conditions (Brandt et al., 2013; Johnston, 2002; Mikkelsen et al., 2017; Olesiuk et al., 2002). Furthermore, limited research has been undertaken on whether the use of ADDs reduces depredation, and there is currently little scientific evidence to support their long-term use. Conversely, several studies have reported habituation by seals to the most regularly used signal types (Götz & Janik, 2010; Ross, 1988; Sepulveda & Oliva, 2005), but the available evidence is very limited.

There is therefore a clear requirement for a better understanding of the extent and use of ADDs at Scottish finfish farms. In particular, it is important to improve understanding about how many devices are currently in use, their acoustic properties, how they are used, how effective they are in reducing depredation, and what impacts they may have on non-target species (e.g. cetaceans).

One of the aims of this project was to collate information from all available data sources, including information held by the aquaculture sector, to provide a description of the current extent of ADD use. In addition, data was also collected on the rate and level of depredation by seals. These data together, provide the best available evidence of ADD efficacy, as well as other anti-predator measures such as modern netting materials and weighting systems, at reducing depredation.

2.1.1 Anthropogenic conflicts with marine predators

Legal protections and the cessation of exploitation of marine mammal species in many parts of the world have contributed to increasing populations, particularly of pinnipeds (Chasco et al., 2017). Whilst this is generally viewed as a conservation success story, it may have led to an increase in negative interactions with some marine industries, such as fisheries and aquaculture in the context of increasing anthropogenic demand for wild-caught and farmed fish (Gales et al., 2003). In some cases, conflicts with wildlife conservation efforts have also emerged. For example, increased pressure from pinniped populations has been linked to reduced recovery of wild salmonid stocks (Butler et al., 2006; Yurk & Trites, 2000).

Fisheries and aquaculture suffer from loss of value as a result of direct depredation of fish (e.g. Figure **1**), through damage to infrastructure such as netting and, in the case of wild

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[1] The Animals and Wildlife (Penalties, Protections and Powers) (Scotland) Act 2020

capture fisheries, possibly through increased competition for resources (MMO, 2019). Seals were reported to be a source of depredation at around 73% of finfish farms, and Northridge et al., (2013) found that almost 1.4 million fish were reported lost to seals at 87 sites over a 129-month period, equating to a conservative estimate of around £26,000 per site per year of lost revenue. Figures produced by the Scottish Salmon Producers Organisation (SSPO) suggests that 500,000 fish were lost to seal depredation in 2020 alone[2]. With farmed salmon prices of around £5 per kg, depredation of harvest weight fish costs the industry between £15 and £35 of revenue per fish. Damage to nets presents an additional cost, requiring maintenance by divers and risking the potential escape of large numbers of farmed fish, which presents a conservation concern for wild salmon stocks.

In the context of finfish aquaculture, conflicts with pinnipeds present an additional concern in terms of the welfare of farmed fish. Aquaculture practitioners have moral and legal obligations for the protection of their fish through the Animal Health and Welfare (Scotland) Act 2006 and must manage any wildlife interactions accordingly. As well as injury and mortality, pinniped attacks can cause stress to captive fish which is in itself a welfare concern. Stress to captive fish is linked to reduced growth rate and increased susceptibility to disease (Barcellos et al., 2007).

Figure 1 Example of seal depredation damage on large salmon at a finfish farm in Scotland (A. Coram).

2.2 ADD usage

2.2.1 Past ADD use

Since their commercial development in the 1980s, ADDs have been used in attempts to deter many different species of marine mammals in a variety of applications, including: protecting migratory fish in river fisheries (Graham et al., 2009) or marine bottlenecks (Mate & Harvey, 1987), in mobile and static fisheries (Gosch et al., 2017; Königson, 2006; MMO, 2020; Petras, 2003; Westerberg et al., 1999) and as a mitigation tool in offshore renewable energy development (Thompson et al., 2020). Where the term ADD is used in this

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[2] https://www.scottishsalmon.co.uk/news/press-release/scottish-farmed-salmon-sector-calls-for-action-on-predation (2021-04-19)

document, it is generally applied to all acoustic devices designed to deter seals, unless otherwise stated.

The use of ADDs in Scottish aquaculture has been increasing since it was first assessed in 1985, when four of 41 (9.7%) sites were using them as a mitigation tool (Hawkins, 1985). By 1988 this had risen to eight sites out of 45 (18%) (Ross, 1988); an increase that continued though the 1990s to 52% in 2002 (Quick et al., 2002), and a similar percentage (49%) was reported again in 2010 (Northridge et al., 2010). The use of ADDs has become more common on the Scottish west coast from 2006 to 2016 (Findlay et al., 2018), and interview surveys with aquaculture site managers suggested that Airmar, Terecos and Ace Aquatec equipment were most widely used in Scottish aquaculture in 2010 (Northridge et al., 2010). Results from acoustic surveys found similar results, with most ADD noise detected on the west coast between 2011-2015 attributed to ‘Airmar-type’ devices (>75%; Findlay et al., 2018).

2.2.2 Rationale for ADD use

Despite the widespread use of ADDs at finfish farms, there is limited published evidence to support the long-term effectiveness of ADDs (reviewed in Coram et al. (2014). To date, scientific research has largely focused on assessing the potential impacts of ADDs on non-target species, rather than on quantifying their efficacy in deterring predators. A comprehensive review of the current evidence for effects of different devices on different species is available from a Joint Nature Conservation Committee (JNCC) report (McGarry et al., 2020).

Effective deterrence is thought to rely on altering the relative costs and benefits to the individual predator by creating a perceived risk associated with human resources, and ADDs are hypothesised to do this by either inducing pain or distraction in the target animals (Schakner & Blumstein, 2013). Captive grey and harbour seals have been shown to find certain sound types aversive and appear not to habituate to these signals (Kastelein et al., 2017; Kastelein, Heul, et al., 2006). One study showed sensitisation toward sound signals that elicited a startle-response (Götz & Janik, 2011). However, some animals (two out of seven) were found not to respond to the startling signals.

Playback experiments at sea, outside the context of aquaculture, have found mixed behavioural responses to ADD sounds. A Lofitech ADD (not in use in Scottish aquaculture) reliably elicited a response from tagged harbour seals at ranges of less than 1 km, but responses did not always result in substantial movements away from the sound source (Gordon et al., 2019). A simulated ADD signal (based on the Lofitech with reduced source levels) caused an increase in observations of seals within 100 m of the ADD signal when it was switched on (Mikkelsen et al., 2017), suggesting that seals do not always find such signals aversive. Additionally, if seals learn to associate an ADD with a source of low cost resources, they may be drawn to the sound source – often termed the ‘dinner bell effect’ (Mate & Harvey, 1987).

While it may seem sensible to draw parallels from other applications, it is important to remember that the behavioural context at a finfish farm may be very different from other situations where research into ADD has been conducted. It is not possible to accurately replicate in captivity the behavioural context where depredation occurs (i.e. motivation and hunger). Trials conducted at sea but away from finfish farms will also have a different behavioural context and may therefore elicit a very different suite of behavioural responses (Coram et al., 2014). Likewise, trials conducted with one ADD type may not be suitable evidence for inferences relating to other ADD types.

Only a small number of ‘real-world’ studies have been conducted into the efficacy of ADDs. In addition to the studies reviewed by Coram et al. (2014) we are aware of three additional studies of ADD use in aquaculture. The use of the acoustic startle reflex to deter pinnipeds has shown success in early trials of a GenusWave device. Götz & Janik (2015) reported a significant reduction in the number of seal tracks within 250 m of the device, and seal distribution was not affected at distances further away from the farm, suggesting a very localised deterrent effect. A longer-term trial at Scottish finfish farm showed a significant reduction in depredation over a period of 12.5 months (Götz & Janik, 2016). Trials have so far been limited in scope, and evidence from commercial application of this device is required before broad conclusions can be made about efficacy. In another study, use of Ace Aquatec US3 and Airmar dB Plus II equipment was found to reduce depredation at Scottish finfish farms by 70% and 50% respectively, compared to baseline with no ADD use, while the use of a Terecos ADD apparently had no effect (Whyte, 2015).

2.3 Policy background

There has been a long-held ambition by the aquaculture sector to reduce the number of seals shot to protect Scottish aquaculture to zero (RECC, 2018).

Legislation passed in the Scottish Parliament in June 2020 (The Animals and Wildlife (Penalties, Protections and Powers) (Scotland) Act 2020)) removed two provisions by which licences could be granted authorising the taking or killing of seals for the purpose of protecting the health and welfare of farmed fish, and to prevent serious damage to fisheries or fish farms. As a result of these changes, which came into force on 1 February 2021, there is consequently a need for effective additional management methods to be developed and implemented. The use of acoustic deterrents is seen by the industry as one effective method.

The Animals and Wildlife (Penalties, Protections and Powers) (Scotland) Act 2020 also includes a requirement for Scottish Ministers to provide a report to the Scottish Parliament on the use of ADDs, including; “information on the use made of acoustic deterrent devices on Scottish fish farms, any known impacts that the use of acoustic deterrent devices has on marine mammals, and consideration of whether the use of acoustic deterrent devices on Scottish fish farms is sufficiently monitored”.

The Conservation (Natural Habitats, & c.) Regulations 1994 (as amended) (‘Habitat Regulations) which apply in Scotland, include protection for cetaceans which are European Protected Species (EPS). Under regulation 39 (1) and (2), it is an offence to deliberately or recklessly capture, injure, kill or harass a wild animal of EPS, and deliberately or recklessly disturb any cetacean. Where an activity takes place that could constitute an offence, a

European Protected Species licence (EPS licence) will be required. Revised guidance in relation to the protection of marine EPS from injury and disturbance in Scottish inshore waters was published in 2020 (Marine Scotland, 2020c), along with an information note to clarify the circumstances in which an EPS licence to use an ADD would be required (Marine Scotland, 2020b). Licences may only be granted if there is a licensable purpose, there are no satisfactory alternatives, and the actions will not be detrimental to the maintenance of the population of the species concerned at favourable conservation status. Licensable purposes include prevention of serious damage to livestock or fisheries.

In addition to their status as EPS, several species of cetacean are also protected by a network of marine protected sites comprising marine protected areas (MPAs) and European sites (Special Areas of Conservation, SACs). The introduction of the Inner Hebrides and the Minches SAC for harbour porpoise focused attention on ADDs as a potential significant source of underwater noise pollution, and a potential source of widespread disturbance in that area. The designation of the SAC created a requirement to ensure that harbour porpoise populations are not impacted within the site. New applications for fish farms within the Inner Hebrides and the Minches SAC are required to provide information on predator management measures adopted, including information relating to the use of ADDs. Such information may not be held for sites which pre-date the SAC designation and have not required any subsequent amendments to planning permission. Further, MPAs recently designated for the protection of Risso’s dolphins (North-East Lewis) and for minke whales (Sea of the Hebrides) have conservation objectives that require the maintenance of the protected features in favourable condition. There is a duty on regulators to ensure there is no risk of hindering the achievement of the conservation objectives of the MPA before consenting an activity such as ADD use associated with a new fish farm application.

The Scottish Government is committed to the UK Marine Strategy (DEFRA, 2019), which requires healthy populations of birds and marine mammals as part of 'Good Environmental Status' (GES). An essential step in achieving GES is the establishment of adequate monitoring programs (Dekeling et al., 2016), and ADDs are listed by OSPAR Monitoring Guidance for Underwater Noise in European Seas as an important sound source to be monitored. In response to this requirement, in the UK information is routinely recorded for some types of underwater sound sources through the Marine Noise Registry (MNR), administered by the Joint Nature Conservation Committee, and includes some information on the use of ADDs when used for offshore mitigation (JNCC, 2020).

3 Extent of ADDs in Scottish Aquaculture

3.1 Description of the collated information on ADDs

One aim of this project was the collation of information on ADDs to provide the most comprehensive and accurate description possible of their extent in Scottish finfish aquaculture. This involved the collation of records from disparate and unsystematic data sources which presented significant challenges.

Available data sources were examined for suitability (i.e. Marine Scotland's Seal Licensing survey and RSPCA Assured's records). This process highlighted some questions regarding the quality and completeness of the information, which are explained below for each data source. Efforts were then made to address these questions and improve the quality of the data by accessing additional data sources. Industry-held data were important to this process, which involved continued liaison with finfish producers and ADD manufacturers, with the assistance of the Scottish Salmon Producers Organisation. Available data sources covered different periods of time and some overlapped. The aim was to verify existing records where possible and identify missing or inaccurate data records wherever necessary, in order to build the most comprehensive dataset possible, with a primary focus on attaining the most up-to-date information possible. Where available, data was also collected that could be used to assess the efficacy of different management measures.

The resulting dataset therefore collates data from various sources with different temporal scales of resolution, covering different but overlapping spatial and temporal extents, and including different variables. Wherever possible matching variables have been combined to produce a semi-continuous time-series for each finfish farm. Where data sources contradicted one another, an order of precedence was adopted by which one data source was assumed to be more accurate than the other[3]. Finfish producer records were taken as the most accurate as they were supplied directly for this purpose and were the most up-to-date information available.

Information collected could not be independently verified and it is therefore possible that inaccuracies remain in the collated dataset, but in the absence of a comprehensive systematic data source, the approach taken for this project was the most practical one available. Despite the limitations of the available data, it provides the best possible description of recent industry practices, and the data are still considered suitable for the identification of broad patterns in ADD use over time and between regions.

3.1.1 Data sources

The primary focus of the data collection was to obtain information on the extent of ADD use within the aquaculture sector.

Where possible, data relating to the use of alternative anti-predator measures was also collected from the same data sources in order to inform the analysis of efficacy of different

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[3] From highest to lowest priority: finfish producers, ADD manufacturers, seal licensing surveys, accreditation schemes

methods (section 4). Information was collected on: net shape and materials, lethal removal of seals, anti-predator nets (secondary layer of netting, usually larger mesh, hung outside of the primary fish net to provide a secondary barrier against predators) and seal-blinds (additional layers of netting attached to the base of nets around the ‘mort-sock’).

A list of all actively producing finfish farms taken from the Scottish Government data portal (Scotland’s Aquaculture, 2020) was used as a reference for the true number of operating sites (216 sites in January 2020). This project only considered sites producing finfish in seawater, with shellfish and freshwater farms excluded from any assessment.

Data obtained from the following data sources have been collated into one dataset, covering the period from October 2014 to July 2020.

3.1.1.1 Seal licensing survey

Information was collected annually through the seal licensing scheme from all sites that applied to Marine Scotland for licences to kill or take seals. The purpose of the survey was to evidence that all suitable non-lethal measures were employed before a licence was granted. This process also provided information on the reported extent of ADD use, including ADD type, number of transducers, monthly seal depredation rate, as well as some information on the use of alternative measures: anti-predator nets, seal blinds and weighting systems. Records also indicated whether or not the ADD was in use during each month.

Almost all actively producing finfish farm sites are contained in this dataset, but the completeness of the ADD information provided varied greatly between sites and producers, leaving omissions relating to the use of ADDs over certain time periods. This information is provided directly from producers, but as ADD usage was not the focus of this data collection, accuracy or completeness was not verified during collection. ADD use may not necessarily have been reported fully or consistently between years and sites.

Seal licensing information has been collected annually since 2014 and was available for each month over the period October 2014 to October 2019.

These records represent a consistent source of information over the period of interest. However, there is no longer a requirement to collect information for this purpose due to changes to the Marine (Scotland) Act 2010. This survey collects retrospective data annually, and the final survey was conducted in October 2019.

3.1.1.2 Accreditation schemes

A number of accreditation schemes are active in Scotland, or have been in the recent past, including but not exclusively: Whole Foods, Aquaculture Stewardship Council, Friends of the Sea, Label Rouge, Best Aquaculture Practice (Global Aquaculture Alliance), as well as organic schemes such as the Soil Association. Where contact information could be obtained, these schemes were contacted to request data relating to anti-predator measures, with a response received from the RSPCA scheme, ‘RSPCA Assured’. The extent of information on anti-predator measures held by other schemes is not known.

Records provided by RSPCA Assured are collected annually through site audits, with additional supplementary information being collected periodically. Records included information on ADD types on site, as well as some data on alternative anti-predator measures (e.g. anti-predator nets, net shape, and net material). Information was obtained for the period January 2014 to July 2020 and the data collected during each audit was assumed to be valid for the following year or until the subsequent audit. These records cover 68% of the actively producing finfish farm sites, with missing data occurring where audit information was incomplete and where companies were not enlisted to the scheme.

3.1.1.3 ADD manufacturers

The manufacturers of all commercially available ADDs were contacted for information on the extent of use of their devices. Data were provided by OTAQ and Ace Aquatec, relating to 32 active sites (15% of all active finfish farms).

Data on the use of ADDs were provided either on a weekly schedule for each site, or as a snapshot of the most up-to-date information relating to what was in use at a particular site. The number of devices installed at each site were also provided. Information supplied covered the period March 2018 to November 2019. Records were assumed to be valid for the year following unless otherwise stated or records provided by finfish producers were in contradiction.

3.1.1.4 Finfish producers

All major finfish producing companies operating in Scotland were contacted with a request for accurate information on use of anti-predator measures, with a focus on ADDs. Requests were made for information focused on ADD type, location and use, with additional supplementary data requested on alternative management measures wherever possible, and any available historic records with evidence on the efficacy of ADDs. Responses were received from all producers contacted, but the extent and resolution of information received varied greatly. Follow-up dialogue was then used, focusing on verifying and, where necessary, correcting information supplied from other sources.

Information was supplied on the types of ADDs installed at time of the request and, in the case of one company, rates of seal predation. A small amount of additional supplementary data relating to other management measures such as net materials was also provided, but data on ADD status (on/off) over time were not provided. Information on ADD installation covered the period March to July 2020. Seal depredation data supplied by one finfish producer covered the period January 2016 to November 2019.

3.1.2 Proportion of stocked time with available data

To assess the completeness of the dataset over time, the number of days each site was stocked with fish was compared against the number of days for which records of ADD use were obtained. Figure 2 shows that for most sites, ADD use information was available for at least 75% of stocked days.

Stocking dates were collated from two sources: the Scottish Government website records of biomass (owned by the Scottish Environment Protection Agency), and the seal licensing dataset. Neither dataset alone was found to contain a complete set of stocking dates, but by combining the two we have the best available record of stocking dates. Different farm identification systems are used for each of these datasets, so they were combined by matching unique farm identification records, such as site name and geographic coordinates.

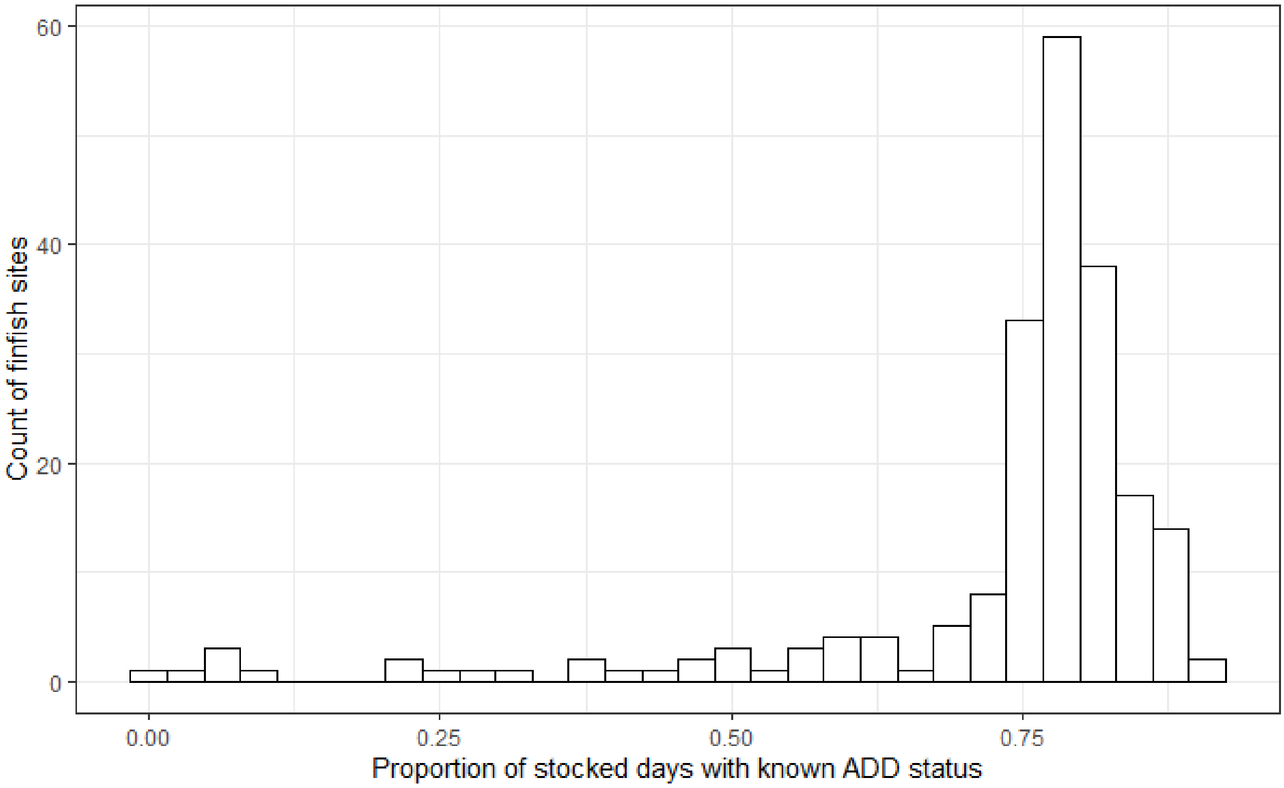

Figure 2 The proportion of stocked days for which data are available on ADD status between 2014 and 2020

3.2 Most recent extent of ADDs at finfish farms

A primary aim of this project was the collection of up-to-date information to describe the most recent use of ADDs. However, the use of ADDs is dynamic and has changed over time, including over the time span of this project. Records collated through this project could be considered as ‘points in time’, i.e. only valid for the date of collection, but data collection did not occur all at one point; it was ongoing through the length of the study. In order to present an overall picture of ADDs, we therefore needed to define a time window within which to describe their extent and use.

The time window for which we have the most complete dataset on ADDs is the winter of 2019 – 2020 (October 2019 to April 2020). This time period includes the very end of the seal licensing survey dataset, along with additional information from ADD manufacturers, finfish producers, and RSPCA Assured. By defining this time period we can describe an overall picture of ADD extent as a snapshot in time, using all available data sources. A total of 193 finfish farms are included, representing 89.4% of the 216 operating farms over the same time period.

Finfish sites have been categorised into regional groups according to their local authority area (see Figure **3**). This level of categorisation was chosen in order to provide insight into geographic variation. Finfish sites in the Firth of Clyde around Arran are included in Argyll and Bute.

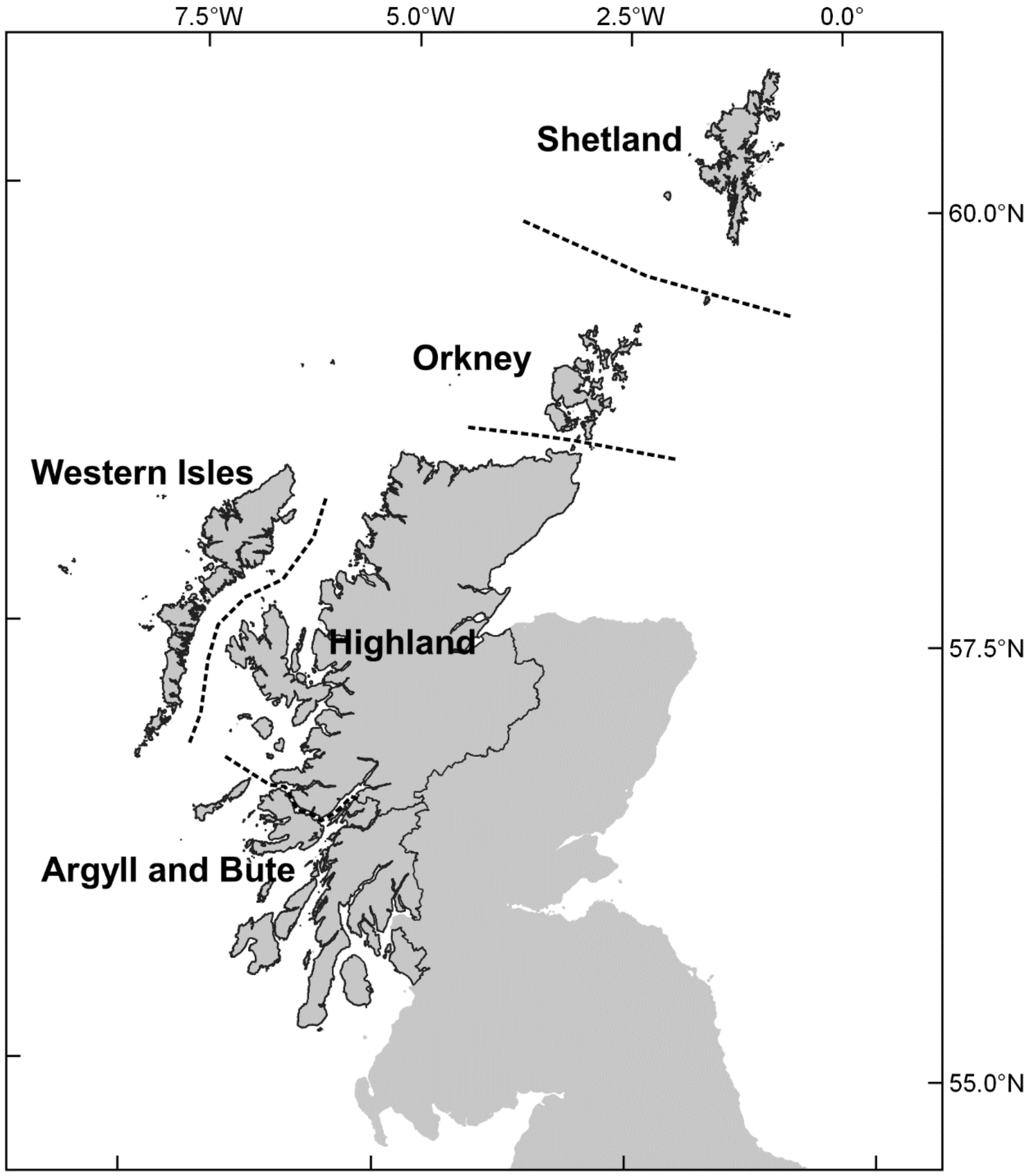

Figure 3 Regional categorisations of Scottish finfish farms according to local authority area

Regions	**ADD Installed**		**Sample size**	**% with ADD**
	Yes	**No**		
Highland	45	8	53	85%
Orkney	8	15	23	35%
Shetland	15	27	42	36%
Argyll and Bute	32	8	40	80%
Western Isles	32	3	35	91%
Grand Total	132	61	193	68%

Table 1 Total number of finfish sites with ADDs installed and not installed over the winter 2019-20, with regional breakdown

The total number of finfish sites which had ADDs installed over the winter of 2019 to 2020 was 132, or 68% of total operating sites. In contrast, there were 61 finfish farms (32%) which did not have an ADD installed over the same time period. This proportion varies by region (Table **1** and Figure **4**), with Shetland and Orkney Isles both having relatively low numbers of ADDs installed as a proportion of the number of sites. The highest proportion can be found in the Western Isles, with 32 sites out of 35 having an ADD installed (91%).

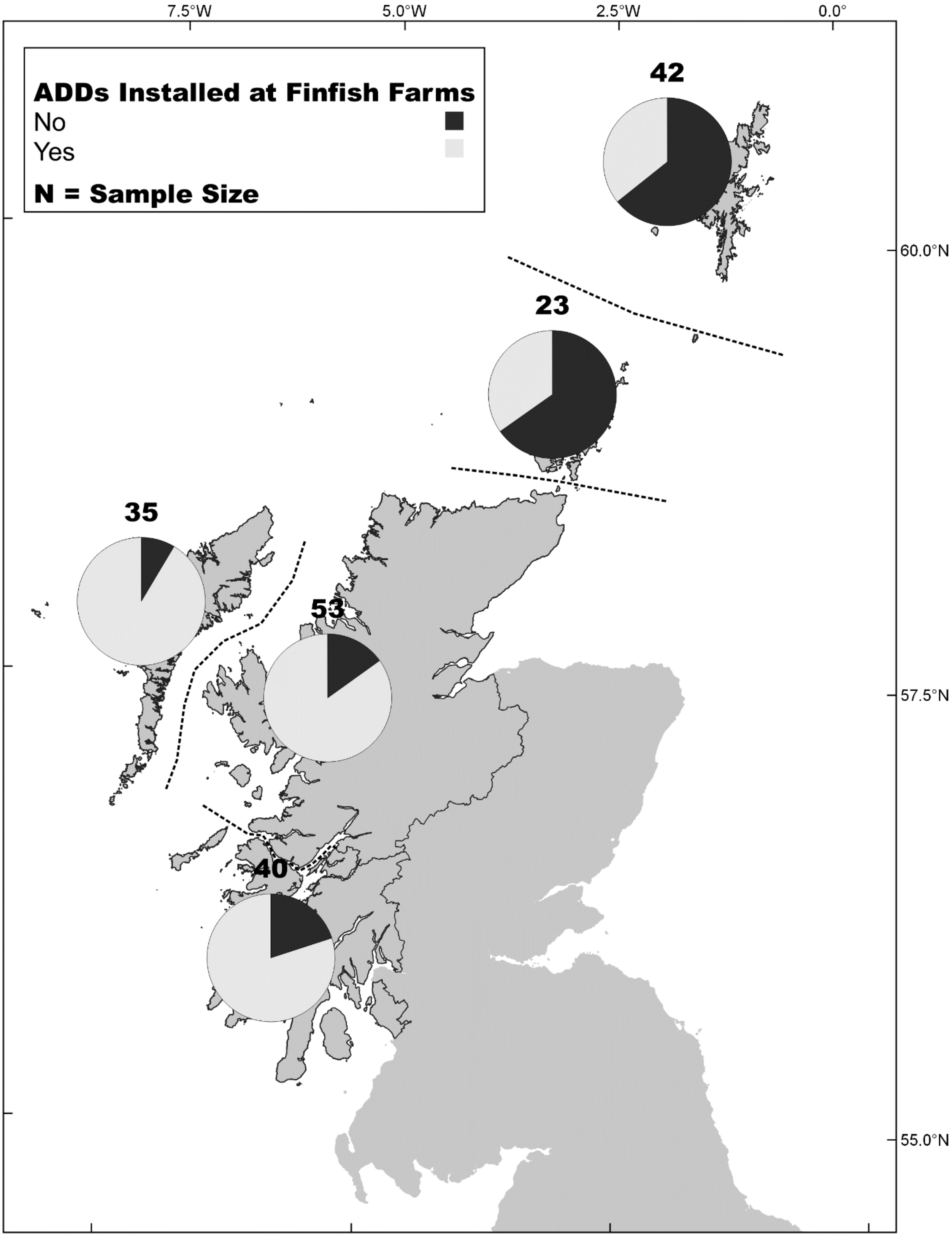

Figure 4 Regional proportion of finfish farms with ADDs installed and not installed in winter 2019 – 2020 (with sample size)

In total there are seven different types of ADD installed at finfish farms over the winter of 2019 – 2020 (listed in Table **2**).

The sound characteristics of each ADD has been described in several other reports (Coram et al., 2014, McGarry et al., 2020, Thompson et al., 2021) but a brief description is included here for reference (Table **2**). Where records indicate that an ADD is installed, but do not specify the ADD type, and where this information could not be verified in communication with operators or manufacturers, these have been recorded as ‘Unknown’.

Device	**Comment**
Airmar dB Plus II	These are different iterations of the original Airmar dB Plus II, which emit the same signal types but may have slight differences in operating features.
GaelForce SeaGuard	
MohnAqua MAG Seal Deterrent	
Ace Aquatec US3	This includes records of older devices listed as US2 which is also made by Ace Aquatec and producing the same signal.
Ace Aquatec RT1	A low-frequency device produced by Ace Aquatec.
Terecos DSMS-4	No longer in production but still in use
OTAQ Seal Fence	Operates in Protect or Patrol mode.

Table 2 The seven ADDs installed on finfish farms over the winter of 2019 - 2020

Region	Airmar	Ace-US3	Ace-RT1	GaelForce	MohnAqua	OTAQ	Terecos	Unknown
Highland	15	5	2	3	3	20	7	3
Orkney	2	1	4	0	1	0	0	0
Shetland	9	2	9	0	1	1	1	1
Argyll and Bute	4	2	0	0	2	24	2	0
Western Isles	1	2	0	2	3	23	1	4
Total	31	12	15	5	10	68	11	8
% of active finfish farms	14%	6%	7%	2%	5%	31%	5%	4%

Table 3 The number of finfish farms with each type of ADD installed over the winter 2019 - 2020 (note that some farms use multiple ADD types)

Table **3** shows the number of sites with each type of ADD over winter 2019 - 2020, broken down by region. Several sites are reported to have multiple ADD types, and therefore the combined totals are higher than the number of sites that have ADDs. The most commonly installed ADD type is the OTAQ system, which was installed at 68 finfish farms during October 2019 to April 2020, this equates to 31% of all active finfish farms (Table **3**). The Airmar and similar devices (GaelForce and MohnAqua) combined are installed at 46 sites, which equates to 21% of active finfish farms.

There are regional differences in the types of devices installed. Figure **5** shows the regional proportions of sites with each of the different types of ADD in winter 2019 - 2020. Airmar, GaelForce and MohnAqua devices are distributed across all regions, with the largest proportions of farms with these devices in Shetland, Orkney and Highland regions. OTAQ equipment is not generally installed in the Northern Isles, but makes up the largest proportion of finfish farm sites in the Western Isles, Highland and Argyll and Bute. The largest proportions of ADDs in the Northern Isles is the Ace Aquatec RT1 and Airmar.

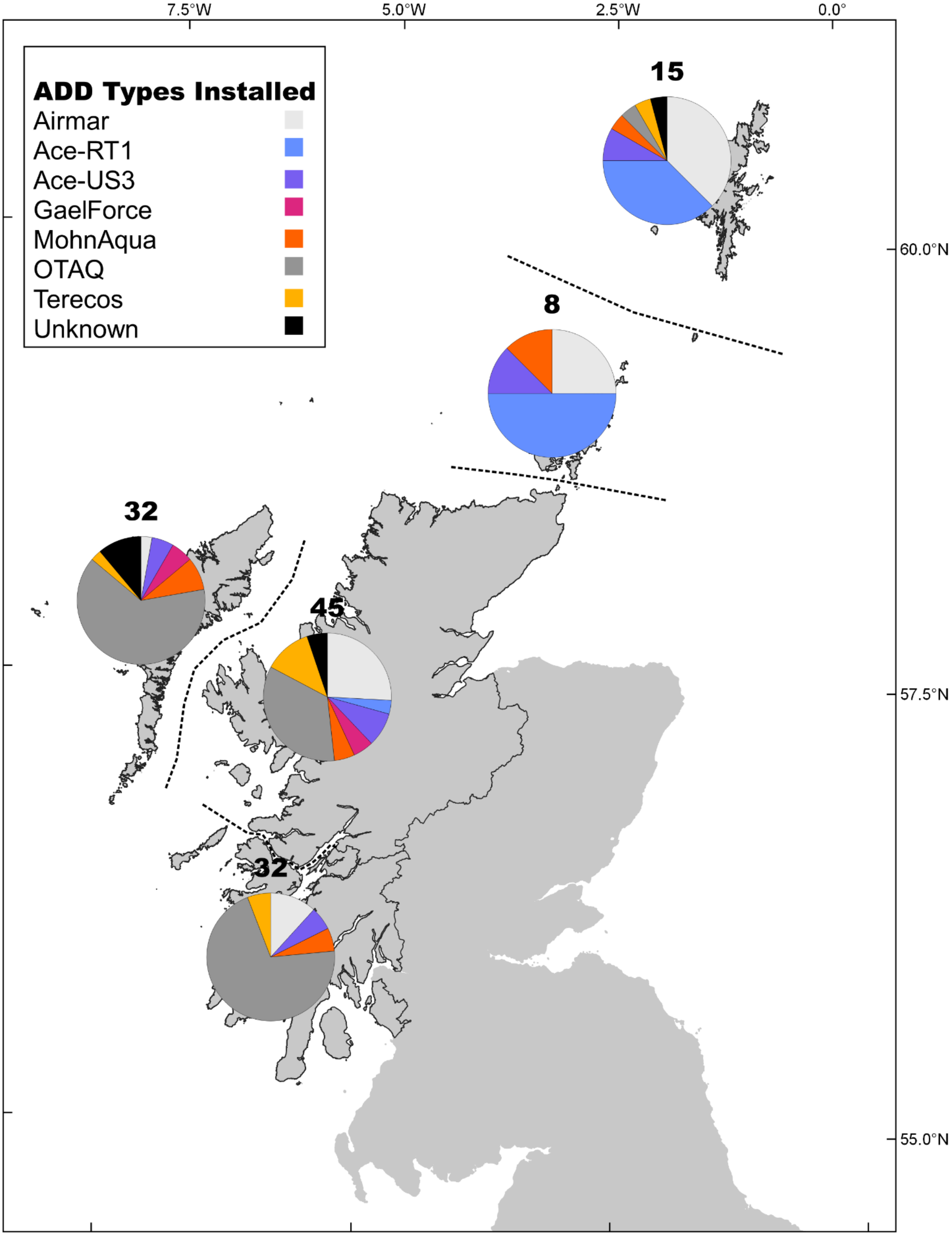

Figure 5 Regional differences in the proportional use of ADD types in winter 2019– 2020 (with sample size)

3.3 Changes in ADDs over time

This section explores the changes in the presence of ADDs at finfish farms over time, providing a broadscale assessment of their historical use from 2014 to 2019. The cessation of the seal licensing survey in October 2019, combined with the collection of additional information from alternative sources after this time, means that the most recent information from 2020 is not necessarily comparable with earlier years and so is not considered here.

3.3.1 Extent of ADDs

From 2014 until 2016, the number and proportion of finfish sites with ADDs increased from 119 to 154 (58% to 67% of total sites). From 2016 to 2018, the number of sites with ADDs was stable at 154/155 (around 70% of active finfish farms). After a peak from 2016 to 2018, the number of sites with ADDs declined to 146 (68%) in 2019 (Figure **6**).

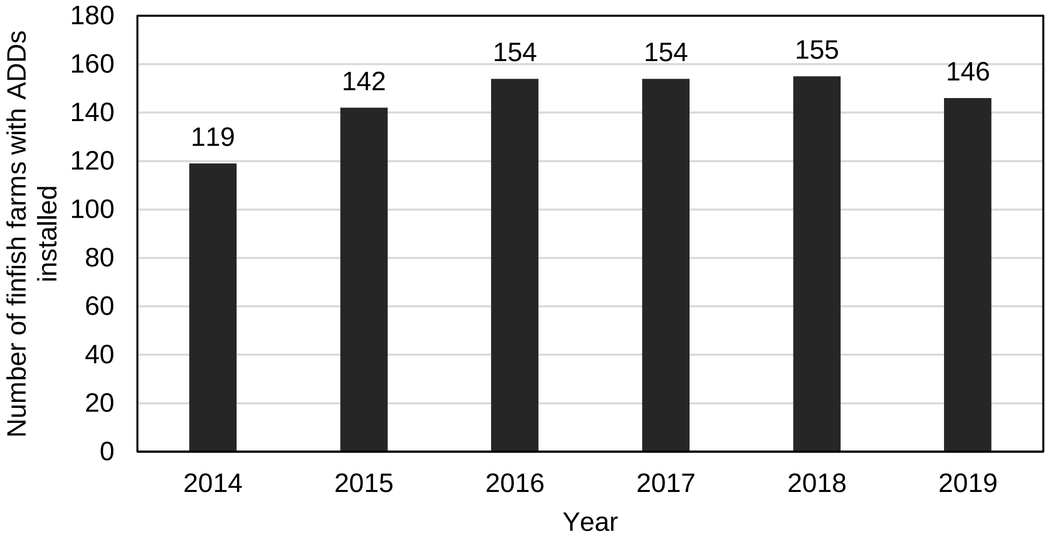

Figure 6 Number of finfish farms with ADDs from 2014 to 2019

These changes over time are shown broken down by region in Table **4**. As described above for the most recent information (section 3.2), the highest proportion of finfish sites equipped with ADDs in recent years has been in the Western Isles and the Highlands. The proportion of sites with ADDs increased in all regions except Argyll and Bute from 2014 to 2019. In Highland, Shetland, Argyll and Bute, and the Western Isles, this increase occurred from 2014 until around 2017, since when it has stabilised or decreased slightly. Orkney has the lowest number and proportion of finfish farm sites with ADDs, but this increased in 2019.

Region	2014		2015		2016		2017		2018		2019	
Highland	41	78.8%	44	72.1%	50	82.0%	51	85.0%	52	85.2%	50	82.0%
Orkney	2	9.5%	4	17.4%	4	17.4%	2	8.3%	2	8.3%	8	36.4%
Shetland	11	21.2%	18	33.3%	22	41.5%	23	48.9%	24	54.5%	16	36.4%
Argyll and Bute	38	88.4%	44	84.6%	44	86.3%	42	82.4%	42	84.0%	37	72.5%
Western Isles	27	77.1%	32	82.1%	34	85.0%	35	94.6%	34	89.5%	34	91.9%
Grand Total	119	58.3%	142	61.7%	154	67.2%	154	70.3%	155	71.1%	146	67.6%

Table 4 Number of finfish farm site with ADDs installed per year and per region (and percentage of active finfish farms sites in that region and year)

3.3.2 Use of ADDs

Only a proportion of the ADDs that are installed on finfish farms are actively used (switched on) at any one time. Table **5** shows the percentage of time (stocked days) where sites with ADDs installed had them switched on, broken down by region and year. From 2014 to 2016, there was a reduction in the proportion of time (days stocked) that sites with ADDs installed had them switched on, from 93% to 77%, but from 2016 to 2019 this value rose again to 90%. There are some regional differences from year to year, but no consistent pattern in the percentage of days that ADDs were switched on.

Region	2014	2015	2016	2017	2018	2019
Highland	93%	91%	89%	89%	91%	91%
Orkney	100%	82%	92%	69%	100%	100%
Shetland	100%	95%	95%	89%	66%	91%
Argyll and Bute	90%	82%	66%	93%	89%	84%
Western Isles	94%	88%	66%	84%	95%	94%
Total	93%	88%	77%	89%	89%	90%

Table 5 Percentage of stocked days with ADD switched on, per year (including only finfish farms with ADDs installed and days where ADD status is known)

The total number of finfish farms actively using ADDs over time, as well as the regional breakdown in this metric, are shown in Figure **7**. The number of farms where ADDs were reported as being in use are plotted from October 2014 to October 2019. Despite fluctuation over time and slight changes in certain regions, the overall total number of farms with ADDs switched on has remained consistently between 80 and 100 farms (apart from one period in 2016 where the total dropped below 80 farms).

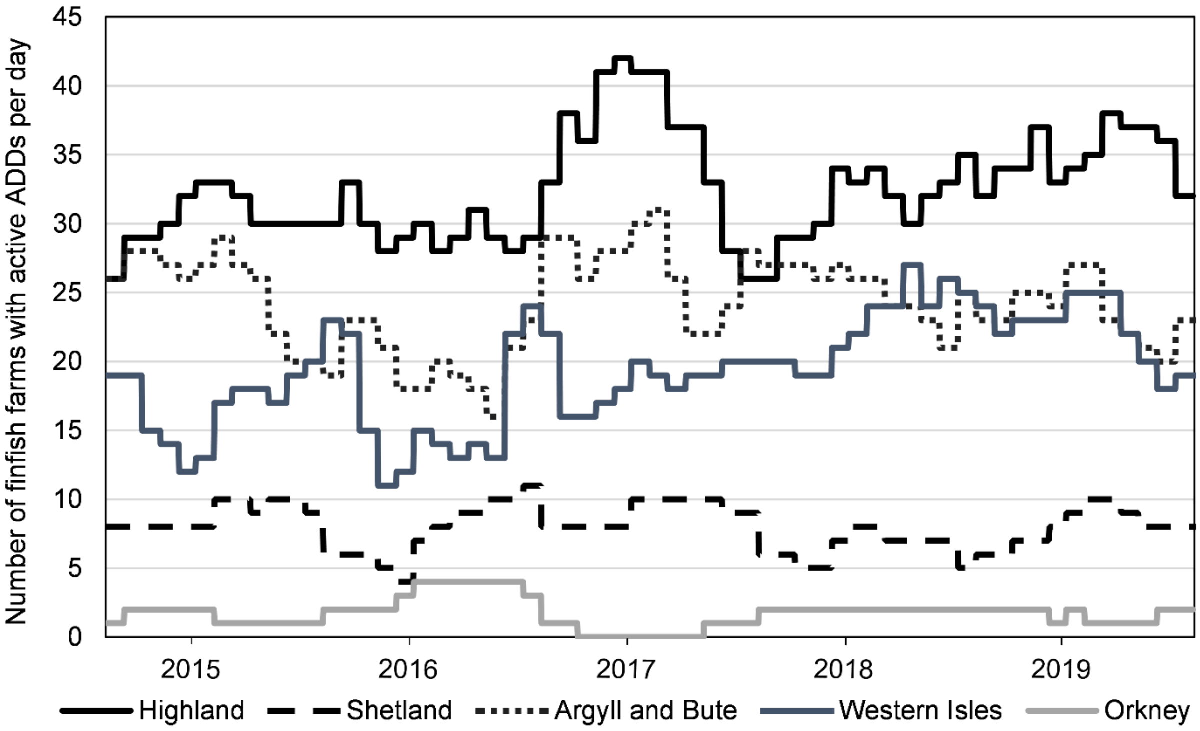

Figure 7 Number of finfish farms with active ADDs over time, per region

3.3.3 Number of transducers in use

As well as the number of finfish farm sites with ADDs, it is important to consider the number of units (transducers) installed, and how many of these have been in active use. Figure **8** shows the change over time in the number of transducers on finfish farm sites. A continuous time series shows the daily total number of transducers installed on finfish sites, separated into two categories depending on whether the ADD was turned on (grey) or turned off (black).

From 2014 to 2016, the number of transducers increases in line with the total number of finfish farms using ADDs, but after 2016, when the number of farms with ADDs peaked and began to decline, the number of transducers continued to increase. The increase continued until the end of 2019, when 1,583 individual transducers were present on farms, although the rate of increase appears to have slowed since 2017. Since early 2019, a gradual reduction in the proportion of transducers being actively used seems to have been occurring, reducing from 72% in February 2019 (1,107 out of 1,532) to 65% (1,027 out of 1,583) in October 2019.

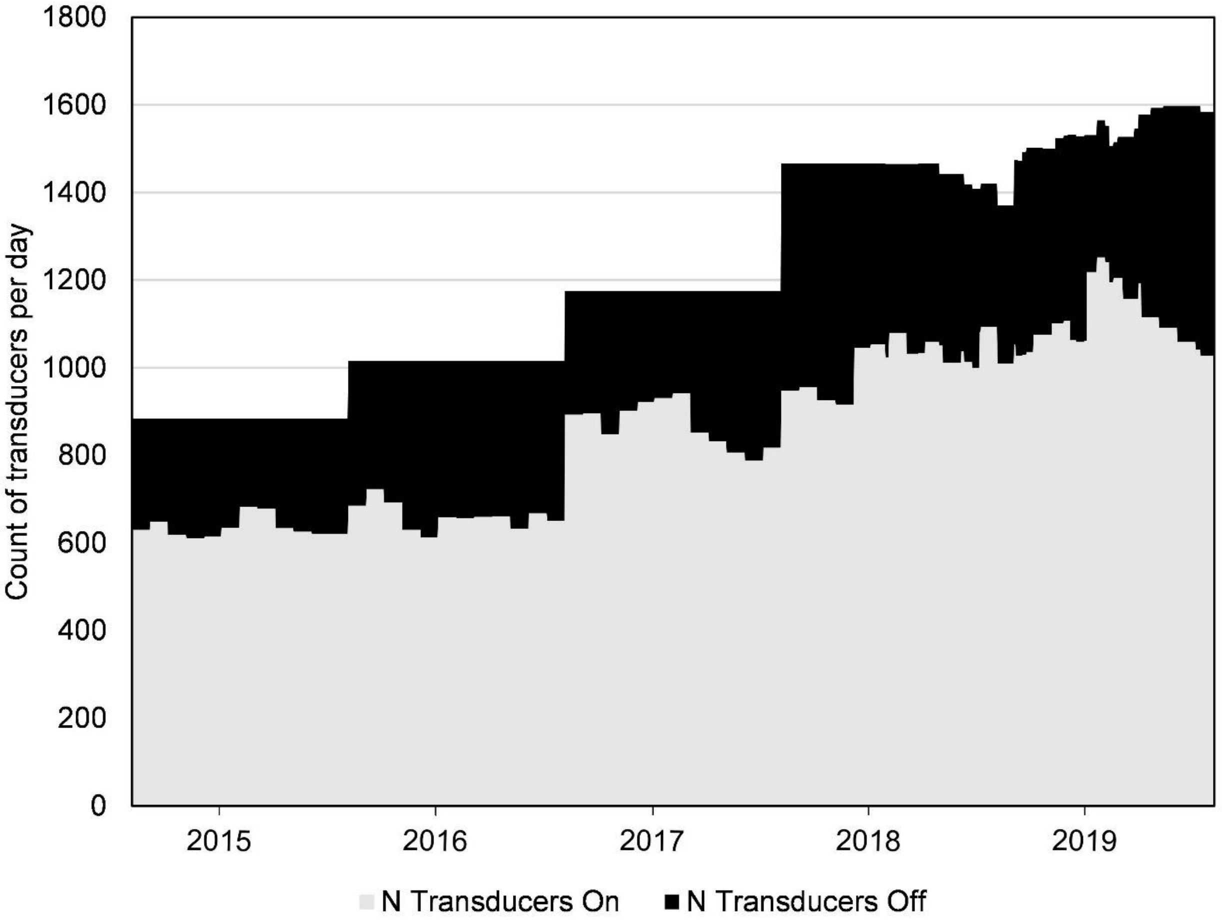

Figure 8 Number of ADD transducers at finfish farm sites over each day (2014 - 2019) and their status (Grey: On, Black: Off)

3.3.4 ADD types

There has been a change in the models of ADDs reportedly being used from 2014 to 2019 (Figure **9**). Use of the Terecos system has declined since 2016, having been installed at 49 finfish farms at the peak, but dropping to 17 by 2019 (Table **6**).

Earlier records show that the majority of farms with ADDs were using either ‘Airmar’ or ‘MohnAqua’ systems, both of which emit the same sound signal (likewise GaelForce). However, use of the MohnAqua and Airmar systems has generally decreased, while OTAQ, Ace Aquatec RT1 and GaelForce (who acquired MohnAqua in 2016) have increased. The newer OTAQ equipment has similar signal characteristics to the Airmar/ MohnAqua/ Gaelforce systems, but it features a second, lower amplitude, mode of operation called ‘patrol mode’.

There has been an increase in the use of the Ace Aquatec RT1, which has been replacing the US3 since 2016. This may be important for the frequency characteristics of sound output and may also have an impact on the total number of transducers operating, as RT1s are generally used in low numbers (i.e. one or two transducers per site).

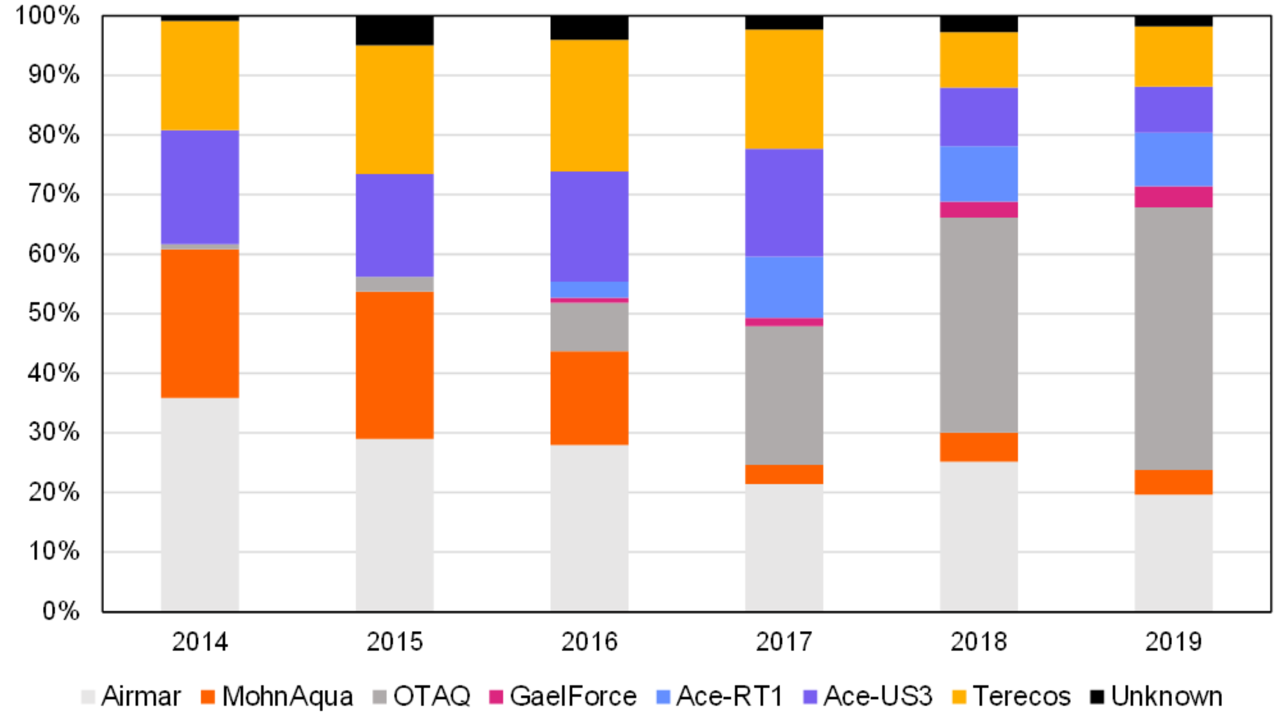

Figure 9 Changes in the percentage of finfish farms using different types of ADD per year

ADD type	2014	2015	2016	2017	2018	2019
Airmar	43	47	62	46	46	33
Ace-RT1	0	0	6	22	17	15
Ace-US3	23	28	41	39	18	13
GaelForce	0	0	2	3	5	6
MohnAqua	30	40	35	7	9	7
Terecos	22	35	49	43	17	17
OTAQ	1	4	18	50	66	74
Unknown	1	8	9	6	6	3

Table 6 Number of sites with each type of ADD per year

3.3.5 Number of farms with multiple ADD types

From 2014 to 2017 there was an increase in the number of farms equipped with multiple types of ADD, particularly in certain regions (Figure **10**). At the peak in 2017, there were 12 finfish farm sites which had multiple types of ADD installed. In some cases, farms have up to three different models of ADD installed. In 2014 and 2015, only one site reported having more than one type of ADD but since 2016 this appears to have become more common, with 12 sites reportedly having more than one device in 2017. Figure **10** shows this is mostly due to deployment strategies in two regions, with this practice initially adopted in Highland, and since 2017 in Shetland (and to a lesser extent the Western Isles). Since 2017, the number of finfish farms using multiple ADD types has reduced to just 4 (Figure **10**), which has been mostly driven by changes in practice in the Highland region.

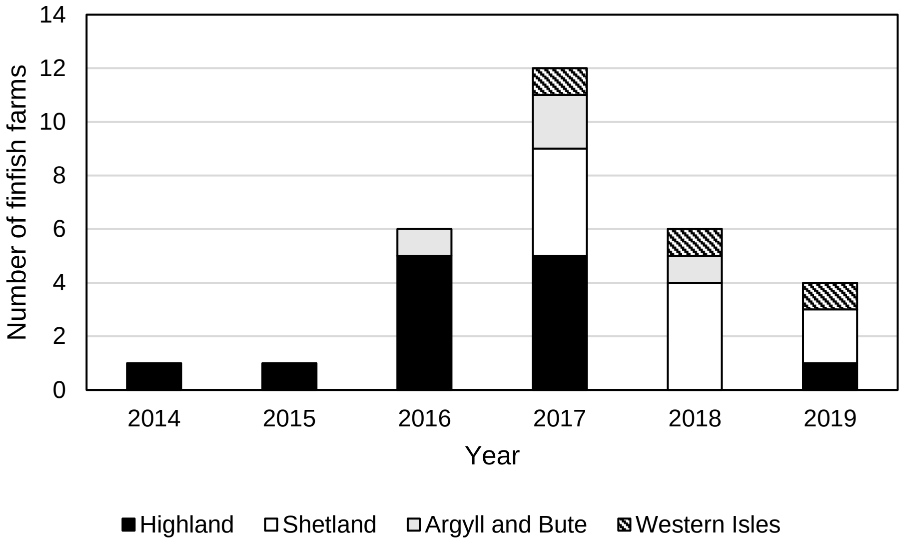

Figure 10 Number of finfish farms with multiple types of ADD per region from 2014 to 2019

3.4 Use of multiple transducers

ADD systems usually comprise of multiple transducers, each of which generally emits an intermittent sound pattern when the system is turned on. The effective, or 'real-world' duty cycle of the ADD system is the proportion of time that the overall ADD system is actively emitting sound. This is an important factor in assessing the cumulative sound output, but the sound characteristics derived ADD manufacturer specifications that are often used for assessments typically relate to a single unit only. The effective duty cycle will depend upon (1) the duty cycle of signal emissions per transducer, (2) the total number of transducers per farm, and (3) any method of synchronising or otherwise limiting the effective duty cycle.

There is an important link between the impact of increasing duty-cycle and number of transducers on the overall effective duty-cycle. Assuming multiple transducers in the same system are active within the same time period, but not synchronised, the consequence is likely to be an increase in the effective duty cycle. In instances where sites use large numbers of unsynchronised transducers, this could in theory result in an effective duty cycle of 100% (continuous noise emission).

Table **7** provides device duty cycle values that are derived from a typical single transducer for the main ADD types, although where options for reducing the effective duty cycle are available (e.g. synchronising the sound output from multiple units, or limiting the effective duty cycle) these are included.

Manufacturer	Mode	Single Transducer Duty-cycle	Notes	Source
Airmar/ GaelForce/ MohnAqua	N/A	50%		Lepper et al. (2014)
Ace Aquatec US3	All	0.7% - 8%	Signals from individual units can be synchronised to avoid increasing duty cycle. A feature allows automatically 'ramp-down' duty cycle from 8% - 0.7% after a period of depredation	Ace Aquatec (personal communication, 26/11/2020)
Ace Aquatec RT1	All	0.7% - 8%	Signals from individual units can be synchronised to avoid increasing duty cycle. A feature allows automatically 'ramp-down' duty cycle from 8% - 0.7% after a period of depredation	Ace Aquatec (personal communication, 26/11/2020)
Terecos	All	100%		Lepper et al. (2014)
OTAQ	Patrol	9.1%	Asynchronous, each unit fired in turn	OTAQ (personal communication, 2/3/2021)
	Protect	31.6%		OTAQ (personal communication, 2/3/2021)

Table 7 Summary of duty cycle relating to each ADD type

In practice for most models of ADD, multiple units (transducers) are typically installed at finfish sites, although the number of transducers will vary by site. Figure **11** shows the number of units typically used for each of the ADD types at finfish farms. The distribution for the Airmar device is bimodal, with peaks at four and 12 units per site, but with some sites having up to 24 units. This distribution is similar for GaelForce, and MohnAqua with a peak around 12 and likely reflects the same deployment plan of approximately one unit per net. The Terecos and Ace Aquatec US3 devices have a lower mean number of devices per site, and the RT1 is typically installed as a single unit or in pairs. The highest numbers of devices are generally seen for the OTAQ devices, with over 30 installed in some instances, which may reflect the installation of this equipment on sites with a larger number of nets.

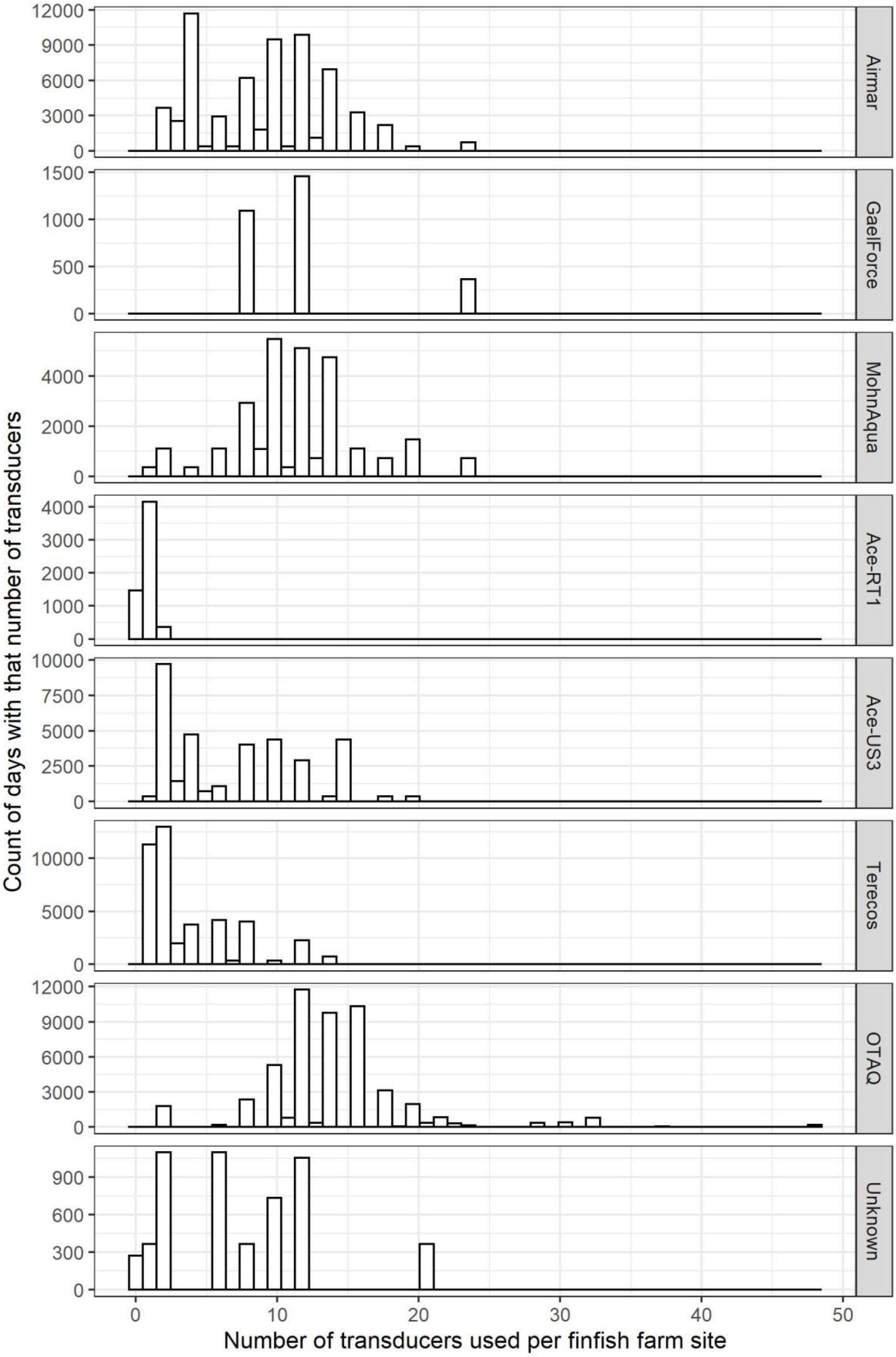
Count of days with that number of transducers
Number of transducers used per finfish farm site
Airmar
GaelForce
MohnAqua
Ace-RT1
Ace-US3
Terecos
OTAQ
Unknown
0
10
20
30
40
50
12000
9000
6000
3000
0
1500
1000
500
0
4000
2000
0
4000
3000
2000
1000
0
10000
7500
5000
2500
0
10000
5000
0
12000
9000
6000
3000
0
900
600
300
0

Figure 11 Differing distributions of the daily number of transducers installed on finfish farms, by device type, 2014 - 2020. Y-axis shows the count of days where each number of transducers was installed (note varying y-axis).

The number of transducers installed at a site is typically agreed between the site manager and ADD manufacturer. Deployment strategies recommended by the manufacturer typically use one device per net. In some cases, the manufacturer or installer may recommend additional units (for example at the end of a group of nets) to provide homogenous coverage around the site perimeter.

As well as changing the effective duty cycle, the sound emitted from multiple transducers may interact and modify the received amplitude of sound signals. There is potential for constructive and destructive acoustic interference when the maxima of two acoustic waves add together, or work to cancel each other out, depending on the phase difference, and this has the potential to affect the received amplitude in parts of the sound field. Where signals overlap in time, constructive interference is likely to increase the received amplitude above the measurements typically made for only one transducer (e.g. in Lepper et al., 2004). There is a need for additional research on the effect of signal overlap on received amplitude in real-world application.

3.5 Characterisation of ADD use patterns

In order to accurately assess the sound output from ADDs under real-world conditions, it is important to understand their typical patterns of use. It has been reported that different farms adopt a variety of ‘strategies’ in relation to ADD use (Northridge et al., 2010). Specifically, some finfish farm managers preferred to use ADDs continuously in order to discourage seals from learning to become interested in nets. Other managers switch ADDs on once fish are over a certain size, and others switch them on only when seals are around nets, or when depredation is being observed. No information on such strategies were available for analysis from the seal licensing survey, finfish producers or accreditation schemes.

As systems have developed, some ADD manufacturers now have the ability to remotely monitor ADD status by the collection of real-time usage data on farms through a 4G linked online portal. At the time of writing this type of system is used by two manufacturers which have the option to automate the collection of data on ADD use at a per-device basis and at a fine temporal resolution (for example in ten-minute blocks). This feature has the potential to allow the collection of data that can inform our understanding of real-world patterns of ADD use.

3.6 Summary

There is no single, comprehensive source of information on the nature and extent of ADD use at finfish farms in Scotland. A collated dataset has been created, combining information on ADDs from a variety of disparate sources. The complete collated dataset covers the time period from 2014 to 2020. This dataset was collated from a variety of sources, none of which were completely comprehensive, verifiable or systematic, therefore these results should be interpreted with a degree of caution. Regardless, these data are still considered suitable for the identification of broadscale patterns in ADD use over time between regions, and provides the best possible description of recent industry practices.

The most recent information available was examined to indicate levels of recent ADD use (winter 2019 – 2020), including regional differences, while data on historic use between 2014 and 2019 was examined to determine changes in use over time. The extent to which different ADD devices were used and how this varied between regions and over time was also examined.

Data from the most recent period available (October 2019 – April 2020), revealed that ADDs were installed at 68% of all Scottish finfish farms, although this percentage varied regionally. Highest levels of ADD use were recorded in the Western Isles, where 91% of farms reported ADD use. Lowest levels were recorded in Orkney and Shetland with 35% and 36% of farms using ADDs respectively. The most commonly installed ADD type during this time was the OTAQ, which was in installed at 31% of active farms over the same time period. Again, this varied between regions; the OTAQ device was not reported at any farms in Orkney and only by a single farm in Shetland, whereas it was more prevalent across farms in Argyll and Bute and in the Western Isles. In the Northern Isles the Ace Aquatec RT1 and the Airmar devices were most commonly reported.

When considering trends over time (2014 to 2019), the number of sites with ADDs installed increased between 2014 and 2018, peaking at 155 in 2018, which was around 70% of active farms, and declined slightly in 2019 to 146 sites. The total number of ADD transducers at farms steadily increased over the time period 2014 to 2019. This may have been largely driven by changes in the device types being used, towards types which are typically used in larger numbers. It could also be influenced by changes in the size of finfish farms over this time period.

There was a change in the ADD types installed over time. In 2014 the ‘Airmar’ type ADDs (Airmar, MohnAqua and latterly GaelForce) were the most widely installed devices, together being present at 73 finfish farms. By 2019, the OTAQ device was the most commonly installed device (74 finfish farms), with Airmar and MohnAqua installed at 46 sites.

Between 2014 and 2016 the total number of transducers installed increased in line with the reported increase in total number of farms with ADDs. After 2016, when the number of farms with ADDs stabilised, number of transducers continued to increase between 2016 and 2019, although the rate of increase slowed after 2017.

Between 2014 and 2016 there was a reduction in the proportion of time that ADDs were reported as being actively used (turned on), from 93% to 77%, this increased following 2016 and has remained at 89 - 90% since 2017. The total number of farms where ADDs were reported as being turned on remained between 80 and 100 for most of the period between 2014 and 2019. The number of finfish farms actively using ADDs reduced in Argyll and Bute and the Western Isles through 2019, which may be driving the observed reduction in the overall number of transducers being used over the same time period. Changes to a small number of large finfish farms (which typically use larger numbers of transducers), would explain why this pattern is not obvious in the number of farms actively using ADDs. At some finfish sites multiple ADD types are also installed, although this appears to be relatively uncommon. This practice increased between 2015 and 2017, when 12 sites had more than one type of ADD, and then subsequently decreased again.

Different device types are installed with different numbers of transducers. Information collected by this project show that GaelForce, MohnAqua and Airmar ADDs usually have around 12 transducers per finfish farm site, which indicates they are typically installed with one per net. Terecos and Ace Aquatec US3 devices are generally installed in slightly lower numbers. The highest number of transducers are typically found at sites with OTAQ equipment. This may be representative of differing deployment strategy suggested by ADD manufacturers, or may be a result of OTAQ equipment being installed at larger sites. The Ace Aquatec RT1 is usually installed singly or in pairs.

The effective duty-cycle of an ADD system is greatly increased by the use of multiple unsynchronised transducers. Unless transducers are synchronised with each other, or the duty-cycle of each transducer is adjusted in relation to the total number of units, the effective duty-cycle increases in relation to the number of transducers. In instances where sites use large numbers of unsynchronised transducers, this may result in an effective duty cycle much greater than the duty cycle of the individual units, and in some cases could in theory, lead to duty cycles of up to 100% (continuous noise emission).

The use of multiple transducers also has the potential to increase the peak received amplitude of sound around a finfish farm, but this effect is complex. There is a need for additional research on the effect of signal overlap on received amplitude in real-world application.

The availability of data from automated systems developed by ADD manufacturers may be a useful way of collecting and providing detailed records of patterns of ADD use to inform future assessments.

Finally, while these data sources have allowed general conclusions in trends in time and space, they do not explain why these changes have occurred. There is very little fine-scale information on temporal patterns and strategies of ADD use which would be required to fully understand the nature and extent of noise emissions from ADDs and to be able to predict potential effects.

4 Efficacy of ADDs and alternative measures in preventing seal depredation

4.1 Introduction

The data collated for this report were analysed to quantify any associations between ADD usage and depredation by seals (mortality of stocked fish, caused by the predatory behaviour of seals). This analysis examined the dataset for evidence of ADD efficacy and to investigate which factors might influence this. For a complete description of the data preparation and the methods used for this analysis, including technical detail on the modelling process, and more detailed results, please see the Appendix sections 1 and 2. A summary of the methods, key results and the outcomes of the analysis are provided in this section of the report.

4.1.1 Caveats on observational data

It should be noted that all data collated under this project are observational in nature, and not part of any controlled trials. The use of ADDs in this dataset is therefore not randomised or controlled. There is also an underlying assumption that ADD use is not associated with increased depredation. In practice this assumption is likely not to be the case due to the reactive nature of management decisions, but the strength of this association is not known. Additionally, the available data on ADDs was not systematically collected or standardised. The temporal scale of data on ADD use was relatively coarse (monthly), and may have excluded relevant detail relating to its impact on depredation.

No two finfish farm sites are the same and so drawing comparisons between data collected at a range of sites is problematic. The many factors, both biotic and abiotic, which might influence seal depredation are not well understood; the proximity to seal haul-outs, size of local seal populations as well as individual behaviour of seals may all have an impact. These factors could not be included here due to lack of suitable data.

Nevertheless, convincing arguments for causation can be derived from observational data (for example, observational data are often important in medical studies where experimental approaches would be unethical) (Rubin, 2007) and this dataset represents the best available information currently available describing the use and efficacy of ADDs in Scottish finfish aquaculture.

4.2 Methods

Records of ADD use from Scottish aquaculture sites from 2014 to 2020 (as described in section 3) were combined with additional variables available for each record, collected from the same data sources described in subsection 3.1.1. Data were available on: depredation rate (measures as number of fish mortalities), stocking dates, variables describing net shape and material, presence of seal blinds and anti-predator nets, biomass and whether or not ADD use was permitted.

The use of ADDs is not permitted at certain locations, depending on planning conditions defined by the local authority, and this information is often captured by the seal licensing system. This allowed a form of control in the dataset, by assuming that sites without permission to use ADDs are representative of all sites but without the effect of ADD use.

Research questions to inform the design of the analyses were initially defined to allow testing at a range of temporal scales, with three different temporal scales examined: monthly, per stocking period, and per depredation event. Data were available at a range of temporal scales but were collated to a minimum scale of monthly resolution for analysis. The temporal scale of monthly was the highest resolution for which a large enough dataset including the key variables of ADD status, ADD type and depredation, was available. Data were then grouped to the level of stocking period (the period over which a farm was stocked with fish). This allowed comparison of the longer-term efficacy of management measures. Analysis was also conducted at the scale of depredation event, defined as a set of successive months where a stocked farm was recorded as having been depredated by seals, with at least a one-month gap before and after where there was no depredation. This allowed comparison between the characteristics of depredation events, for example looking for changes in the frequency or length of depredation events in relation to ADD use.

Monthly

1. Is the monthly presence or absence of depredation at a finfish farm associated with ADD usage and does any association depend on ADD type?
2. Is the monthly level of depredation (i.e. number of fish killed by seals) at a finfish farm associated with ADD usage and does any association depend on ADD type?

Per stocking period

3. Are the number of depredation events during a stocking period at a finfish farm associated with ADD usage and does any association depend on ADD type?
4. Is the total level of depredation during a stocking period at a finfish farm associated with ADD usage and does any association depend on ADD type?
5. Is the proportion of months during which depredation events occur during a stocking period at a finfish farm associated with ADD usage and does any association depend on ADD type?

Per depredation event

6. Is the total level of depredation at a finfish farm associated with ADD usage and does any association depend on ADD type?
7. Is the duration of a depredation event at a finfish farm associated with ADD usage and does any association depend on ADD type?

Data were initially tabulated and each metric for ADD conditions was compared (ADD on vs ADD off, ADD type). This approach does not account for potentially confounding effects of additional explanatory variables such as farm, region, year, month and presence of other anti-predator devices. These dependencies were then accounted for in a statistical modelling approach using Generalized Additive Models (GAMs). GAMs were used to model relationships between the response and explanatory variables with separate models constructed for each of the seven questions listed above. The response variable for each question related to depredation occurrence or level of depredation observed, depending on the question. Two models were compared for each question: one using presence or absence of ADDs as a two-level factor covariate, the other using presence or absence of each type of ADD type as eight two-level factor covariates. For the first two questions, at the monthly level, an additional potential complication is that the presence or level of depredation may not be independent between months, even after the explanatory variables are modelled. Residual autocorrelation was therefore checked for, and if found this was accounted for in the modelling. Full details are given in the Appendix section 2.

4.3 Results

4.3.1 Exploratory analysis

4.3.1.1 Monthly

Of the 8,644 monthly records considered in the dataset, a total of 3,384 (39%) recorded depredation occurring. Across all months where ADDs were used (4,624), 45% of these recorded depredation (Figure **12**) in contrast to 32% of the total months where ADDs were not used (4,020).

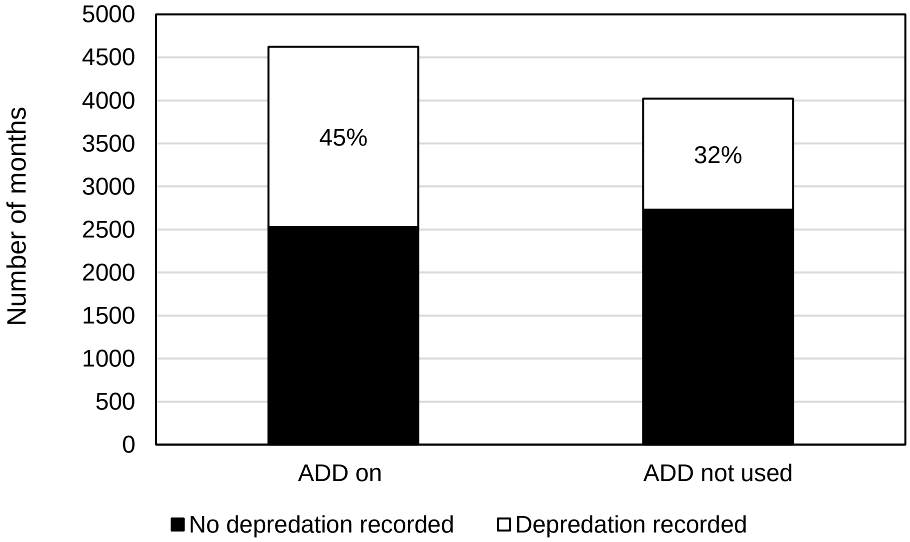

Figure 12 Comparison of depredation occurrence on a monthly basis between periods where ADDs were used and not used

When considering sites where ADDs were not used (either because they were not permitted or a decision was made not to use them), we found the proportion of months with depredation was higher where ADD use was not permitted (47%) compared to when it was permitted but not used (23%) (Figure 13).

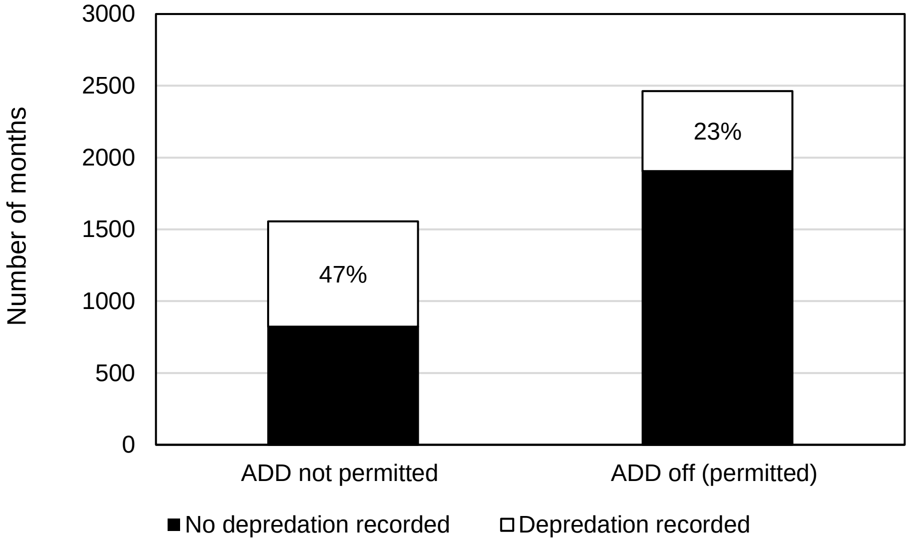

Figure 13 Depredation occurrence on a monthly basis for all months with no ADD use, depending on the permission status of ADDs.

When ADDs were recorded as ‘on,’ the proportion of months recording depredation varied considerably depending on the ADD type in use (Figure 14). Proportions of months with depredation were lowest for Ace Aquatec US3 (30%) and highest for GaelForce (71%), although GaelForce had the lowest number of months in which it had been used.

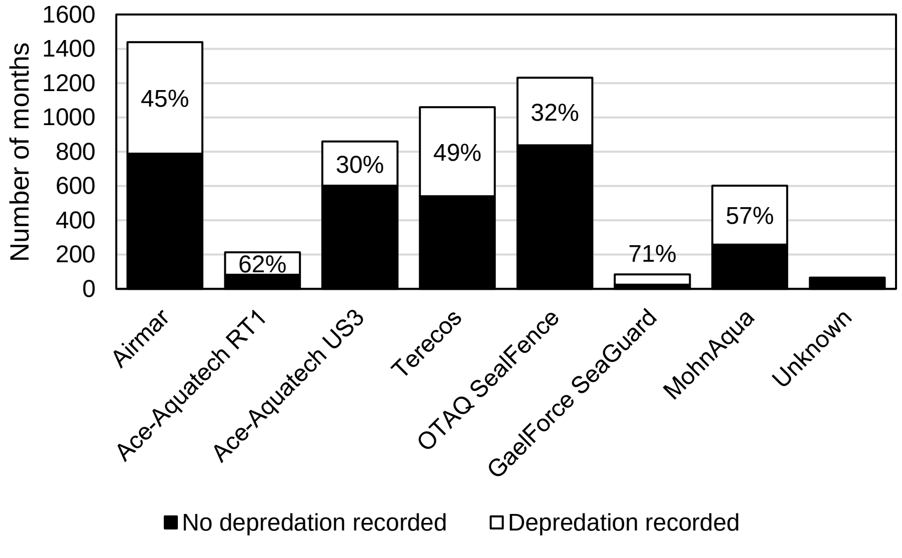

Figure 14 Depredation occurrence on a monthly basis for all ADD types (only including months in which the ADD was recorded as on).

The level of depredation in terms of numbers of fish lost was highly variable across months. Patterns of depredation levels in relation to ADD use and ADD type were similar to the monthly analysis of depredation events, with a higher mean level of mortality when ADDs were on relative to off and higher levels of depredation where ADDs were not permitted compared to where they were.

There was also variation in depredation levels between different ADD types, but patterns were different to those for depredation occurrence. Unknown ADD type was associated with the highest mean levels of depredation, followed by Ace Aquatec RT1. Lowest mean levels of depredation were associated with MohnAqua.

4.3.1.2 Per stocking period

Of the 509 stocking periods (from 179 farms) for which complete ADD usage was available, depredation was recorded in 361 (71%) of the periods. The length of stocking periods was highly variable, ranging from one to 42 months. The number of depredation events had an approximately linear increase with the duration of the stocking period. ADDs were typically either on or off for the whole stocking period, although there were some variations to this pattern.

The pattern of depredation in relation to ADD use is similar to the monthly exploratory analysis, with greater occurrence of depredation in stocking periods where ADDs were used at least 90% of the time (48%) compared to stocking periods where ADDs were not used (36%). Stocking periods where ADD use was not permitted were more likely to experience depredation, with 54% recording depredation. Trends in the number of depredation events (as discrete events) and the level of depredation (in terms of numbers of fish lost) followed the same pattern, with higher levels and likelihood of depredation associated with ADD use.

As described in section 3.3.5, some sites use multiple types of ADD. To examine the effect of ADD type at the level of the stocking period, only stocking periods that used a single device for more than 90% of the time across the stocking period were included. This led to variable sample sizes with only four ADD types being used for a large enough number of stocking periods to draw statistical conclusions (Airmar, Ace Aquatec US3, Terecos and OTAQ). Across these four ADD types, Terecos was associated with the highest number of depredation events, levels of depredation and percentage of stocking periods where depredation occurred.

4.3.1.3 Per depredation event

There were a total of 803 depredation events (from 438 stocking periods and 179 farms) where complete ADD usage information was available. Depredation events ranged in length from 1 to 24 months with a mean of 4.2. The most common length of a depredation event was 1 month (269 or 33%), followed by 2 months (133 or 17%).

As was the case at the level of the stocking period, there was an increase in the level of depredation as the length of the depredation event increased. The patterns of depredation in relation to ADD use and type was found to be similar to the monthly and stocking period results with higher depredation associated with events where ADDs were on compared with off, higher depredation when ADDs were not permitted (for the whole depredation event) compared with when ADDs were permitted but not used, and variation among ADD types in the amount of depredation recorded.

4.3.2 Statistical modelling

4.3.2.1 Monthly analysis

Q1: Is the monthly presence or absence of depredation at a finfish farm associated with ADD usage and does any association depend on ADD type?

Statistical models were developed with the response variable being the presence/absence of depredation per month. Initial modelling indicated auto-correlation so subsequent models accounted for this. For details of the model type and structure, and model selection process, see Appendix section 2.2.

Significant explanatory variables (based on a model co-efficient having a p value of ≤ 0.05) along with the direction of their influence on the probability of depredation, are detailed in Table 8.

Variable	**Effect on the probability of depredation presence**	**Significance**
ADD on	Positive	***
Region – Orkney	Higher than baseline region of Highland	**
Region – Western Isles	Lower than baseline region of Highland	**
Use of square net	Positive	*
Use of APN	Positive	***
Use of seal blind	Positive	*
Month	Higher in winter than in summer	***
Biomass	Positive	***
Length of stocking period	Positive	***
Farm ID	Normally distributed random effect (logit scale)	***

Table 8 Variables which modelling indicated a significant effect on the probability of depredation occurring within monthly periods. All ADD usage modelled as a single factor covariate on or off (not accounting for ADD type). Significance codes relate to the following P value categories: *** <0.001, ** <0.01, * <0.05.

Although not preferred by the model selection criterion, there was variation in the probability of depredation associated with different ADD types.

ADD usage was associated with increased probability of depredation at the monthly level, increasing the odds of depredation by a factor of 2.2 once other variables had been accounted for. The effect of ADD type was also tested, and there was some evidence that the magnitude of the effect varied by ADD type. The model including different device types as factor covariates indicated significant effects of individual ADD types but the model selection process did not prefer this model over the model with ADD on or off as the factor covariate.

Q2: Is the monthly level of depredation (i.e. number of fish killed by seals) at a finfish farm associated with ADD usage and does any association depend on ADD type?

Models were developed with the depredation level in terms of the total number of fish depredated at a site in a month as the response variable. Initial modelling indicated auto-correlation so subsequent models accounted for this. For details of the model type and structure, and model selection process, see Appendix section 2.2.1.

Significant explanatory variables (based on a model co-efficient having a p value of ≤ 0.05) along with the direction of their influence on the levels of depredation, are detailed in Table 9.

Variable	**Effect on the levels of depredation**	**Significance**
ADD on	Positive	***
ADD not permitted	Positive	*
Region – Orkney	Higher than baseline region of Highland	**
Year - 2015	Lower than baseline year of 2014	*
Year - 2017	Lower than baseline year of 2014	*
Year - 2019	Lower than baseline year of 2014	*
Use of APN	Positive	***
Use of seal blind	Positive	***
Month	Higher in winter than in summer	***
Biomass	Positive	***
Length of stocking period	Positive	***
Farm ID	Non-normally distributed random effect (logit scale)	***

Table 9 Variables which the indicated a significant effect on the levels of depredation occurring within monthly periods. All ADD usage modelled as a single factor covariate on or off (not accounting for ADD type). Significance codes relate to the following P value categories: *** <0.001, ** <0.01, * <0.05.

The number of fish depredated per month was estimated to be 2.6 times greater when ADDs were on versus when ADDs were off. The model with ADD types as individual factor covariates (Table 10) showed a positive association between depredation level and ADD on for all ADD types, although only Terecos and OTAQ were statistically significant, with depredation level being 2.9 times higher with Terecos and 4.1 times higher with OTAQ.

The overall conclusion from this analysis is that ADD usage is associated with increased monthly level of depredation (2.6 times higher with ADD on versus off) once other available variables were accounted for, and that there is evidence that this varied significantly by ADD type.

Variable	Effect on the levels of depredation	Significance
ADD on = Terecos	Positive	***
ADD on = OTAQ SealFence	Positive	***
ADD not permitted	Positive	*
Region = Orkney	Higher than baseline region of Highland	**
Year = 2015	Lower than baseline year of 2014	*
Year = 2016	Lower than baseline year of 2014	*
Year = 2017	Lower than baseline year of 2014	**
Year = 2019	Lower than baseline year of 2014	*
Use of APN	Positive	***
Use of seal blind	Positive	***
Month	Higher in winter than in summer	***
Biomass	Positive	***
Length of stocking period	Positive	***
Farm ID	Non-normally distributed random effect	***

Table 10 Variables which the indicated a significant effect on the levels of depredation occurring within monthly periods. ADD usage modelled as individual factor covariates for each ADD type. Significance codes relate to the following P value categories: *** <0.001, ** <0.01, * <0.05.

4.3.2.2 Per stocking period

Q3: Are the number of depredation events during a stocking period at a finfish farm associated with ADD usage and does any association depend on ADD type?

Models were developed with the number of depredation events per stocking period as the response variable. For details of model type and structure, and model selection process, see Appendix section 2.2.2.

Significant explanatory variables (based on a model co-efficient having a p value of ≤0.05) along with the direction of their influence on the number of depredation events, are detailed in Table 11.

Variable	Effect on the number of depredation events per stocking period	Significance
ADD on = Ace Aquatec RT1	Positive	**
ADD on = Terecos	Positive	**
ADD on = MohnAqua	Positive	***
ADD not permitted	Positive	*
Region = Orkney	Higher than baseline region of Highland	**
Year that stocking started = 2015	Lower than baseline year of 2014	*
Use of square nets	Positive	**

Length of stocking period	Positive	*

Table 11 Variables which modelling indicated a significant effect on the number of depredation events per stocking period. ADD usage modelled as individual factor covariates for each ADD type. Significance codes relate to the following P value categories: *** <0.001, ** <0.01, * <0.05.

The number of depredation events per stocking period was estimated to be 1.5 times greater when ADDs were on versus when off. This effect was stronger for individual ADD types, with MohnAqua being associated with 2.1 times higher predation events when it was on compared to when it was off.

The overall conclusion from this analysis is that ADD usage is associated with an increased number of depredation events once other available variables were accounted for, and that there is strong evidence that this varied significantly by ADD type. The number of depredation events is also positively associated with the use of square nets.

Q4: Is the total level of depredation during a stocking period at a finfish farm associated with ADD usage and does any association depend on ADD type?

Models were developed with the response variable being the total level of depredation per stocking period. For details of model type and structure, and model selection process, see Appendix section 2.2.2.

The results and conclusions from this model are very similar to Q3 so the details are not displayed here (but can be found in Appendix section 2.2.2), The overall conclusion is that ADD usage is associated with an increased level of depredation per stocking period (4 times higher when ADDs on for the whole stocking period) once other variables were accounted for, and that there is good evidence that this varied by ADD type.

Q5: Is the proportion of months during which depredation events occur during a stocking period at a finfish farm associated with ADD usage and does any association depend on ADD type?

A model was developed with the number of months within a stocking period in which depredation was recorded as the response variable. For details of the model type and structure, and model selection process, see Appendix section 2.2.2.

The conclusions from this model are very similar to Q3 and Q4 so the details are not displayed here (but can be found in the Appendix section 2.2.2). The overall conclusion regarding this question is that ADD usage is associated with an increased proportion of months with depredation per stocking period (odds of predation 4.6 times higher when ADDs are on for the whole period) once other variables were accounted for, and that there is good evidence that this varied by ADD type.

4.3.2.3 Per depredation event

Q6: Is the total level of depredation at a finfish farm associated with ADD usage and does any association depend on ADD type?

A model was developed with the number of fish depredated by seals per depredation event as the response variable. For details of the model type and structure, and model selection process, see Appendix section 2.2.3.

Significant explanatory variables (based on a model co-efficient having a p value of ≤0.05) along with the direction of their influence on the number of depredation events, are detailed in Table 12.

Variable	**Effect on the number of fish per depredation event**	**Significance**
ADD on = GaelForce	Negative	*
Region – Argyll and Bute	Lower than baseline region of Highland	*
Region – Western Isles	Higher than baseline region of Highland	**
Year - 2015	Lower than baseline year of 2014	*
Year - 2017	Lower than baseline year of 2014	**
Year - 2018	Lower than baseline year of 2014	**
Year - 2019	Lower than baseline year of 2014	***
Length of depredation event	Positive	***

Table 12 Variables which modelling indicated a significant effect on the number of fish depredated per depredation event. ADD usage modelled as individual factor covariates for each ADD type. Significance codes relate to the following P value categories: *** <0.001, ** <0.01, * <0.05.

The model with ADD use as a single covariate did not indicate a significant effect of ADD use on the number of fish affected per depredation event. The overall conclusion is that overall, there is no statistically significant association between ADD use and depredation level per depredation event. There is a negative association between the use of the GaelForce and the number of fish depredated, although this ADD was in use during only 14 depredation events.

Q7: Is the duration of a depredation event at a finfish farm associated with ADD usage and does any association depend on ADD type?

Models were developed with the duration of the depredation event in months as the response variable. For details of the model type and structure, and model selection process, see Appendix section 2.2.3.

Significant explanatory variables (based on a model co-efficient having a p value of ≤0.05) along with the direction of their influence on the number of depredation events, are detailed in Table 13.

Variable	**Effect on the duration of depredation event**	**Significance**
ADD on = Airmar	Positive	**

ADD on = Ace Aquatec RT1	Positive	*
ADD on = Terecos	Positive	**
ADD on = OTAQ SealFence	Positive	***
ADD on = Unknown	Positive	***
ADD not permitted	Positive	*
Region – Shetland	Lower than baseline region of Highland	*
Region – Western Isles	Lower than baseline region of Highland	***
Year - 2015	Lower than baseline year of 2014	**
Year - 2017	Lower than baseline year of 2014	*
Year - 2018	Lower than baseline year of 2014	**
Year - 2019	Lower than baseline year of 2014	***
Use of seal blind	Negative	*
Month	Longer in summer	***
Stocking biomass	Positive	***

Table 13 Variables which modelling indicated a significant effect on the duration of the depredation event in months. ADD usage modelled as individual factor covariates for each ADD type. Significance codes relate to the following P value categories: *** <0.001, ** <0.01, * <0.05.

The overall conclusion is that ADD usage is associated with slightly longer depredation events. Depredation events where ADDs were on were estimated to be 1.3 times longer than those with ADDs off. This trend is the case for most ADD types but there is variation among types.

The length of depredation events is also positively associated with month (summer months having longer events), and with biomass on site. The use of seal blinds is negatively associated with the duration of depredation events.

4.4 Summary

A collated set of observational data from a variety of sources (section 3.1.1) was analysed to quantify any association between ADD use and depredation by seals.

A consistent finding of this analysis was that ADD use is associated with higher levels of predation, regardless of the temporal scale of the analysis (monthly, per stocking period and per depredation event). This association was evident even when available potential explanatory covariates were accounted for. However, this should not be over interpreted as the relationship between higher levels of depredation and ADD use could be caused by ADDs being more likely to be used where there is an identified depredation problem. The available data were not sufficient to not validate or eliminate this possibility. What is clear from the available data is that ADD use does not eliminate the problem of depredation. How much ADD use may have reduced depredation relative to what it would have been at those sites without the ADD operating, is unknown.

There are indications of variation in the relationships between ADD use and depredation occurrence between ADD type. Ace Aquatec RT1, GaelForce and ‘Unknown ADD type’ were used relatively few times (214, 85 and 122 months respectively; 8, 5 and 7 stocking periods), and so the sample size is too small to draw any inference. All other ADD categories were significantly positively associated with seal depredation at various magnitudes, depending on the question and modelling approach used. However, this result should not be taken as evidence that certain devices are ‘more effective’ than others due to the inability of this analysis to provide causal evidence between ADD use and depredation occurrence (there are differences between sites and specific details of usage which could not been accounted for in this analysis). Other factors unaccounted for in this analysis and unrelated to device effectiveness could drive any association between device type and higher occurrence of predation.

This analysis has demonstrated that seal depredation was reported in 39% of the monthly periods in the dataset, and in 71% of all stocking periods. Use of ADDs was common, with ADD use reported in 53% of the recorded monthly periods.

If it were possible to show sites where ADD use is restricted were representative of baseline levels of depredation for all farms, then the effectiveness of the overall strategy employed by finfish farmers could be quantified. When ADDs were restricted, depredation occurred in 47% of months; where ADD use was not restricted depredation occurred in 37% of months. However, this observed reduction could be due to differences in anti-predator measures being installed at sites where depredation is, and is not, expected.

Where the use of anti-predator nets, seal blinds or square nets had any significant associations with the occurrence of seal depredation, these tended to be positive. This should be interpreted in the same way as results on ADD usage: anti-predator measures may be more likely to be adopted where there is a problem or there is anticipated to be a problem. The exception to this was where the presence of seal blinds was associated with a reduced duration of depredation event.

However, it is important to note that there are a number of caveats that must be considered when interpreting the results of this section. The analysis used a collated set of observational data from a variety of sources. Therefore, the data collection was not designed to explicitly test hypotheses about the efficacy of ADDs and was not designed as to be able to reliably determine causality of variation in the levels of seal depredation. Instead, to develop a robust understanding of how ADD use influences seal depredation, specifically designed, randomised, replicated, control/treatment trials would be required.

Whilst the analytical techniques employed were designed to account for the confounding effects of multiple covariates on the resulting relationships between ADD use and variation in depredation activity, there were a number of additional extrinsic and intrinsic factors that were not known and were therefore unable to be included. These include elements such as site-specific differences in the size of farms, number of cages, locations, proximity to seal haul outs, local density of seals, differences in local species composition and differences in depredation behaviour between seal species and individuals, history of depredation issues and history of the control measures installed at each site.

In addition, the temporal resolution of the data on depredation was not available at a very fine temporal scale (monthly). There could be patterns at a daily or weekly level that would not be evident from this dataset. Depredation by seals is likely to vary considerably throughout a month, and this variation will be missed by such coarse data.

Further implications of these findings, and the recommendations for research to further determine ADD efficacy are provided in section 6.2 and 5.4 respectively.

5 Future research priorities

5.1 ADD extent of use

From the data sources considered in this project, information presented in the seal licence survey to support applications have been the most consistent source of information on ADD use over time. These surveys were not systematic or rigorously controlled, but provided a centralised record of broadscale ADD use over several years. With the changes to the seal licensing regime that came into force on the 1st of February 2021, such information will no longer be collected through this approach. Contributions to this study from finfish producers and ADD manufacturers were variable in content and dependent on their own degree of record keeping and willingness to share information. Information from accreditation schemes were limited to those farms and producers signed up to the scheme. Furthermore, data collected by these schemes is not standardised or necessarily accessible for research purposes.

Systematic record keeping and centralised data collation is essential to ensure that ADD use can be monitored, assessed and managed effectively. This should include all information relevant to understanding the sound output from ADDs (the ADD model and operating mode, duty cycle and number of transducers) relating to each finfish farm site and should be collected at an appropriate temporal scale to assist in answering key research questions. At least daily record-keeping is recommended. A centralised online system with automated data logging of ADD status might be a suitable solution for collecting such data at a very high temporal resolution.

5.2 Alternative non-lethal measures

Alternative measures for managing depredation were considered in detail under this project, and results have been included in an associated project report (Thompson et al., 2021). Research recommendations relating to alternative measures considered as part of that report include the use of novel physical barriers and netting materials, conditioned taste aversion, non-lethal removal of predators (trapping) and the development of methods for real-time predator detection.

5.3 Impacts on non-target species

The use of ADDs inevitably increases the level of anthropogenic underwater noise, which is recognised as a potential chronic stressor of marine mammals (OSPAR, 2014). However, the ecological significance of this increase is not easily defined. This section gathers relevant scientific literature on the use of ADDs and the potential for impacts on marine mammals.

There are three key ways in which non-target species may be impacted by the use of ADDs; displacement, habitat degradation and auditory injury (e.g. hearing threshold shifts). Failure to consider all potential pathways of effects is likely to lead to underestimation of true cumulative impacts (Williams et al., 2020). Each of these pathways are considered in turn.

Research is recommended on the potential impacts of ADDs on each of the marine mammal hearing groups defined by Southall et al. (2019), low frequency, high frequency and very high frequency, all of which are present in Scottish waters. Further understanding of the population size and trajectory, as well as the ecology of the species in these groups, would assist in defining and understanding the potential significance of any impacts. The minke whale is a low frequency species which is relatively abundant around Scotland, and has been successfully studied in an ADD exposure experiment (McGarry et al., 2017). Bottlenose dolphins and harbour porpoise are relatively abundant around Scotland and are suitable candidates for studying the potential impact of ADDs on high frequency and very high frequency hearing groups, respectively.

There are three pathways of potential impacts on non-target species which require investigation: the potential for disturbance and displacement, the risk of habitat degradation (e.g. through auditory masking), and the likelihood of auditory injury (PTS). Habitat exclusion and the likelihood of auditory injury are closely linked, because the risk of auditory injury is dependent on cumulative exposure levels to ADD noise, which is influenced by changes in animal distribution in response to noise. Potential approaches to understanding these issues are considered below, followed by a discussion of the need for development of population-level approaches, which applies across all the pathways of potential impacts.

Displacement and disturbance

The question of whether ADDs installed at Scottish finfish farms can disturb marine mammals in an ecologically significant way is complex to answer, and research has so far not fully answered the question.

There is evidence that ADD noise is widespread in the Scottish marine environment. An increasing trend in ADD detections within the Inner Hebrides and the Minches SAC was found from 2006 to 2016 (Findlay et al., 2018), with a peak in 2013 (12.6% of sampled locations) suggesting that a significant proportion of the monitored habitat is acoustically affected by their use. Evidence from this report shows that the number of farms using ADDs has increased since 2016 to 2019, and so the proportion of impacted habitat may also have increased. Furthermore, the audible range of ADDs is likely to be many kilometres or tens of kilometres, and will vary depending on signal and local propagation characteristics. Simple geometric models of sound propagation have been found to be inadequate for predicting complex sound fields in near-shore environments (Shapiro et al., 2009).

There is currently no established methodology in the UK for assessment of marine mammal disturbance from underwater noise. Disturbance of cetaceans can be difficult to detect, but can include: changes in (direction or speed of) swimming or diving behaviour; bunching together or females shielding calves; changes in breathing patterns; changes in vocalisation; aggression, agitation or panic behaviour; certain surface behaviours such as tail slashes and trumpet blows; moving out of an area previously occupied (Marine Scotland, 2020a). The likelihood of marine mammals being impacted by an underwater noise is likely to be affected by the type of device and the number of transducers being used as well as the site-specific sound propagation characteristics and the behavioural, physiological and motivational state of the animals.

Several studies have found that wild harbour porpoises avoid signals from a range of ADD types, both real and simulated, including ADDs used in aquaculture (Johnston, 2002; Olesiuk et al., 2002) as well as ADDs that are not used in aquaculture (Benjamins et al., 2018; Brandt et al., 2013 Mikkelsen et al., 2017). One study found similar avoidance in minke whales to a Lofitech device (McGarry et al., 2017). These studies have invariably considered only short-term displacement, whereas the potential impact of ADD use in aquaculture could be long-term. Short-term displacement does not necessarily lead to long-term displacement. Porpoises were temporarily displaced by Lofitech ADDs used for offshore mitigation, but detections were observed again after a minimum of 133 minutes within 1 km (Thompson et al., 2020). In addition, behavioural response to marine noise may change over time, for example the probability of porpoises being disturbed by pile-driving was found to diminish over time (Graham et al., 2019). Results of a trial using pingers (low amplitude acoustic deterrents) showed a similar reduction in the level of displacement to harbour porpoises (Kyhn et al., 2015). This shows that research seeking to understand population level consequences of anthropogenic marine noise should aim toward understanding the drivers of behavioural response in a range of contexts and attempting to predict the fitness consequences of observed alterations in behaviour.

Different species of marine mammals are known to react quite differently to sound signals (Kastelein et al., 2006). Furthermore, responses also vary between and within individuals and populations (Harris et al., 2017), highlighting the importance of behavioural context in modulating dose–response relationships.

Behavioural responses can be energetically costly, both in terms of additional movement and stress responses, but also in terms of lost foraging opportunities. Harbour porpoises showed increased respiration rates and swim speed (indicative of stress) when exposed to ADD signals in captivity (Kastelein et al., 2015), though this has not been demonstrated outside of captivity. Studies have found similar results for other cetaceans exposed to vessel noise (e.g. humpback whales, *Megaptera novaeangliae*, Sprogis et al., 2020). Harbour porpoises have very high metabolic rates and therefore energy requirements (Rojano-Donãte et al., 2018) and this may make them especially vulnerable to the effects of displacement if they cannot compensate for increased metabolic costs or lost foraging (Booth, 2020).

Research is required to better understand the level of disturbance and displacement potentially caused by different types of ADDs in different contexts. Specific approaches to address these research requirements are outlined below.

Approach 1: Monitoring the distribution of marine mammal species in a ‘real-world’ scenario.

Monitoring changes in species distribution around existing finfish farm infrastructure has the advantage of being a true representation of marine mammal interactions with ADDs. Information collected in this way will therefore be ecologically relevant. It has the disadvantage of many confounding factors: sources of noise other than ADDs, potentially complex geo-acoustic environments, potentially low encounter rates of the species of interest and the fact that animals may already have been exposed to noise sources, preventing any assessment of habituation or sensitisation. Controlling the use of ADDs would require collaboration with the site owner and manager.

Approach 2: Use of a targeted approach (not based at a finfish farm), utilising another platform to deploy an ADD.

This could involve controlled exposure experiments in combination with telemetry or visual tracking. Alternatively, this could involve long-term deployment of different ADDs at sea in areas away from fish farms with a network of associated acoustic monitoring devices deployed around the ADD. The advantage of this approach would be that high population density areas could be targeted, increasing the sample size, and subsequent statistical power. A location could be selected that is not deemed to be critical habitat (e.g. not inside an SAC), and potentially without complex bathymetry that may affect sound propagation or animal movement. This approach would also allow for strict control of experimental parameters, allowing for direct comparison between the effects of different device types. The disadvantage of this approach is that results may not be applicable to finfish farm habitats, where the behavioural context could be different, for example with respect to animal motivation and human activity.

Habitat degradation

While several studies have demonstrated harbour porpoise avoidance of ADD signals, none have demonstrated complete habitat exclusion. This may be context dependent, for example if animals are highly motivated to remain in an area of increased underwater noise. If animals are not displaced, there is a risk of negative impacts associated with underwater noise, such as increased stress which has been linked with suppression of the immune system and reproduction, disruption of foraging and social learning, and increased rate of mortality (Atkinson et al., 2015).

Acoustic masking has also been raised as a concern in relation to ADD use (Shapiro et al., 2009). Masking occurs where an introduced sound makes it harder for an animal to hear another signal (the process of one sound increasing the threshold at which another sound can be heard). The transmission characteristics, frequency spectra, duty cycle and number of transducers will be important factors in assessing the potential for masking to occur. The potential for masking will be higher where noise sources are continuous and similar in frequency to ecologically important sounds, which is primarily a problem where anthropogenic noise occupies the same bandwidth as animal vocalisations. The ecological consequences of masking are poorly understood, but thought to be potentially significant for species that rely on sound for navigation, communication and foraging (Erbe et al., 2016). Masking can also affect an animal's ability to hear sounds that they rely upon to avoid danger. Although masking has been raised as a potential concern in relation to ADD use, there have been no published studies of the potential for masking to occur as a result of ADD use.

It is important that the impacts of potential habitat degradation are considered cumulatively, including the potential impacts of other marine stressors and anthropogenic activities such as climate change, fishing, disease, algal blooms, contaminants, and additional threats such as bycatch and ship-strike (Wright et al., 2007), most of which have yet to be quantified.

Understanding the effect of ADD noise on the acoustic environment of marine mammals is complex and would involve prediction and assessment of changes in communication and listening space as a result of auditory masking by the introduced ADD signals. Masking is a complex phenomenon and masking levels are difficult to predict for any combination of source, environment and receiver characteristics (Erbe et al., 2016). Predicting the effects of masking requires an understanding of species-specific audiograms, critical ratios, critical bandwidth and auditory integration times (Erbe et al., 2016). Marine mammals have been documented to have evolved strategies for enhancing the detectability of signals in the presence of masking noise; this has been demonstrated in receivers which can exploit additional acoustic information to reduce the expected effect of masking (Bain & Dahlheim, 1994; Turnbull, 1994) and in senders which can alter the characteristics of their signals in the presence of noise (e.g. Hotchkin & Parks, 2013). Erbe et al. (2016) provides a framework to enable the construction of models of masking to determine the potential limitations of communication in marine mammals in the presence of anthropogenic sound. Pine et al. (2019) demonstrate a method for calculating the effects of masking in terms of the reduction in listening space that occurs as a result of anthropogenic noise emissions. The listening space differs from communication space in that it extends beyond intra-specific communication and also includes the detection of acoustic signatures from conspecifics, prey, predators and/or danger (Pine et al., 2019). It also differs in that prior knowledge of the species-specific auditory filter, gain, detection threshold, signal directivity and duration are not needed; the only species-specific data required is an audiogram. A review is recommended to assess the potential for ADDs to cause masking to the detriment of the most commonly occurring marine mammal species in areas of ADD use. This could include consideration of the methods described in Erbe et al. (2016) and Pine et al. (2019) to quantify the potential for masking to occur to assess its potential significance.

Auditory injury

Marine mammals exposed to intense sound, either instantaneously or over time, have the potential to exhibit reduced hearing sensitivity, termed 'threshold shift. Threshold shifts occur when the hearing sensitivity at a particular frequency (or a range of frequencies) is reduced, either temporarily (temporary threshold shift – TTS), or permanently (permanent threshold shift – PTS). PTS is a form of auditory injury (also known as hearing damage) and is generally considered to be the primary risk from intense underwater sound to marine mammals. TTS is a precursor to PTS, and is often measured in experimental studies as an indicator of PTS risk. The link between TTS and PTS is complex, but well established (NOAA & NMFS, 2018). An offset of 20 dB above measured TTS onset is recommended to predict PTS onset (Southall et al., 2019).

While TTS is not considered as a form of injury in the UK, in the presence of chronic noise such as continuous or intermittent exposure to ADD noise, repeated TTS may also have ecological consequences, for example due to lost foraging opportunities during recovery time.

Captive studies of harbour porpoises and seals have confirmed that a simulated ADD signal can cause TTS under certain conditions. In a study by Schaffeld et al. (2019), a porpoise was exposed to a simulated Lofitech ADD noise at 14 kHz, and TTS onset was found at amplitudes above 141.8 dB re 1 μPa^2 s Sound Exposure Level (SEL - a measure of cumulative sound exposure), and 155.2 dB re 1 µPa peak-to-peak Sound Pressure Level (a measure of instantaneous exposure). This onset level was significantly lower than the most recent marine mammal noise exposure criteria for continuous noise (Southall et al., 2019). Using the 20 dB offset between TTS onset and PTS onset, this would suggest PTS onset at 162.8 dB re 1 μPa^2 s SEL (or 158 dB re 1 μPa^2 s after adjusting for harbour porpoise hearing sensitivity).

In empirical studies with seals and porpoises, TTS is typically observed at frequencies 0.5-1.5 octaves higher than that of the sound stimulus. A harbour seal exposed to a 4.1 kHz pure tone suffered TTS at 5.8 kHz, approximately 0.5 octaves higher (Reichmuth et al., 2019). TTS was observed in a harbour porpoise at 20 and 28 kHz, an octave above the stimulus frequency, and artificial 14 kHz ADD signal (Schaffeld et al., 2019).

The risk of hearing threshold shift to marine mammals from underwater noise depends not only on the source amplitude and frequency, but also critically the length of exposure time (cumulative sound exposure) (Southall et al., 2019). Behavioural responses and avoidance are not well enough understood to reliably estimate the risk of PTS to individual animals, but modelled sound exposure from ADDs indicates there is a credible risk of injury to the hearing of seals and porpoises from cumulative exposure to some ADDs (Götz & Janik, 2013; Lepper et al., 2014). Susceptibility will likely be affected not only by the level of cumulative sound exposure, but also the acoustic properties of the sound stimulus. The risk is mediated by species hearing sensitivity, the frequency of the signal, and for intermittent noise the inter-pulse interval (Kastelein et al., 2014). The cumulative exposure of an animal to a sound signal will be affected by movement patterns and any behavioural response to the sound; understanding movement patterns (especially in areas of continuous or intermittent noise) is therefore highly important (Aarts et al., 2016).

Available information on the likelihood of ADDs causing auditory injury in marine mammals is mostly derived from captive and modelling studies. Research is recommended to translate this information into a real-world approach, to inform commercial use of ADDs in aquaculture.

Approach 4: Individual based modelling

Individual based modelling (IBM) approaches could be used to simulate movement of cetaceans in response to spatially explicit modelled sound, potentially building upon existing IBM work for estimating the movements of harbour porpoises and seals (e.g. Chudzinska et al., 2021; Nabe-Nielsen et al., 2018). Cumulative sound exposure could be estimated for individual animals by making assumptions about movement patterns and behavioural responses to noise. Variables such as ADD source levels, effective duty cycles and propagation characteristics could be estimated based on available data.

There is little information currently available relating to animal responses to ADDs to parameterise such a modelling approach. Suitable data might be obtained from ongoing tagging programs in Greenland and Denmark (Nielsen et al., 2018; van Beest et al., 2018), or the feasibility of investigating a programme of tagging in Scotland could be investigated. Captive animal studies might provide some useful data where it is not available elsewhere, but would not remove the need for long-term field studies. Using such data to simulate a range of possible scenarios would provide insight into the potential risk of hearing damage. This would also allow the parallel prediction of injury risk and (if using a model with an energetic component) the prediction of energetic and life history consequences of disturbance and displacement such as the consequences of re-directed transit or the consequences of exclusion from feeding grounds. This approach could also be used to guide future research priorities by identifying parameters that have the most influence on the severity of impacts. It is likely that any studies carried out under approach 1 and 2 would provide useful data to inform such modelling approaches and parameterise elements of the models.

Population consequences of impacts

Most conservation legislative frameworks require a prediction of the effects of anthropogenic activities on the conservation status of the affected population (for example, EPS licensing), so future ADD use may require further detailed consideration of this, across all of the potential impact pathways. However, for all of the potential impacts on non-target species detailed above, there are significant knowledge gaps relating to our ability to determine population consequences of impacts. This problem is shared with other noise related impacts on marine species, and is not unique to the understanding of ADD impacts. While it may be possible to estimate the number of animals that exposed to ADD sound emissions and experience the different effects (disturbance, auditory injury and masking) using local density estimates, noise propagation models and animal movement models; predicting individual and population consequences of these effects is extremely difficult. The development of approaches to predict the population consequences of noise related impacts is an active area of research and there are developing approaches and frameworks that could be adopted, modified and developed further to improve our understanding of the effects of ADDs on non-target species.

Understanding species’ functional use of the area affected by the impact (and the availability of alternative areas for that function) is crucial to our ability to predict the likelihood and consequences of displacement and masking, as well as the likelihood of response movement in relation to the prediction of noise exposure and injury risk. Understanding the nature and degree of observed displacement and its effect on individual survival and reproduction is also important and to translate these into population consequences, knowledge about the conservation status of the population is required.

Only a very limited number of these elements (energetic and fitness consequences of effects, population conservation status, functional use of habitats and availability of alternative habitats) can be quantified or measured at present, which restricts the development of existing frameworks into more meaningful predictive modelling frameworks. However, the development of such a framework in the absence of data is valuable, in that it could be used to determine the most sensitive elements of the process, in order to guide future development of the modelling and prioritise data gathering. This approach could also be used to simulate and test hypothetical outcomes at the population level. For example, simulations to quantify the energetic consequences of different scenarios could be used to inform population-based models (e.g. Harwood et al., 2020). This may provide a hierarchy or ranking of concerns that could identify metrics and triggers for monitoring and adaptive management and would highlight where research effort should be focussed.

5.4 ADD efficacy

Analysis of the available observational data through this project indicated a positive relationship between ADD usage and seal depredation, even when other available factors were accounted for through statistical modelling. As discussed previously, the data do not enable a definitive understanding of the cause of this relationship and alternative approaches are required to draw meaningful conclusions. We discuss three potential approaches to investigate the effectiveness of ADDs in reducing seal depredation. Consideration may also be required of the impact of ADDs on seal presence, in order to assess the effect of seal presence on stress caused to fish.

5.4.1 Additional data collection

Data available for the analysis in this report was mainly at the temporal scale of a month, with some depredation data available at approximately weekly scale. Finer temporal scale data could potentially be gathered on ADD usage and depredation, for example at the daily or weekly level, combined with more explanatory variables related to depredation, which would allow more refined statistical models to be constructed. However, this type of observational data is not designed to infer causation and depending on the strength of any relationships found, it may still be possible to argue that they were caused by some unmeasured factor.

It is sometimes possible to present a convincing causal argument from observational data alone (for example in many medical studies) but a detailed understanding of the mechanism and evidence for rejecting all credible alternatives is required, and the task is more difficult when the effect size is small. Results from the analysis in this report indicate that the overall effect of ADD use on depredation is not overwhelmingly large, but it is important to note that the observational nature of the available data preclude a direct assessment of ADD use versus the same situation without ADD use. To discount the observed positive association between ADD use and high depredation rates, an extensive and detailed dataset would be required. A suitable number of sites would also need to be observed both with and without ADD use. ADDs are either used or not used, which precludes the collection of data from both of these treatments from the same site. This leaves the option of comparing data from different sites, which may not be comparable for underlying reasons such as differing site infrastructure, local seal population size etc. If finfish farm managers are becoming more ‘reactive’ in their use of ADDs, this may present an opportunity to collect such comparable data, as ADD state (on/off) will be switched more frequently. This factor, combined with the potential for high-resolution automated data collection through online web interfaces, may provide the means for collection of such information in future.

5.4.2 Experimental controlled trials

There are multiple ways that experiments could be undertaken to estimate the effect of particular anti-predator treatments, including ADDs, on seal depredation. Randomized trials, involving controls and replication, are widely accepted as the best way to estimate the effect of an intervention, where it is possible ethically and financially to perform them. An experimental design based on these principles is strongly recommended, and one potential approach is described here.

The aim of such an approach would be to estimate the reduction in depredation frequency that occurs from a single ADD type, deployed in a particular way (the design is readily expanded to include other types, other treatments, etc.). The experimental unit is a stocking period at a finfish farm. The way that farms are chosen to participate will affect the inferences that can be drawn from the experiment. For example, if farms are selected on the basis that they have high expected levels of depredation then inferences that can be drawn from the study about any effect will apply only to farms with high expected levels of depredation. This would not necessarily be a problem if conclusions about ADD efficacy will only be applied to farms with high depredation, and will not be extrapolated to farms where depredation rate is lower. Ideally, farms would be selected at random from the pool of all farms of interest. The most readily available unit of measurement is the number of fish killed by seals, but there may be a more accurate way of measuring the potential impact of ADDs on seal behaviour, such as sighting rate of seals within a certain distance. This latter approach would be required to understand the extent to which ADD use prevents the presence of seals around farms, and therefore eliminates the potential for seal presence to cause stress to the fish.

Multiple finfish farms should be selected to provide replication, and treatments should be allocated randomly to chosen farms (suggested treatment regimes are given below). Those collecting the resulting data would ideally be blind to whether the treatment involves the ADD producing sound or not. In the case of certain ADD types, this might be possible through remote cycling of ADD status via the manufacturers’ online portal. Ideally, data should be collected independently to ensure that those collecting the data (depredation rates) are not invested in the outcome.

An example treatment regime would involve treatment periods of one week. This is timed to coincide with a typical inspection routine (mortality removal) and could be adjusted if a different period is more convenient. However, regime timing must remain consistent throughout the study. Each week within a stocking period would be randomly allocated to ADD on or ADD off. During weeks where the ADD is off, all equipment would be left in the water but no sound would be produced by the ADD. Mortality would be recorded each week, with depredation rate quantified by a trained member of staff.

One advantage of this approach would be that additional investigations could be conducted concurrently to gain a better understanding of seal depredation behaviour. For example, depending on the number of sites involved and the timespan required for the different treatments, observers could be stationed on site to track the movement of individual animals. This type of approach has been used successfully in the past by Harris et al. (2014), who used photo-identification of individual seals at coastal bagnets to assess the level of depredation behaviour attributed to small proportion of identified seals (termed ‘rogue seals’ or ‘specialists’). Alternatively, a visual tracking approach was used by Graham et al. (2009) to show patterns of seal movement in response to an ADD, and theodolite tracking was used by Götz and Janik (2015) to record precise movements of seals and non-target species at finfish farms.

To illustrate the strength of an experimental approach we undertook a simple prospective power analysis using a simulation approach. The question was defined as whether ADD use reduced the proportion of months in which depredation occurred. Details of the methodology and full results are given in Appendix section 3.

Results indicate that, based on the specific research question outlined, at least 15 finfish farms might need to be tested with a monthly on/off ADD treatment for the length of one stocking cycle (typically 12 to 18 months) in order to show a significant result. If treatments could be switched at the weekly level instead of monthly, and data could be collected weekly, this would be likely to reduce the monitoring period required considerably.

5.4.3 Adaptive management

A formal experimental setup such as that described in subsection 5.4.2 may be considered impractical for use on a large number of commercial farms. However, it is clear that an experimental approach would be required to resolve the issue of whether, and how, ADDs affect depredation. In this context, the framework of adaptive (resource) management (Walters, 1986; Williams, 2011a; Williams, 2011b) may prove useful. Adaptive management approaches allow exploration of different ways to meet a defined management objective. One or more of these alternatives is implemented and monitored to learn about the effects of management decisions, and then results are used to improve knowledge and adjust management actions appropriately. In the case of ADDs this would allow for ongoing decision-making on permitted use of ADDs in the light of best available science while at the same time designing and implementing regulated experiments as part of a broader management approach and using feedback from results to update the optimal management strategy.

5.4.4 Effect of stress caused by depredation on finfish growth and disease

It is widely considered by finfish producers that the presence of seals causes stress to stocked fish, which leads to reduced growth rates and increased disease (The Scottish

Government, 2021). If there is a clear link between seal presence and reduced fish health, even in the absence of direct injury and mortality, then there would be strong case for the use of anti-predator measures which prevent fish from detecting the presence of a predator, as opposed to those which simply prevent the predator from accessing the fish, such as anti-predator netting. No scientific studies have been published on whether or not predatory behaviour by seals has a negative impact on the health or welfare of stocked finfish through increased stress. There is some evidence of predatory behaviour reducing the health of stocked fish based on captive trials with other fish species (Barcellos et al., 2007), but no published evidence is available in the context of predatory seal behaviour.

This question could be addressed either through captive trials or through data collection at fish farms. Captive trials could be split into two parts: quantification of the level of stress created by predatory seal behaviour on finfish, and then assessment of how that level of stress affects finfish health outcomes. Such trials would require ethical assessment. Trials at finfish farms could take advantage of large volumes of ‘real-world’ data on growth rate, feed rate and / or rates of disease, but linking these with an accurate measure of predation behaviour is more challenging. If reliable metrics could be obtained on the efficacy of ADDs, or any other anti-predator management measure, then this could potentially be used as a proxy for predator presence/absence. For example, mimicking the format of the trial described above, we could compare feed conversion rate during periods of ADD use (assumed to be low rate of stress caused by predatory seal behaviour) against periods of no ADD use. This approach would have the fundamental problem of being observational in nature, and therefore the true cause of any effect could not be conclusively attributed to seal presence/absence, as there may be underlying factors linking ADD use with growth rate.

6 Conclusions

6.1 Extent of ADDs

The number of farms with ADDs installed on site has increased between 2014 to 2016 (with a peak between 2016 and 2018) and reduced slightly from 2018 to 2019, but the number of farms who reported having ADDs switched on has remained relatively consistent. This suggests that more sites may have devices installed, but not actively used.

Since 2016, when the number of farms with ADDs began to plateau, the number of transducers installed on finfish farms continued to increase until the end of 2019, but this rate of increase has slowed from 2018. This could, in part, be due to the uptake of ADD models that generally operate with low numbers of transducers per site. The effective duty-cycle of an ADD system is greatly increased by the use of multiple unsynchronised transducers, and the use of multiple transducers could increase the peak received amplitude of sound around a finfish farm, but this effect is complex.

There was an increase in the prevalence of sites using multiple (different) device types between 2014 and 2017, but the total number of sites remained relatively low, and this trend reduced again after 2017. Conversations with farm managers suggest that multiple ADD types may be used simultaneously to produce an increased deterrent effect, for example the novel sound signal from the second ADD might have a stronger effect, or that one type may replace the other if it is found to be ineffective for a period of time. There is currently no published scientific information to explore the validity of these theories.

There are regional differences in the use of different types of ADD, which could be caused by the operation of different finfish producers. Companies operating exclusively in the Northern Isles report to be more likely to use the Ace Aquatec RT1 device in the most recently available data (2019/2020). Whereas companies operating mainly on the west coast and Western Isles, report to be more likely to use the Airmar/GaelForce or OTAQ devices.

There are some differences between the proportion of time that ADDs are switched on across the different regions, but no consistent patterns or trend. Differences could be caused by the types of device used in different regions or the differences in management strategies of fish farms between regions. Despite changes to the proportion of sites with ADDs, and changes in the proportion of time that ADDs are switched on, there has been a relatively consistent number of farms actively using an ADD since 2014 (in the region of 80 and 100 farms). Alternative management measures such as anti-predator nets could also be having an effect on the number of ADDs in use.

The decrease in the proportion of transducers which are actively being used suggests there may be an increase in the active, or responsive, use of ADDs; only using them when depredation is ongoing or when the threat is considered to be high. This may indicate the start of a more active management approach to ADD use, potentially caused by increased awareness of farm managers to the potential impact on sensitive non-target species. If so, this would have the effect of reducing the overall amount of noise pollution created. There is currently little understanding of how the likelihood of disturbance to non-target species is mediated by different usage strategies of ADDs, such as duty-cycling and triggering.

While the available data have allowed general conclusions on usage trends in time and space, they do not explain why these changes have occurred. There is very little fine-scale information on temporal patterns and strategies of ADD use which would be required to fully understand the nature and extent of noise emissions from ADDs and to be able to predict potential effects.

The availability of data from automated systems developed by ADD manufacturers may be a useful way of collecting and providing detailed records of patterns of ADD use to inform future assessments.

The observed changes in the use of ADDs over the time-period covered in this report may have impacts on sensitive non-target species in Scotland. The large number of transducers installed on some sites is likely to increase the effective duty cycle and potentially the peak received amplitude. The increased prevalence of lower frequency devices replacing higher frequency ADDs may reduce the potential for impacts on high-frequency sensitive species (dolphins and harbour porpoises), but evidence is not available to quantify relative sound exposure levels between different devices. Additionally, this change may lead to increased impacts on low frequency species, such as minke whales. This depends crucially on animals' behavioural response to noise, which is poorly understood at present.

6.2 Analysis of efficacy

From data analysed in this project, seal depredation of finfish farms appears to be a common occurrence, reported to occur in 39% of the months that farms were stocked, and in 71% of stocking periods. The median number of fish reported as being killed by seals per finfish farm in months with depredation was 111 fish; with 5% of these farms having reported depredation of more than 1,000 fish.

Use of ADDs in the dataset was also common, being recorded in 53% of observed months, and 61% of stocking periods. Where they were used, they were typically recorded as being kept on for most of the time, for example in 70% of stocking periods where ADDs were used, they were reported to be turned on in >90% of the months within that stocking period.

In our exploratory analysis, we found a consistently higher frequency and level of depredation associated with ADD use. For example, depredation occurred in 47% of months where ADDs were used and 23% where they were not. Mean depredation was 3,177 fish over the entire stocking period when ADDs were used for >90% of the time and 2,261 when they were not used. Attempts were made to account for geographic, temporal and farm-level factors through a set of statistical models, looking at the data at three different levels of temporal aggregation: month, stocking period and depredation event. Broadly, we found that ADD usage was still associated with increased frequency and level of depredation at all three temporal levels) even after accounting for the other available variables. The only exception was that no relationship was found between ADD usage and the total mortality per depredation event once the length of the event was accounted for, although ADD usage was associated with longer depredation events and these in turn were associated with greater mortality.

The observed positive relationship between ADD use and predation could possibly be attributable to ADD usage causing more seal depredation events, which would align with the so-called ‘dinner bell’ theory. However, it should be considered that ADD usage may simply be associated with other factors that cause seal depredation. A likely explanation for these findings is that some other factor(s) are linking ADD usage with high depredation. For example, that ADDs are used responsively when depredation is first detected, or that they are used pre-emptively when depredation is anticipated based on previous experience or local knowledge. In either case, ADD use cannot be completely effective, but the level by which they reduce predation, compared to what it would have been without ADD use, is unknown. We did not find strong evidence that ADDs were being used in response to seal depredation: for those stocking periods where ADD use was less than 90%, ADDs tended to be used less before the first recorded depredation (39%) than after it (59%), but the same pattern of increasing use of ADDs over time occurred in stocking periods where no depredation was recorded (e.g. 41% usage in months 1-3 and 58% thereafter).

One option we explored is whether sites not permitted to use ADDs could be viewed as a quasi-experiment (i.e. an experiment without randomisation). In such a situation, the level of depredation in sites, stocking periods or months where ADD usage was prevented could be taken as representative of the baseline level. This could then be compared with depredation levels where ADDs were allowed (whether used or not). The frequency of depredation was generally higher (47% of months) when ADD use was restricted compared to when it was not (37%), and this was supported by the modelling, which showed a positive association (after accounting for other known variables) between ADD restrictions and the monthly level of depredation, the number of depredation events and level of depredation within a stocking period, and the length of the depredation events. This would tend to suggest that restricting ADD use may lead to higher rates of depredation. However, the assumption that locations and times where ADDs are restricted are representative of background levels of depredation may not be valid. For example, ADDs may be more likely to be restricted near to conservation areas and these areas may also have higher seal density and therefore higher expected rates of depredation.

There were differences in depredation frequency and level associated with the different types of ADD. Wherever enough data were present, ADDs models were significantly positively associated with depredation in one or more of the models – for example in the monthly model of depredation frequency, Airmar, Ace Aquatec US3, Terecos, OTAQ and MohnAqua all had statistically significant positive coefficients.

The major factor limiting inferences that can be made from these data are that they are observational rather than experimental. However, other limitations of the data analysis should be noted.

In our analyses the response variables we used related to the frequency of depredation (typically proportion of months) and level of depredation (number of fish killed). However, fish early in a stocking period are typically less valuable than those later on, and so a useful third metric to include in future analyses would be the economic value of the losses.

The relatively coarse temporal resolution means that fine scale-details may have been missed. Stocking periods were delimited by having a clear month with no stocking. Depending on the length of the fallow period between stocking periods, two separate stocking periods could have been recorded as a single longer one. A similar issue exists for depredation events, although it is more ambiguous what the correct definition of a depredation event is since, unlike stocking periods, each incidence of depredation is a discrete event, and so there is no natural clustering. Additionally, the level of depredation that could be considered problematic is not a fixed value (e.g. a particular number of fish) but will vary depending on the size of the fish and other factors. Nevertheless, it was observed that even at the month level there were periods where no depredation occurred interspersed with months of continually recorded depredation. In the statistical modelling, some of the final models did not fit the data well, either explaining a low percentage of the overall variation in the data, or with response variable distributions that produced a residual distribution different from that expected. Overall, it is unlikely that any of these issues affected the overall inferences drawn from the models.

Fundamentally, it is difficult to attribute causation to the observed pattern based on purely observational data unless the magnitude of the effect is large. Without adequate experimental control there is always a risk that some hidden variable that is not measured is causing the association. We were not able to differentiate between any effect of ADDs in reducing depredation and underlying factors that link ADD usage with increased depredation. Randomised, replicated and blinded experiments are the gold standard, while adaptive management can also potentially identify causation. Recommendations for both approaches are provided in section 5.3.

Data collected in this study were not sufficient to provide conclusions about the impact of different netting materials on seal depredation. New netting materials have been increasingly used in Scottish aquaculture and there is anecdotal evidence that some types are resistant to seal depredation, but no information is available for quantitative assessment. Conversations with site managers suggested that initial effects in preventing predation lessened over time, possibly due to changes in the qualities of the net material, or possibly due to seals successfully adapting behaviours.

Anti-predator nets are still in use in Scotland, although there are relatively small numbers of sites using them. One primary concern cited by farm managers in relation to their use was entanglement leading to the drowning of predators, particularly diving birds and seals (Northridge et al., 2010). Their apparently widespread use in industries overseas suggests that problems with entanglement of animals may have been overcome. Alternatively, it may be that conditions in those industries overseas are somehow different to the Scottish conditions in a way which allows their effective use (e.g. lower rates of tidal flow). Research recommendations relating to netting materials are considered in detail as part of an associated report (Thompson et al., 2021).

6.3 Summary of research priorities

To monitor, manage and measure the efficacy of ADD use and any resulting effects on non-target species there is a need for comprehensive and systematic collection of standardised data on the nature and extent of ADD use in Scottish aquaculture. This would include the following information for each site on at least daily basis: ADD model(s), sound source levels, number of transducers, duty cycle, times of operation. Associated information on depredation rates at the same temporal resolution would also be valuable and these should be collated into a centralised data collection system.

The feasibility of the use of anti-predator net systems which have proven to be successful overseas should be explored, including the consideration of controlled trials at Scottish sites, and research recommendations have been outlined as part of an associated report (Thompson et al., 2021).

The following research priorities have been identified:

Effects of ADDs on non-target species:

- Although several studies have demonstrated that ADDs can elicit behavioural responses in cetaceans, there is limited evidence for broadscale displacement around sites where ADDs are used.
- Research into the potential for ADDs to cause significant habitat degradation, using quantitative modelling approaches to explore the potential for masking to occur.
- The development and application of movement models to predict the risk of auditory injury under a range of scenarios with the potential extension of being able to simulate the energetic consequences of predicted responsive behaviour.
- All of these potential effects require to be placed in the context of individual life history consequences, and ultimately population consequences.

Efficacy of ADDs.

- Site based control-treatment trials would be required for this type of study although there may be difficulties in achieving the idealised design in a way that is compatible with an ongoing industry.
- Adaptive management may be a more practical approach to work with the industry to ensure that any ADD use is managed and monitored in a way that maximises the information available to evaluate effectiveness.

These will require dedicated experimental studies designed explicitly to answer the question of effectiveness of ADDs in reducing depredation:

In addition, there is a requirement for research into the effects of stress caused by predation on finfish health, growth and disease. Understanding the effects of predator presence of fish health will help in the design of control measures to ensure that all negative effects of seal presence and depredation can be reduced though active management.

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The Scottish Government
St Andrew's House
Edinburgh
EH1 3DG

ISBN: 978-1-80435-069-0 (web only)

Published by The Scottish Government, April 2022

Produced for The Scottish Government by APS Group Scotland, 21 Tennant Street, Edinburgh EH6 5NA
PPDAS1029518 (04/22)