



Monitoring and mitigating cetacean bycatch and entanglement in fishing gear, with a focus on humpback whales (*Megaptera novaeangliae*) in Iceland

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Monitoring and mitigating cetacean bycatch and entanglement in fishing gear, with a focus on humpback whales (*Megaptera novaeangliae*) in Iceland

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Dissertation submitted in partial fulfillment of a
Philosophiae Doctor degree in Biology

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Abstract

As industries expand in sub-Arctic and Arctic waters there are increased conflicts between these industries and cetaceans. The aim of this work was to investigate the issue of cetacean bycatch/entanglement in Iceland, with a particular focus on the understudied issue of humpback whale entanglement. Bycatch/entanglement in fishing gear is a serious threat to cetaceans, as well as a detriment to fisheries, and mandatory bycatch reporting in logbooks could be of immense scientific value; however cetacean bycatch is considered greatly under-reported. I determined that cetacean bycatch was significantly under-reported in fisher logbooks in nearly all (7/8) trawl, net, and hook and line fisheries that could be examined in New Zealand, Iceland, and the USA when compared to observer data. The cod gillnets in Iceland had the biggest difference between fisher and observer catch per unit effort (with the observer estimate being 270 times greater). Large whale entanglements only accounted for an average of 12% of reported incidents, supporting the idea that these events are the most under-reported. Through scar-based analysis I determined that at least 25% of Icelandic humpback whales have been entangled and this is occurring at a rate of 2% annually. I tested acoustic alarms as an entanglement mitigation tool and through experimental exposure trials it was determined that humpback whales responded to the “whale pinger” by significantly increasing their speed and decreasing their surface feeding. These pingers were also fitted on a capelin purse seine net and I observed that humpback whales still entered the net from the bottom, but they were able to escape through a pinger-free opening. Using anonymous questionnaires and interviews, I gained further insight into entanglement from the fishers’ perspective. Humpback whales were the most commonly reported species that was witnessed entangled, and this occurred most often in capelin purse seines. Damage and losses due to whale collisions with gear was reported to cost fishers up to 55.000.000 ISK. Overall, this work resulted in the first systematic quantification and statistical comparisons of cetacean bycatch under-reporting in logbooks versus observer data. This assessment of whole fisheries in individual countries provides baseline data for improvement of mandatory cetacean bycatch data for scientific use. Additionally, I provided first scientific evidence that entanglement is a prevalent issue in the Icelandic humpback whale population and Icelandic fisheries, sometimes having detrimental effects on both parties. Furthermore, this work resulted in the first evidence that whale pingers may be a useful entanglement mitigation tool in humpback whale feeding grounds. The experimental exposure trials revealed that surface feeding behaviour can be used as a response variable, while results of the *in-situ* capelin purse seine trial suggested humpback whales may have good directional hearing that can be examined through pinger experiments.

Útdráttur

Samfara útpenslu iðnaðar og sjávarútvegs á hafsvæðum norðurslóða (kaldtempruðum og heimskautasvæðum) aukast hagsmunaaðrekstrar milli þessara athafna mannsins og hvala. Markmið þessarar vinnu er að rannsaka ánetjun hvala í veiðarfæri við Ísland, með sérstakri áherslu á ánetjun hnúfubaka þar sem rannsóknir hefur skort. Meðafli/ánetjun í veiðarfærum er alvarleg ógn við hvali og skylduskráning þeirra í afladagbækur gæti haft mjög mikið vísindalegt gildi; en meðafli hvala er talinn mjög vanskráður. Ég dró þá ályktun að meðafli hvala var marktækt vanskráður í afladagbækur næstum allra (7/8) tog-, neta-, króka- og línuveiða sem við náðum að rannsaka í Nýja Sjálandi, Íslandi og Bandaríkjunum samanborið við gögn eftirlitsaðila. Mestur var munurinn (270x meiri) milli skráninga fiskimanna og eftirlitsmanna hvað varðar afla á sóknareiningu í þorskanet við Ísland. Ánetjun stórhvala var að meðaltali einungis 12% af tilkynntum atvikum, sem styður þá hugmynd að þessi atvik séu mest vanskráð. Með greiningu á örum ályktaði ég að minnst 25% íslenskra hnúfubaka hafa flækst í veiðarfæri og að tíðni slíkrar ánetjunar sé um 2% árlega. Ég prófaði hljóðfælar sem tæki til að minnka ánetjun og út frá tilraunahljóðsendingum ályktaði ég að hnúfubakar bregðist við hljóðfælum með því að auka marktækt sundhraða og minnka fæðunám við yfirborð sjávar. Þegar hljóðfælurnar voru festar við loðnunætur fóru hnúfubakar eftir sem áður inn í þær neðan frá, en náðu að komast út um hljóðfælulaust op á nóttinni. Nafnlausir spurningalistar og viðtöl gáfu frekari upplýsingar um ánetjun frá sjónarhóli sjómanna. Í þessum hluta voru hnúfubakar oftast nefndir og loðnunót var algengasta veiðarfærið varðandi ánetjun. Skemmdir á veiðarfærum og annað tjón sjómanna vegna árekstra hvala við veiðarfæri gat numið allt að 55 milljónum króna samkvæmt þessum skýrslum. Þessi vinna leiddi af sér fyrstu kerfisbundnu mælinguna og tölfræðilegan samanburð á vanhöldum í skráningu hvala í afladagbækur, samanborið við skráningar eftirlitsmanna. Þetta heildarmat fiskveiða í einstökum löndum sýnir viðmiðunargögn sem bætt geta skyldubundnar upplýsingar um meðafli, til vísindalegra nota. Að auki leiddi ég fram fyrstu vísindalegu sannanir þess að ánetjun hnúfubaka er reglubundið fyrirbæri í íslenskum fiskveiðum sem getur haft alvarleg áhrif bæði á hvalina og fiskveiðarnar. Rannsóknirnar leiddu einnig til fyrstu vísbendinga um að hljóðfælar geti verið gagnlegar við að minnka líkur á ánetjun hnúfubaka á fæðuslód. Tilraunahljóðsendingarnar leiddu í ljós að fæðunám við yfirborð er nýtanlegt sem svarbreyta, en niðurstöður tilraunar með herpinót *in-situ* gáfu til kynna að hnúfubakar kunni að hafa góða stefnuheyrn sem hægt er að rannsaka í gegnum tilraunir með hljóðfælu.

List of Original Papers

This thesis is based on the following five original papers which are referred to throughout the text by the roman numerals assigned to each of them. These papers are included at the end of this thesis.

Paper I: Basran CJ, Rasmussen MH (2020) Conflict Between Arctic Industries and Cetaceans. In: *Arctic Marine Sustainability, Arctic Maritime Businesses and the Resilience of the Marine Environment*. Eds. Eva Pongrácz, Victor Pavlov & Niko Hänninen. Springer Nature Switzerland. <https://doi.org/10.1007/978-3-030-28404-6>

Paper II: Basran CJ, Sigurðsson GM (n.d.) Using case studies to investigate cetacean bycatch/interaction under-reporting in countries with reporting legislation. Manuscript.

Paper III: Basran CJ, Bertulli CG, Cecchetti A, Rasmussen MH, Whittaker M, Robbins J (2019) First estimates of entanglement rate of humpback whales *Megaptera novaeangliae* observed in coastal Icelandic waters. *Endangered Species Research* 38: 67–77. <https://doi.org/10.3354/ESR00936>

Paper IV: Basran CJ, Woelfing B, Neumann C, Rasmussen MH (2020) Behavioural responses of humpback whales (*Megaptera novaeangliae*) to Two Acoustic Deterrent Devices in a Northern Feeding Ground off Iceland. *Aquatic Mammals* 46(6): 584-602. DOI 10.1578/AM.46.6.2020.584

Paper V: Basran CJ, Rasmussen MH (2021) Fishers and whales in Iceland: Whale interactions with fishing gear from the fishers' perspective, with focus on humpback whales (*Megaptera novaeangliae*). *Journal of Cetacean Research and Management*: in press.

Table of Contents

List of Original Papers	vii
List of Figures	xi
Acknowledgements	xiii
1 Introduction.....	1
1.1 Cetaceans: importance and plight.....	1
1.2 Anthropogenic threats to cetaceans	1
1.2.1 Biology of cetacean bycatch and entanglement.....	2
1.2.2 Under-reporting of cetacean bycatch and entanglement.....	3
1.3 The humpback whale (<i>Megaptera novaeangliae</i>).....	4
1.3.1 Humpback whales in Iceland	5
1.3.2 Humpback whale entanglement studies.....	5
1.3.3 Mitigating humpback whale entanglement	6
1.4 Using questionnaires to gather local knowledge from fishers	9
2 Objectives	11
3 Materials and Methods.....	13
3.1 Cetacean bycatch and entanglement under-reporting case studies	13
3.1.1 Data collection	13
3.1.2 Catch per unit effort calculations and comparisons.....	13
3.2 Fieldwork study sites.....	14
3.2.1 Skjálfandi Bay.....	15
3.2.2 Eyjafjörður	15
3.2.3 Faxaflói Bay.....	15
3.3 Humpback whale fluke identification	15
3.4 Entanglement scar analysis	16
3.4.1 Image quality	16
3.4.2 Peduncle scar analysis and entanglement estimate calculations.....	17
3.5 Acoustic alarm trials.....	19
3.5.1 Acoustic alarms.....	19
3.5.2 Individual experimental exposure trials.....	19
3.5.3 Capelin purse seine trial.....	21
3.6 Fisher questionnaires and interviews	22
4 Results and Discussion.....	25
4.1 Paper II: Bycatch and entanglement under-reporting case studies.....	25
4.2 Paper III: Entanglement Scar Analysis	29
4.3 Paper IV: Acoustic Alarm Trials.....	31
4.4 Paper V: Fisher Questionnaires and Interviews	38
5 Conclusions.....	45

References	49
Appendix 1	59
Paper I	63
Paper II.....	87
Paper III.....	121
Paper IV	143
Paper V.....	175

List of Figures

<i>Figure 1 Humpback whale in Skjálfandi Bay, Iceland (Photo: Yann Kolbeinsson)</i>	4
<i>Figure 2 Map of Iceland showing the data collection sites for this study</i>	14
<i>Figure 3 Photograph of the unique pattern on the underneath side of the humpback whale's fluke used for identification (Photo: Charla Basran)</i>	16
<i>Figure 4 Image showing four of the six scar coding areas around the peduncle of the whale: i) left flank, ii) dorsal peduncle, iii) ventral peduncle, iv) left leading edge and insertion point of the fluke. Not shown: v) right flank, vi) right leading edge and insertion point of the fluke</i>	17
<i>Figure 5 Image showing notches and wrapping scars (indicated by arrows) indicative of a prior entanglement</i>	18
<i>Figure 6 Image showing an individual whale with increased entanglement scarring (indicated by ellipses) between sightings in consecutive years</i>	18
<i>Figure 7 Image showing unhealed entanglement injuries (indicated by arrows) indicating the whale had likely been entangled within the last year</i>	18
<i>Figure 8 Future Oceans whale pinger acoustic alarm (left) and Lofitech seal scarer acoustic deterrent device (right)</i>	19
<i>Figure 9 Photos showing lunge feeding behaviour (left) and expanded throat pleats (right) which were used to determine feeding behaviour from the video recording of the humpback whale experimental exposure trials</i>	21
<i>Figure 10 Schematic of the whale pinger attachment to a capelin purse seine net (©Future Oceans)</i>	22
<i>Figure 11 Photos showing four examples of humpback whales photographed with entangling gear attached to the body (indicated by ellipses) both within and outside the coding areas. i) monofilament line, ii) monofilament line and hooks, iii) rope and netting, iv) rope</i>	30
<i>Figure 12 Averages of the behavioural response variables breathing rate, dive time, directness and speed for the pre-exposure (PrE), exposure (E) and post-exposure (PoE) phases of each whale pinger (WP) trial. Stars highlight individual whale pinger exposure trials in which the response variable differed significantly between the phases (* uncorrected $p < 0.05$; ** Bonferroni-corrected $p < 0.05$). Letters indicate between which phases significant differences occurred. Models for individual whale pinger exposure trials were only calculated for response variables for which overall models found a significant effect of phase or random slope</i>	32

<i>Figure 13 Graph showing the probability of surface feeding during whale pinger trials for each phase (PrE = pre-exposure phase, E = exposure phase, PoE = post-exposure phase).</i>	33
<i>Figure 14 Averages of the behavioural response variables breathing rate, dive time, directness and speed for the pre-exposure (PrE), exposure (E) and post-exposure (PoE) phases of each seal scarer (SS) trial. Stars highlight individual seal scarer exposure trials in which the response variable differed significantly between the phases (* uncorrected $p < 0.05$; ** Bonferroni-corrected $p < 0.05$). Letters indicate between which phases significant differences occurred. Models for individual seal scarer exposure trials were only calculated for response variables for which overall models found a significant effect of phase or random slope.</i>	34
<i>Figure 15 Video still showing one of two humpback whales going down for a dive while encircled in the capelin purse seine net.</i>	35
<i>Figure 16 Graph showing how often questionnaire respondents reported seeing whales of any species (Whale spp.), humpback whales (Mn), dolphins and/or porpoises (Dol +/- Por) and pinnipeds (Pinn) while fishing in Iceland.</i>	38
<i>Figure 17 Graph showing how often questionnaire respondents witnessed whales of any species (Whale spp.) and dolphins and/or porpoises (Dol +/- Por) in their fishing gear while fishing in Iceland.</i>	39
<i>Figure 18 Graph showing the number of each species of whale, and the percent of the total that each species represents, that questionnaire respondents reported witnessing interacting with their fishing gear while fishing in Iceland. Mn = humpback whale, Oo = orca, Pm = sperm whale, Bm = blue whale, Ba = minke whale, Unk = unknown.</i>	39
<i>Figure 19 Map showing the eight locations in the fishing grounds where respondent reported witnessing humpback whales in their fishing gear around Iceland. Solid black boxes indicate reported locations, solid grey boxes indicate two locations given in the same report, however the report was counted as one witnessed entanglement since it was unclear if they were reporting two incidences or estimating where one incident occurred. The dotted box indicates a report of an incident “southeast of Scorebysund” only indicating that this would be in open ocean to the far northwest of Iceland.</i>	40
<i>Figure 20 Graph showing responses that questionnaire respondents provided for why they would or would not report whales in their fishing gear in Iceland.</i>	42
<i>Figure 21 Image showing a humpback whale in Skjálfandi Bay, Iceland with monofilament line (possibly long-line fishing gear) wrapped tightly around the tail stalk causing deep lacerations. (©Húsavík Research Centre).</i>	44

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1 Introduction

1.1 Cetaceans: importance and plight

Cetaceans (order *Cetartiodactyla*, infraorder *Cetacea* (Brisson, 1762)) is the collective term for all whales, dolphins, and porpoises (currently 90 species in total) which can be split into the two suborders *Mysticeti* (baleen whales) and *Odontoceti* (toothed whales) (Perrin 2021; Carwardine 2020). Cetaceans are long-lived, relatively slow-maturing (e.g. 4 – 11 years for humpback whales (*Megaptera novaeangliae*, Borowski, 1781)) mammals, of which many species, particularly the baleen whales, have long migration routes and large habitat ranges (Carwardine 2020). Baleen whales in particular, play important roles in the ocean ecosystem, including enhancing primary productivity through their fecal plumes and serving as large carbon sinks through accumulating carbon throughout their lifetime and depositing this to the bottom of the ocean when they die (Roman et al. 2014). Unfortunately, their life-history traits make their populations vulnerable to an array of current anthropogenic impacts. Different from the cases of many of their terrestrial counterparts, these ocean-dwelling mammals have little refuge from large industrial operations which extensively overlap with their migration corridors and important feeding and breeding habitats. Previous modelling results determined approximately 70% of areas with high anthropogenic impacts were within, or in close proximity to, the same areas determined to be key conservation sites for marine mammals, and other key conservation sites are the same areas where the highest global commercial fishing catches are recorded (Pompa et al. 2011). With only 7.7% of Earth's oceans given some level of protection (compared to 15.7% of land) (Protected Planet 2021), and only 2.7% considered fully/highly protected (Marine Conservation Institute 2021), greater conservation research efforts are warranted. Monitoring, and then mitigating, anthropogenic impacts on cetaceans is imperative to preserve their populations and therefore their important role in the ecosystem.

1.2 Anthropogenic threats to cetaceans

Cetaceans face a wide range of anthropogenic threats throughout their habitat ranges. **Paper I** serves as an introduction to the main anthropogenic threats facing cetaceans in Arctic/sub-Arctic regions using six exemplary species from both the toothed whale (odontocetes) and baleen whale (mysticetes) groups: sperm whale (*Physeter macrocephalus*, Linnaeus, 1758), white-beaked dolphin (*Lagenorhynchus albirostris*, Gray, 1846), orca (*Orcinus orca*, Linnaeus, 1758), harbour porpoise (*Phocoena phocoena* Linnaeus, 1758), blue whale (*Balaenoptera musculus*, Linnaeus, 1758) and humpback whale. The first major threat, particularly to the slower moving baleen whales, is ship strikes. Both blue whales and humpback whales are vulnerable to ship strikes (McKenna et al. 2015; Laist et al. 2001), which can often be fatal if the ship is great than 80 m long or traveling at 14 knots or faster (Laist et al. 2001). Humpback whales are one of the most reported species involved in ship strike incidents, though this is likely due in-part to their

preference for coastal habitat and therefore the higher chance of detectability of ship-struck animals in coastal waters (Jensen and Silber 2004).

A second major anthropogenic threat is the effects of oil exploration, which uses seismic airgun blasts that can cause behavioural disruption and communication masking for cetaceans (Di Iorio and Clark 2010). These airgun blasts are believed to be audible to all cetacean species (Goold and Coates 2006), though their reactions differ. Masking of communication between individuals has been specifically noted for blue whales (Di Iorio and Clark 2010). All six of the exemplary species have shown evidence of avoidance behaviour to active airguns (McDonald et al. 1995; Malme et al. 1985; Stone and Tasker, 2006; Miller et al., 2009), with evidence that harbour porpoises are the most sensitive (Bain and Williams, 2006) while sperm whales may be the least (Madsen et al. 2002). Humpback whales have been shown to have interesting, varied reactions to seismic airgun blasts, where some animals avoided a vessel with an airgun in operation when it was 1.2-4.4 km away (McCauley 2000) while others were observed approaching a vessel with an active airgun within 100-400 m. This is hypothesized to be male humpback whales that are responding to the airgun sound believing it is that of a competitor breaching (jumping out of the water) (McCauley 2000). This could potentially cause at least temporary hearing impairment when animals are exposed to the airgun at close range (Gedamke et al. 2011).

Lastly, entanglement (when a cetacean gets caught up in, or incidentally interacts with, fishing gear, sometimes resulting in injuries and/or gear damage) and bycatch (when a cetacean gets caught in fishing gear and drowns) are known to be a major threat to all cetaceans. The global fishing fleet in 2016 was estimated to have been 4.6 million vessels (FAO 2018) causing wide-spread concern over this issue, which is considered one of the leading global causes of human-induced cetacean mortality (NOAA n.d.). It is estimated over 300,000 cetaceans die due to bycatch every year (Read et al. 2006). Entanglement and bycatch are known to occur in many kinds of fishing gear, with set nets, long-lines, traps/pots and purse seines being the main contributors (Butterworth et al. 2012). Though there is evidence for all six exemplary species being affected by entanglement or bycatch (e.g., Robbins and Mattila 2004; Visser 2000; Pace et al. 2008; Palsson et al. 2015; Ramp et al. 2021), the most susceptible of the exemplary toothed whales is the harbour porpoise (Brown et al. 2013) and of the baleen whales is the humpback whale, which, for example, made up 50-95% of all cetacean entanglements between 1979-2008 in North Atlantic Canada (Benjamins et al. 2012).

Specifically in Iceland, the main anthropogenic threats that have been identified as affecting cetaceans are pressure from whale watching tourism, including engine noise which can disrupt natural behaviour patterns such as feeding (Christiansen et al. 2013; Ovide 2017), and entanglement/bycatch in fishing gear (Basran 2014; Palsson et al. 2015). Entanglement is arguably the largest anthropogenic issue in the country, which is particularly known to affect both harbour porpoises, which are often caught in the gillnet fisheries (Ólafsdóttir 2010), and humpback whales (Basran 2014), for which little research has been conducted prior to the work conducted for this thesis.

1.2.1 Biology of cetacean bycatch and entanglement

Despite their different biological adaptations which allow them to orient and navigate in the marine environment, both odontocetes and mysticetes continue to suffer from

becoming bycatch or entangled in fishing gear. Much of the fishing gear that has been implicated in these events, such as gillnets, is set in shallow waters with low visibility or deep waters with low light where it is very unlikely for cetaceans to see the gear in time to avoid it (Kastelein et al. 2000). Though odontocetes are using echolocation, the acoustic reflectivity of nets is relatively weak, meaning these animals also have difficulty detecting them with their echolocation (Au and Jones 1991; Mooney et al. 2007). This has been noted particularly for harbour porpoises which have lower intensity echolocation clicks than dolphins and are often victims of bycatch (Kastelein et al. 2000; Mooney et al. 2007). Even if gear is detectable with echolocation, it is believed that the animals are not constantly echolocating and may collide with the gear during a time when they are not using this technique, or at a time of high swimming speed where they were not able to react fast enough to its presence (Au and Jones 1991).

Though not using echolocation, hearing and interpretation of sounds is likely an important method for mysticetes to orient themselves and navigate in their environment (Lien et al. 1990) and it is hypothesized that they may not be able to acoustically detect fishing gear in such a way that they can avoid colliding with it and potentially becoming entangled. This may be because some gear does not produce a strong enough acoustic signal, or the sound is being masked by other underwater noises (Lien et al. 1990), rendering it undetectable by large whales, such as the humpback whale and North Atlantic right whale (*Eubalaena glacialis*, Müller, 1776), which are known to be particularly susceptible (Benjamins et al. 2012; Moore et al. 2021)

1.2.2 Under-reporting of cetacean bycatch and entanglement

Understanding the number of cetaceans becoming bycatch or entangled in fishing gear is a serious hurdle for fisheries and cetacean population management. Having fishers log all cetacean bycatch and entanglement incidents would be of immense scientific value to aid in understanding the magnitude of this issue and making informed management decisions. However, accurate and reliable reporting is rare, and relatively few countries have systematically reported data (Read et al. 2006). Informal interviews with researchers focused on bycatch and entanglement at the World Marine Mammal Conference (Barcelona, Spain 2019) revealed that under-reporting of all species, and in particular large whales, is considered a serious problem by experts; however, this has rarely been quantified (pers. comm. 10-12 December 2019). Twelve out of the top 30 countries with the largest commercial fisheries in the world have legislation making reporting of cetacean bycatch and/or interactions with fishing gear in logbooks mandatory by law (See **Paper II** for details of each country's legislation), but these laws are difficult to enforce. Iceland is one of the countries with bycatch reporting legislation; however, as with many other countries, logbook reporting is thought to underestimate cetacean bycatch (Marine Research Institute pers. comm. 03 December 2020). A questionnaire study previously carried out in Iceland determined that logbook data in the gillnet fishery was unreliable and underestimated harbour porpoise bycatch by a ratio of approximately 1000:2600 (Ólafsdóttir 2010).

The issue of bycatch and entanglement under-reporting by fishers has led to the need for onboard observer programs to independently calculate bycatch estimates; however, these programs can be costly (79.5 million USD in 2018 for coverage in 54 fisheries (National Marine Fisheries Service 2020)) and therefore not feasible for all fisheries in all countries

(Reeves et al. 2013). Despite evidence for under-reporting of cetacean bycatch/entanglement in fishing gear from strandings (e.g., Peltier et al. 2016; Vikingsson 2015) and scar-analysis (e.g., Robbins 2012), this under-reporting has not been consistently and accurately quantified for different fishing gears or species in countries where reporting is mandatory. In order to improve upon the accuracy of fisher logbook reporting to aid in minimizing the need for expensive observer programs, it is important to first have a baseline understanding of how logbook reporting compares to onboard observer bycatch estimates. Once this is established, pilot programs can be put in place to improve logbook reporting, and improvement can be verified against past data.

1.3 The humpback whale (*Megaptera novaeangliae*)

The final three chapters of this thesis (**Papers III, IV, V**) focus primarily on issues surrounding entanglement of humpback whales (*Megaptera novaeangliae*, Borowski 1781) (Figure 1) belonging to the family Balaenopteridae, also known as rorquals. This family also includes two species of minke whale (*Balaenoptera acutorostrata* Lacepède, 1804 and *Balaenoptera bonaerensis* Gray, 1874), sei whale (*Balaenoptera borealis* Lesson, 1828), Bryde's whale (*Balaenoptera edeni* Anderson, 1878), fin whale (*Balaenoptera physalus* Linnaeus, 1758), blue whale (*Balaenoptera musculus* Linnaeus, 1758), and Omura's whale (*Balaenoptera omurai*, Wada, Oishi and Amada, 2003). All rorqual whales are also baleen whales, meaning they have keratin baleen plates along their upper jaw used to filter their food out of the water (Bannister 2009).



Figure 1 Humpback whale in Skjálfandi Bay, Iceland (Photo: Yann Kolbeinsson)

Humpback whales are found globally in all oceans and all populations are considered to be a single species (Johnson and Wolman 1984), though it has been suggested that they be split into three subspecies, North Pacific, North Atlantic and Southern Hemisphere, based on genetic analysis (Jackson et al. 2014). The whales grow to a length of approximately 16 m long and weigh an estimated 34 tonnes (Johnson and Wolman 1984). Like several other baleen species, these whales have a life history strategy of making long migrations between sub-polar and polar summer feeding grounds and tropical winter breeding grounds. Modelling of humpback whale hearing estimates that they have hearing sensitivity between 700 Hz and 10 kHz and have maximum sensitivity between 2-6 kHz (Houser et al. 2001). Research suggests that hearing is likely the most important sense used by baleen whales to orient themselves in their environment (Todd 1991).

1.3.1 Humpback whales in Iceland

The subpopulation of humpback whales in Iceland is part of the larger North Atlantic population, estimated to consist of approximately 18,000 individuals based on survey data (Smith and Pike 2009) or up to approximately 112,000 individuals based on gene diversity (Ruegg et al. 2013). It is estimated there are approximately 10,000 individuals in the central North Atlantic, primarily in Icelandic waters, during the summer feeding season spanning April through October (Pike et al. 2019). Humpback whales have been sighted all around Iceland during the summer months, though the majority of the of the animals counted in surveys were concentrated in the north/northeast of the country. In addition, some humpback whales have also been found to spend the winter in Icelandic waters as well (Magnúsdóttir et al. 2014). Fish species are thought to make up an estimated 60% of the humpback whales' diet in Iceland (Sigurjónsson and Víkingsson 1997), with capelin (*Mallotus villosus*, Müller, 1776) being one of the primary prey species for North Atlantic humpback whales (Johnson and Wolman 1984).

1.3.2 Humpback whale entanglement studies

Humpback whale entanglement has been extensively studied and monitored on the east coast of the USA (Robbins and Mattila 2001; 2004, Robbins 2009; 2011; 2012; Cole et al. 2006, Johnson et al. 2005) and on the East Coast of Canada (Volgenau et al. 1995, Benjamins et al. 2012), as well as in Hawaii (Mazzuca et al. 1998), Alaska (Neilson et al. 2009), and Ecuador (Alva et al. 2012). In Iceland, there have been incidental reports from whale watching vessels of humpback whales observed with gear attached to the body, and there have been further reports of stranded humpback whales where the cause of death was determined to be entanglement-related (Víkingsson and Ólafsdóttir 2003, Víkingsson et al. 2004; 2005; Víkingsson 2011).

Entanglement can cause a wide array of impacts on the animals at both the individual and population levels (Read 2008). Due to the humpback whale's large size, entanglement often does not lead to immediate drowning, and can last for hours, days, or months. Humpback whales were only found to have died in 16% of reported entanglement cases in eastern Canada since most of the animals were either disentangled or freed themselves (Benjamins et al. 2012). Though the whale may not drown, an animal carrying gear often incurs laceration injuries which can lead to infection in some cases (Cassoff et al. 2011). An entanglement around the head and mouth region may impair the animal's ability to feed properly and can lead to starvation. If a whale is carrying very buoyant gear, this can also

lead to starvation if they are unable to dive to depths where preferred prey is located (van der Hoop et al. 2014). In addition, if a whale is carrying heavy gear or incurring a lot of drag, this can disrupt the animal's energy budget. This may particularly impact whether the whale is able to partake in its long-distance annual migration (Moore and van der Hoop 2012; van der Hoop et al. 2014). Furthermore, an entanglement event is known to lead to an increase in stress hormones, which has been linked to a compromised immune system and lower reproductive success in some cetacean species (Robbins and Mattila 2001; Rolland et al. 2017).

Whale entanglement is an issue that not only affects the animals involved, but also the fisheries. Large whale collisions with fishing gear can lead to extensive gear damage or gear-loss, which in-turn leads to downtime for repairs and loss of catch (Lien 1979). This all equals a financial burden to the fishing companies. In the Canadian western North Atlantic alone, reported gear loss due to whales has been estimated to cost hundreds of thousands of dollars per year and could be upwards of one million dollars, or 90 million Icelandic kronas (ISK), when including down-time losses¹ (Lien 1979; Lien and Aldrich 1982). In Iceland, the capelin purse seine industry in particular is known to sustain gear damage and downtime due to humpback whales in their gear (MH Rasmussen pers. comm. 2015).

Assessment of humpback whale entanglement can be conducted using systematic scar analysis to estimate the baseline percent of the population which has been entangled at least once and survived, and to estimate an entanglement rate per year for a population (Robbins and Mattila 2001; Robbins 2012). It has been determined that the tail-area is the most common part of the humpback whale's body involved in entanglement, with 53% of documented humpback whale entanglements in the eastern North Atlantic involving the tail (Robbins and Mattila 2004; Johnson et al. 2005), and therefore this area can be analyzed for entanglement-related scarring or injuries (Robbins and Mattila 2001).

A long-term humpback whale scar-analysis study has been carried out in the Gulf of Maine. There, it was determined that 48-65% of the humpback population has been entangled at least once, and the whales were most recently estimated as becoming entangled at a rate of 14-17% per year (Robbins and Mattila 2004; Robbins 2009; 2012). In addition, scar analysis was also carried out on the southeastern Alaskan humpback whale population, where it was determined a minimum of 54% had been entangled at least once, and the entanglement rate was 8% per year (Neilson et al. 2009). A preliminary humpback whale scar-analysis study was carried out by Basran (2014) and estimated that 42% of Icelandic humpback whales had been entangled at least once, suggesting this is a prevalent issue in the Icelandic subpopulation, just as it is in the other well-studied populations in the USA.

¹ converted into current krona/dollar estimates to account for inflation

1.3.3 Mitigating humpback whale entanglement

Fisheries closures and fishing gear restrictions

Fisheries management and legislation is sometimes implemented to protect cetaceans from anthropogenic threats such as entanglement. In cases where there is a serious threat to a population, such as the case of the North Atlantic right whale, dynamic or seasonal fishery

closures can be instated to avoid animals being entangled (Government of Canada, 2021); however, these measures have not been necessary specifically for the recovering humpback whale population globally. Restrictions or bans on certain fishing gears have also been put in place to reduce bycatch/entanglement. For example, drift gillnets, which pose a serious entanglement risk to both small and large whales such as the humpback, as well as other marine life, were banned by the United Nations (European Commission 1991).

Fishing gear modifications

Large whales, including the humpback, are known to be entangled in many different fishing gear types. In order to attempt to minimize both injuries to the whales and potentially expensive damage to gear, different modifications to fishing gear have been developed and tested. For hook and line gear, “weak hooks” have been designed to straighten under the force produced from hooking a dolphin or whale, but withstand the force of the target fish species (Hamilton and Baker 2019). These hooks were designed and tested for interactions between large dolphin species and longlines (McLellan et al. 2015) and have not been considered for large whales specifically, though could work in the same manner if an animal is incidentally hooked. For gillnet gear, a similar concept has been developed in the form of “weak links”. These links are required in Atlantic USA for attachment of buoys and weights and between panels of netting for gear left in the water for long periods of time, and are also designed to release under the force of a cetacean swimming into the net, but not under the force of target fish species (NOAA 2018). The separation of buoys, weights, or net panels may make it less likely for whales, such as the humpback, to become entangled and carry the gear away, though there has yet to be scientific studies supporting the idea (McLellan et al. 2015).

Many large whale entanglements are caused by ropes in the water column, and therefore reducing the amount of rope should reduce overall entanglements. The USA implemented the use of sinking ground lines in pot and trap fisheries which served to minimize the amount of rope in the water column that attaches the traps together (Leaper and Calderan 2018). Despite the sinking ground lines, pot and trap gear still poses a threat due to the vertical buoy lines used to mark the gear location and remove the gear from the water; therefore, development of ropeless pot and trap fishing gear has been underway (Myers et al. 2019). To eliminate the need for these ropes, “acoustic modem-based location systems”, which transmit the location and ID of the gear in real-time, can be used on traps/pots as the location marker. The gear can also be retrieved by acoustic release for which a signal, for example, releases a buoy and rope that was sunk with the trap/pot or activates an inflatable bag that will float the gear to the surface (Myers et al. 2019).

Rope strength also plays a role in whale entanglements. In the 1990s, ropes used for fishing gear became stronger, making it less likely that large whales could break them (Knowlton et al. 2015). Researchers suggest that, similar to the “weak link” concept, weaker rope could be re-introduced into fisheries to reduce entanglements. It was estimated using ropes with a strength of 7.6 kiloNewtons or less could reduce life-threatening large whale entanglements by 72% (Knowlton et al. 2015).

Acoustic alarms

Due to the negative impacts on both the whales and the fisheries, technology has been developed in attempt to mitigate whale entanglement and resulting fishing gear damage. One such technology is acoustic alarms. These devices are developed to emit a tone

underwater within the hearing range of target marine mammals (Erbe and McPherson 2012; Consortium for Wildlife Bycatch Reduction n.d.). A type of acoustic alarm, known as a “whale pinger” is a low-frequency version of a pinger which has been developed to attach to fishing gear and reduce humpback whale entanglement specifically. The devices serve to “illuminate” the gear with sound and warn the animals of its presence to encourage them to avoid it (Todd et al. 1991). Another theory is that the pingers may serve as an annoying, unnatural sound that the animals want to avoid (Kraus 1999). Since large whales in particular can often escape from or carry away entangling gear, it is further suggested that pingers can aid in the whales learning that nets pose a danger (Jefferson and Curry 1996). These whale pingers are already in use for some applications. For example, in Australia, pingers are being used on shark protection nets around beaches during the humpback whale migration seasons (Erbe and McPherson 2012). However, it has been difficult to determine if pingers are effective for mitigating humpback whale entanglements since whale-gear interactions and entanglements are rarely witnessed and behavioural observations need to be made. Further complicating the results of whale behavioural response to sound experiments, it has recently been reported that the initial behavioural state of large whales influences the animal’s response to noise exposure (Southall et al. 2019). During early testing of pinger prototypes, it was found that humpback whales did respond to an active alarm (Todd et al. 1992). In addition, Dunlop et al. (2013) observed that exposing humpback whales to tone-stimuli within their hearing range caused groups of whales to move away from the vessel producing the sound and offshore, an indicator of avoidance behaviour. However, Harcourt et al. (2014) found that there was no detectable response from migrating humpback whales to an active whale pinger alarm, and similarly, How et al. (2015) found that there was no statistical difference between whale swimming behaviour observed during active pinger trials and non-active pinger trials. Most recently, Pirotta et al. (2016) also concluded there was no response to acoustic alarms in terms of swimming direction, dive duration, or speed of migrating humpback whales. Despite this, there are anecdotal reports of commercially available whale pingers lowering the incidence of humpback whale entanglement in the whales’ Alaskan feeding grounds (Alaska Journal of Commerce June 14th 2012; Laine Welch - Anchorage Daily News May 31st 2016). Thus far, little scientific testing has been conducted on behavioural response of whales in their feeding grounds to whale pinger sounds, opposed to when they are migrating.

In addition to low-frequency whale pinger acoustic alarms, other acoustic deterrent devices (ADDs) have also been developed. Primarily used in the aquaculture industry to ward off seals, these devices produce a loud, high-frequency sound designed to scare away the animals (McGarry et al. 2017). Though not designed specifically within the estimated hearing range of baleen whales, it has been suggested that they will react to the loud sound produced by such a device. Therefore, these ADDs could be used in fishing or other marine industry applications, such as to ward-off animals before pile-driving during offshore wind farm construction (McGarry et al. 2017). To date, these loud, high frequency ADDs developed for the aquaculture industry have not been tested on humpback whales; however, some high frequency pinger sounds were tested on one humpback whale and results indicated the whale did not react (Henderson et al. 2016). The only published testing of an ADD device on any balaenopterid species was on the common minke whale in Iceland, where it was determined they do show avoidance behaviour in response to an active device (McGarry et al. 2017).

1.4 Using questionnaires to gather local knowledge from fishers

Questionnaires can be a low-cost research method used to collect data from a wide-ranging group of participants that fall under the scope of the study (Gangrade 1982). Structured questionnaires provide a simple and straight-forward way to obtain facts and expert knowledge directly from those in the desired field of expertise. Given that questionnaires are standardized, and it is easy to ensure anonymity of the respondents, they may be more appropriate to use for data collection on sensitive or controversial topics than other methods, such as interviews, since respondents may be more willing to answer honestly (Gangrade 1982). The anonymity of questionnaires, however, does come with certain drawbacks. Great care needs to be used when designing the questionnaire to ensure that the questions are clear to all respondents, since there is no way to clear up misunderstandings as they arise (Doğan 2016). Additionally, there is no way to verify the responses, meaning they have to be accepted as is and considered trustworthy in order to analyze results and draw conclusions. Despite some disadvantages, the use of questionnaires is wide-spread in the social sciences and is also sometimes used to gather or supplement biology research data.

It has been suggested that questionnaires collecting eye-witness entanglement accounts can provide further information, including important, rarely-witnessed details related to entanglement events (Knowlton et al. 2005; Johnson et al. 2005), as well as providing expert knowledge and perception on the issues this creates for fishers (Peterson and Carothers 2013). Questionnaires have been previously used to gather information about seal-fisheries interactions in Greece and Cornwall (Glain et al. 2001), whale depredation on fisheries in Alaska (Peterson and Carothers 2013), gear damage caused by whales and sharks in Newfoundland and Labrador, Canada (Lien and Aldrich 1981), and bycatch of cetacean species including bottlenose dolphins (*Tursiops truncatus* Montagu, 1821) (Zappes et al. 2016), Irrawaddy dolphins (*Orcaella brevirostris* Gray, 1866) (Whitty 2014) and gray whales (Baird et al. 2002). In Iceland, a marine mammal bycatch questionnaire and follow-up phone interview study was conducted in 2004 and used to estimate bycatch of harbour porpoises and reveal the issue of underreporting of bycatch in Icelandic gill net fisheries (Ólafsdóttir 2010), further highlighting the usefulness of this approach for gathering cetacean data.

2 Objectives

Cetaceans face a wide array of anthropogenic pressures and threats as marine industrial development expands and evolves. An understanding of these threats and the impacts they have is essential to properly managing industries and conserving cetacean populations. The overall objective of this thesis was to investigate the anthropogenic threat of cetacean bycatch/entanglement in fishing gear, with a particular focus on Iceland and humpback whales. This can be further broken-down by the individual objectives of each chapter as follows. The first objective of this study was to provide an overview of conflicts between cetaceans in the Arctic and major industries and highlight some of the main issues in an accessible way by publishing a chapter on this topic in a textbook (**Paper I**). The rest of this thesis focuses specifically on the major threat of cetacean bycatch and entanglement in fishing gear. First, by examining this issue on a global scale by focusing on countries which have cetacean bycatch reporting legislation and using fisher logbook and observer program data from case study countries (USA, New Zealand, and Iceland) to produce quantified under-reporting baseline estimates for different fishing gear types and species for the first time (**Paper II**). This thesis then focuses further in on an understudied entanglement issue in Icelandic fisheries: entanglement of the humpback whale. Given the lack of research on this subject, the further objectives of this thesis were to assess Icelandic humpback whale entanglement and test a possible mitigation measure by 1) calculating the overall entanglement estimate and entanglement rate per year for the Icelandic population using scar-analysis (**Paper III**), 2) testing individual animals' behavioural responses to two acoustic alarms that could be used for entanglement mitigation, and further testing one of the alarms in the Icelandic capelin purse seine industry (**Paper IV**), and 3) examining the issue of whale entanglement in Iceland from the fishers' perspective by conducting anonymous questionnaires and semi-directed interviews (**Paper V**). This work expands the understanding of entanglement in the Icelandic humpback whale population and issues within Icelandic fisheries specifically, which can be compared with other areas globally. Furthermore, this work provides better insight into the use of acoustic alarms for humpback whale entanglement mitigation which is applicable not only to Iceland but other areas where humpback whale feeding grounds and commercial fishing overlaps.

The aim of **Paper I** was to provide a literature review of the conflicts between industries and cetaceans in the Arctic in the form of a marine sustainability textbook chapter. This chapter focused on six exemplary species (harbour porpoise, white-beaked dolphin, orca, sperm whale, blue whale, and humpback whale) and reviewed the conflicts and issues these species face due to major Arctic industries: shipping leading to ship strikes, oil exploration leading to hearing damage and behavioural disturbance, and commercial fishing leading to entanglement in fishing gear. The chapter further touches on issues these cetaceans face due to ship noise, whale watching, and offshore wind development, as well as the conflicts caused by whale depredation (whales targeting fishing as a food source) in some fishing industries. Issues were examined in a unique way by examining them from the perspectives of both impacts to whale conservation and impacts to the industries.

Author contributions. Wrote the paper: CJB, MHR

The aim of **Paper II** was to examine and quantify the global issue of cetacean bycatch/entanglement under-reporting in fisher logbooks by calculating catch per unit effort for different gear types and species from fisher logbook data and statistically comparing this to observer data from case study countries (New Zealand, Iceland, USA). This provides the first cetacean under-reporting baseline data for different gear types in each country as a whole, which can be used to verify if management changes can improve reporting. A further aim of this paper was to discuss the pros and cons of cetacean bycatch reporting in logbooks versus the use of observer programs and make suggestions on how to improve logbook reporting to accurately estimate cetacean bycatch world-wide.

Author contributions. Analyzed data: CJB; Wrote the paper: CJB, GMS

Paper III aimed to calculate the first estimate of humpback whale entanglement in the Icelandic subpopulation and the first estimates of entanglement rate per year using the scar-based analysis technique and 13 years of photographic data. This is the first such assessment conducted in Europe, and it provides the necessary baseline information to compare the entanglement issue in Iceland with other countries and to continue monitoring this issue over time to inform best management practices. In addition, this contributes to the knowledge of what pressures this highly migratory species faces across their different habitats.

Author contributions. Provided data: CJB, MHR, MW; Analyzed data: CJB, JR; Wrote the paper: CJB, CGB, AC, JR

The aim of **Paper IV** was to conduct the first analysis of humpback whale behavioural response to two acoustic alarms (the Future Oceans whale pinger and the Lofitech seal scarer) in Icelandic feeding grounds. An additional aim was to use the whale pinger alarms in a practical trial on a capelin purse seine net for the duration of a fishing season. These were the first behavioural response experiments conducted using pingers in a whale feeding ground and the first to consider feeding behaviour as a response variable. The results from these experiments can be used to determine if acoustic alarms are a useful and practical mitigation tool when it comes to humpback whale entanglement and resulting gear damage in Icelandic fisheries, as well as in fisheries located in other whale feeding grounds. In addition, the trial of the pingers on a capelin purse seine net provided new insight into the currently unknown directional hearing capabilities of humpback whales.

Author contributions. Collected data: CJB, CN, MHR; Calculated and/or analyzed data: BW, CN, CJB; Wrote the paper: CJB, MHR, BW

Finally, the aim of **Paper V** was to collect first-hand information from Icelandic fishers about large whale sightings, entanglements and encirclements in their fishing gear, gear damage caused by whales, and reporting of these incidences, by distributing an anonymous questionnaire to individual fishers and fishing companies around Iceland. In addition, semi-directed interviews were conducted with the aim to gather more in-depth detail about humpback whale entanglement and resulting gear damage in the capelin purse seine fishery. Witnessing an entanglement is a rare event for which fishers are the most likely people to have details that cannot be collected from other scientific methods of studying whale entanglement. This was the first study in Iceland compiling fisher knowledge on large whale entanglements.

Author contributions. Collected data: CJB, MHR; Analyzed data: CJB; Wrote the paper: CJB

3 Materials and Methods

3.1 Cetacean bycatch and entanglement under-reporting case studies

3.1.1 Data collection

For **Paper II**, the search for countries which have cetacean bycatch/entanglement reporting laws was based on the top 30 countries with the largest fishing industries (FAO 2018). Researching the laws consisted of gathering information from government websites and, in some cases, email contact to government and research agencies for clarification. Fisheries legislation from each country was searched for the keywords “mammal”, “bycatch”, “reporting” and “log”. The list of countries with such legislation is publicly available at www.heimahafro.is/~gudjon/marinemammallegislation and will be updated as more information becomes available and as laws change. The governing bodies of all the countries with reporting legislation were contacted through email to enquire about data sharing. Fisher-reported cetacean bycatch logs (including year, species, number of animals, and fishing gear category) were provided directly from Fisheries New Zealand, National Oceanic and Atmospheric Administration (USA), Fiskistofa and Hafrannsóknastofnun (Iceland), and Fiskeridirektoratet (Norway). Fishing effort data per year was provided by Fisheries New Zealand, Fiskistofa and Hafrannsóknastofnun (Iceland), and Havforskningsinstituttet (Norway). For the USA, effort data was provided by Pacific Fisheries Information Network, Western Pacific Fisheries Information Network, Alaska Fisheries Information Network, Gulf States Marine Fisheries Commission, and Atlantic States Marine Fisheries Commission, which included data for each state and territory (including Puerto Rico and the US Virgin Islands), except for Alabama, where permission was not granted to release this data. For comparison, observer reported cetacean bycatch/entanglement data was also provided by Fisheries New Zealand and Hafrannsóknastofnun (The Marine Research Institute Iceland). Observer data for the USA was collected through the National Bycatch Report Database System ([https://www.st.nmfs.noaa.gov/apex/f?p=243:101:4398085890586:::~:::](https://www.st.nmfs.noaa.gov/apex/f?p=243:101:4398085890586:::)). Norwegian “reference fleet” data, which is used to estimate cetacean bycatch in Norwegian waters, was not available for comparison for this study. All data was requested from the years 2009-2019, but not all datasets covered all requested years.

3.1.2 Catch per unit effort calculations and comparisons

Fisher-reported cetacean bycatch/entanglements (“catch”) per unit effort (CPUE) per fishing gear type was calculated based on kgs of catch (New Zealand, USA, Norway), number of trips (Iceland lump sucker gillnets), and number of net-nights (number of nets x soak time) (Iceland cod and other gillnets). CPUE was also calculated for individual species per gear type when data were sufficient. All fisher logbook CPUEs were calculated using all reports where gear type was specified, regardless of the reported life-status of the animal. To compare the two methods of quantifying bycatch (logbook vs. observer), pairwise t-tests or Wilcoxon tests were conducted to examine differences between fisher logbook CPUE and observer CPUE for each gear category and species, where data were

sufficient, for New Zealand and Iceland. Since the USA observer bycatch/entanglement estimates were available in the form of estimated average number of individuals caught per year, based on 5-year time blocks, this data was compared to the average number of cetaceans caught per year in the fisher logbook data, based on the same 5-year time blocks, also using pairwise t-tests or Wilcoxon tests. T-tests were used to compare “early time period” vs. “late time period” CPUE for each gear category in order to investigate logbook reporting over time in each of the case study countries where data were sufficient. All tests were performed using a set alpha of 0.05 in the statistical software R (The R Foundation for Statistical Computing, version 3.6.1).

3.2 Fieldwork study sites

Fieldwork and data collection for **Paper III** took place in three sites, in northeast (Skjálfandi Bay and Eyjafjörður) and southwest (Faxaflói Bay) Iceland (Figure 2). Fieldwork for **Paper IV** took place in the two northeastern sites (Skjálfandi Bay and Eyjafjörður) and additionally a trial was conducted in the capelin fishing grounds in the south/southwest. Data collection for **Paper V** involved collecting questionnaires from fishers/fishing companies based all around Iceland.

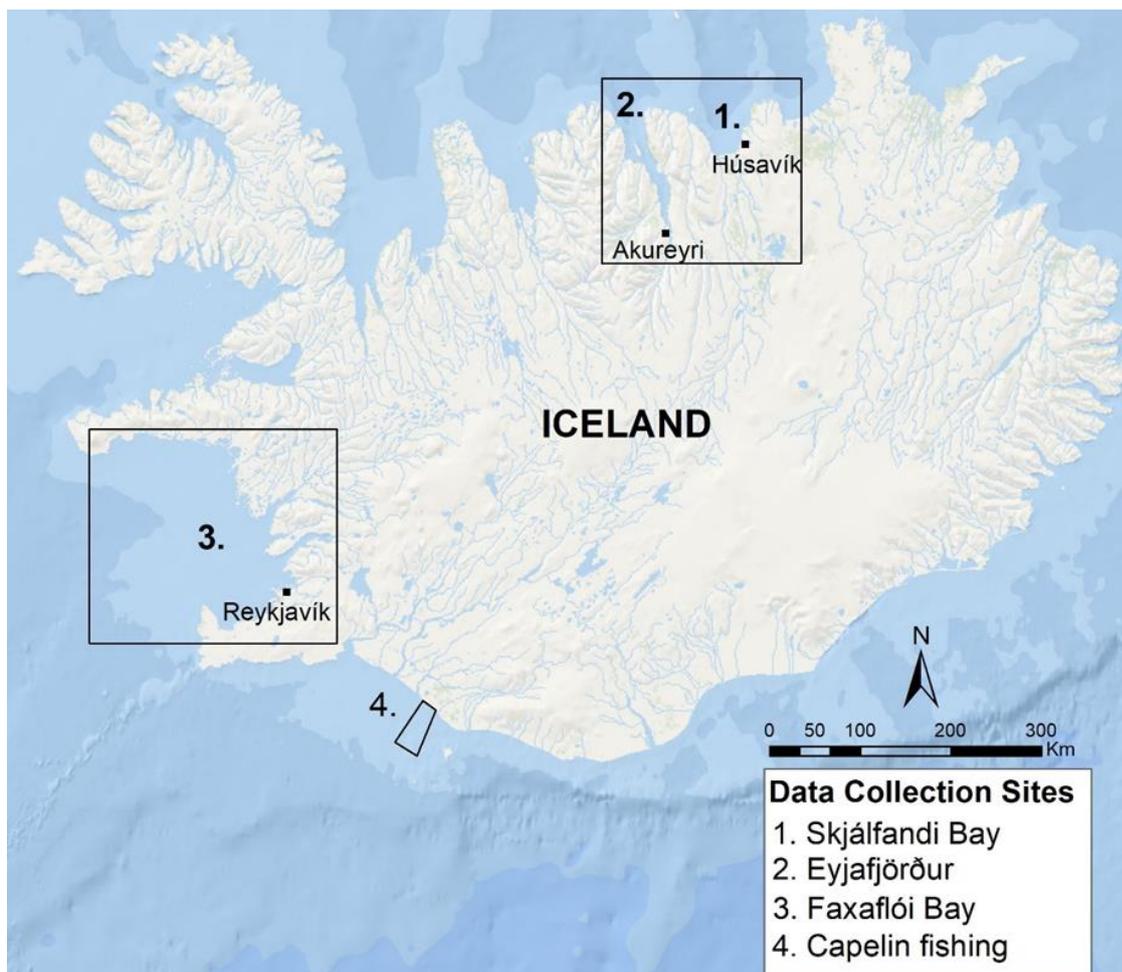


Figure 2 Map of Iceland showing the data collection sites for this study

3.2.1 Skjálfandi Bay

Skjálfandi Bay (66°05'N17° 33'W) is a 10-50 x 25 km bay, located on the northeast coast of Iceland. (A. Gíslason unpub. data). The highly productive bay is fed by two rivers at the south end and the deepest point is 220 m. It is a well know feeding ground for humpback whales, as well as other cetacean species, primarily hypothesized to be feeding on euphausiids spp. and capelin (Pike et al. 2019; Víkingsson et al. 2015). The bay harbours the fishing and whale-watching village of Húsavík situated on its southeast shore (Einarsson 2009).

3.2.2 Eyjafjörður

Eyjafjörður (65°50'N18° 07'W) is a 5-15 x 60 km narrow fjord also located on the northeast coast of Iceland (S. Jónsson unpub. data). This fjord, fed by 4 main rivers, has a deepest point of approximately 200 m and similarly to Skjálfandi Bay it is highly productive and a well-know feeding ground for humpback whales during the summer months (Pike et al. 2019; S. Jónsson unpub. data). The fjord harbours the second-largest Icelandic city, Akureyri, at the southern end and the fishing and whale watching villages of Dalvík and Hjalteyri along the western shore.

3.2.3 Faxaflói Bay

Faxaflói Bay (64° 24'N23°00'W) is a 50 x 90 km (approximately 4,500 km²) bay in southwest Iceland (Stefánsson et al. 1987). This large bay is rather shallow, with the deepest point being approximately 139 m. Humpback whale sightings have decreased in this area over recent years likely due to decreased sandeel (*Ammodytes sp.*) and euphausiid spp. populations and a northward and westward shift of capelin (Víkingsson et al. 2015). However, some humpback whales are still seen in the bay each year and documentation of humpback whales in this area has shown that many of the whales seen there are not documented in the northeastern sites (pers. obs.). Therefore, sightings from Faxaflói Bay, though less, increase the data on the Icelandic humpback whale population as a whole. On the southwest coast of the bay is Iceland's capital city Reykjavík, hosting the largest and busiest fishing, shipping, and whale watching port in the country (Faxaflóahafnir 2018).

3.3 Humpback whale fluke identification

Papers III and **IV** both required that individual humpback whales were photo-identified and catalogued. Humpback whales are among the easiest species to recognize individuals due to the unique colouration pattern on the underneath side of the fluke and the fact that they often show this pattern when lifting the tail to go down for a terminal dive (Katona and Whitehead 1981) (Figure 3). For **Paper III**, DSLR cameras with 55-300, 70-300, and 100-400mm telephoto zoom lenses were used to take photographs of humpback whales from whale watching vessels operating in Skjálfandi Bay, Eyjafjörður and Faxaflói Bay. Each individual included in the scar analysis was identified using a fluke photograph from each year that it was included in the study. Individuals that only had dorsal fin pictures for identification were not included in the study since humpback whale dorsal fins are less reliable for long-term identification due to the likelihood of them changing over the years

(Katona and Whitehead 1981). DSLR cameras with telephoto zoom lenses were also used to take identification photos of each individual used in the acoustic alarm trials (**Paper IV**) to ensure that an individual was not used in a trial of the same device within the same year. Since only short-term identification was required for this, some individuals were identified by dorsal fin pictures only if they did not raise the fluke when diving.



Figure 3 Photograph of the unique pattern on the underneath side of the humpback whale's fluke used for identification (Photo: Charla Basran).

3.4 Entanglement scar analysis

3.4.1 Image quality

Images used for entanglement scar analysis (**Paper III**) needed to adhere to a standardized set of criteria developed by Robbins and Mattila (2001) which included quality selection based on angle, contrast (lighting) and clarity as discussed by Friday et al. (2000). Useable photographs had to be taken parallel to or slightly in front of the animal as it lifted its fluke to take a terminal dive and needed to show at least two out of six coding areas around the tailstock of the animal. The coding areas are left flank, dorsal peduncle, ventral peduncle, left leading edge and insertion point of the fluke, right flank and right leading edge and insertion point of the fluke (Figure 4). In order to minimize bias, photos were taken regardless of whether the animal appeared to have scarring or injuries. Photographs taken from the correct angle showing at least two coding areas then underwent quality assessment for lighting and clarity. Images had to have high enough resolution to be zoomed in without losing detail and were considered Q4 or higher based on the rating scale developed by Gowans and Whitehead (2001). Useable images were selected of 379 individuals spanning 13 years (2005-2017).

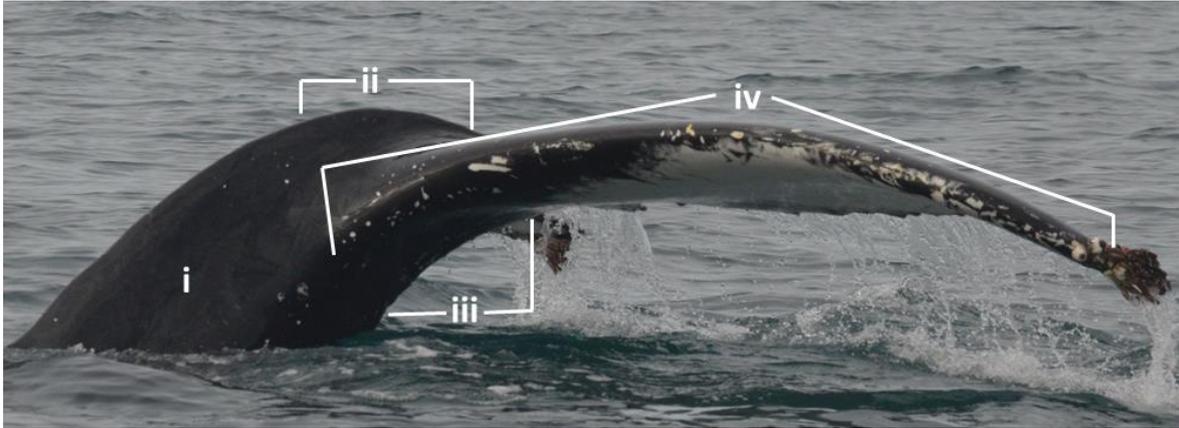


Figure 4 Image showing four of the six scar coding areas around the peduncle of the whale: i) left flank, ii) dorsal peduncle, iii) ventral peduncle, iv) left leading edge and insertion point of the fluke. Not shown: v) right flank, vi) right leading edge and insertion point of the fluke.

3.4.2 Peduncle scar analysis and entanglement estimate calculations

Each image of every individually identified humpback whale was assessed for wrapping scars, notches or unhealed injuries, indicative of a prior entanglement in fishing gear, in the coding areas of the peduncle region (Figure 5). Following Robbins and Mattila (2001; 2004), each coding area visible in an image was scored on a scale from S0 (no scarring) to S5 (extensive or deforming entanglement related injuries), and then each individual whale was given an overall likelihood of prior entanglement score based on all images of the individual as follows – HP: high probability of prior entanglement, if evidence was found in 2 or more coding areas; U: uncertain, if evidence was only found in one coding area; or LP: low probability of prior entanglement, if no clear evidence was found in any coding areas. Individuals were given an overall score per year, and their overall score the first year that they entered the study was used in the calculation of the scar-based frequency of prior entanglement estimate. The minimum estimate was calculated as HP divided by the total number of individuals, and the maximum was calculated as HP + U divided by the total number of individuals. The rate at which entanglement-related injuries were acquired per year was then calculated using two different metrics, one based on increased entanglement scarring on individuals seen in consecutive years and a second based on number of individuals with unhealed entanglement injuries documented per year. Firstly, individuals seen in consecutive years which were given an HP overall score in at least one year were compared across sightings (Figure 6). Changes in entanglement-related scarring for each consecutive year the animal was seen was scored as having increased scarring, equal scarring or decreased scarring compared to the previous year. From this, the inter-annual entanglement rate based on scar acquisition (E_s) was calculated as the percentage of individuals resighted that were assigned increased entanglement-related scarring out of the total usable individuals that year. This could be calculated for the years 2011 to 2017, and then the average percentage over these years was calculated as an estimate of the overall entanglement acquisition rate per year. Secondly, a yearly entanglement rate was calculated using the percentage of individuals with unhealed entanglement related injuries documented per year (E_u). Unhealed injuries were considered an indicator of a recent

entanglement, likely within the past year (Robbins 2011) (Figure 7). This percentage was calculated for each year between 2007 and 2017 and then averaged across the earlier time period (2007-2011) and the latter time period (2012-2017). Statistical comparisons using Wilcoxon rank sum tests between the calculated entanglement acquisition rates were performed.

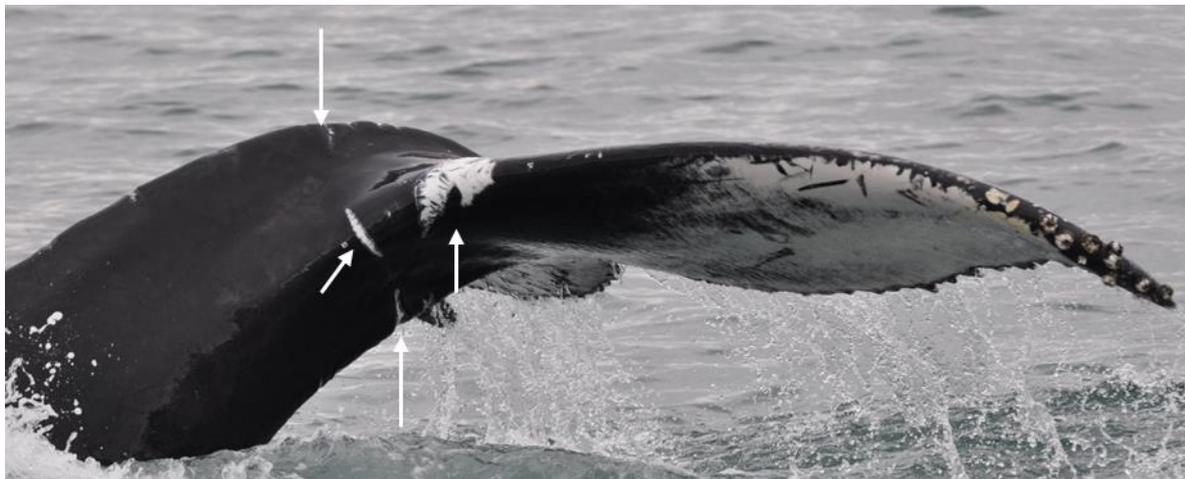


Figure 5 Image showing notches and wrapping scars (indicated by arrows) indicative of a prior entanglement.



Figure 6 Image showing an individual whale with increased entanglement scarring (indicated by ellipses) between sightings in consecutive years.



Figure 7 Image showing unhealed entanglement injuries (indicated by arrows) indicating the whale had likely been entangled within the last year.

3.5 Acoustic alarm trials

3.5.1 Acoustic alarms

Two acoustic alarms were used in humpback whale experimental exposure trials (**Paper IV**): the 2016 version of the Future Oceans “whale pinger” and the Lofitech AS ltd. “seal scarer” (Figure 8). When active, the whale pinger alarm produces a 145 decibel re 1 μ Pa tone at 3kHz for 300 ms at 5 sec intervals (Future Oceans). The Lofitech AS ltd. seal scarer ADD produces a 191 decibel re 1 μ Pa sound between 10-20 kHz for 500 ms at random intervals of 5-60 sec. A calibration of both acoustic alarms using a Reason 4032 hydrophone and an Etec amplifier was conducted in the Húsavík harbour to confirm the manufacturers specifications. The emitted sound from the whale pinger had an actual source level of 137 dB re 1 μ Pa (rms) recorded at a distance of 1 m. Based on previous studies where modelling of the pinger sound was compared to modelling of humpback whale hearing, humpback whales should detect the pinger sound at a distance of at least 500 m from the source (Pirotta et al. 2016; Harcourt et al. 2014). The seal scarer had an actual source level of 189-198 dB re 1 μ Pa (rms).



Figure 8 Future Oceans whale pinger acoustic alarm (left) and Lofitech seal scarer acoustic deterrent device (right).

3.5.2 Individual experimental exposure trials

Individual experimental exposure trials were conducted, designed to determine if humpback whales responded to the sound of either acoustic device, in Skjálfandi Bay and Eyjafjörður in 2017 and 2018. Onboard the boat during a trial, a computer running the Logger 2010 program (IFAW) tracked the boat’s GPS position and heading and the time. In addition, all data entered by the recorded was saved in Logger 2010 with a GPS and time stamp. Each trial was also video recorded using a Sony HDR-CX160E handycam

hand-held video camera. During a trial, an individual focal humpback whale was chosen, and photo-identification images of the individual were taken as described in section 3.2. When the whale was identified, the pre-exposure phase (PrE) began with the boat following the focal whale from a distance of approximately 100 m for 30 mins to obtain a baseline of behaviour of the individual. The 100 m distance complies with whale watching criteria set forth in many countries around the world to minimize disturbance to the animal (Carlson 2009) while still being within range to collect all necessary data. Each breath the whale took was recorded as “up” and each terminal dive was recorded as “dive” in Logger 2010. Furthermore, one researcher used an angle-board and rangefinder to obtain the angle to the whale in relation to the boat and the distance to the whale, and this data was also recorded into Logger 2010. Once the PrE phase was complete, the boat was positioned beside where the focal whale was seen taking its last terminal dive and the engine was turned off. To begin the 15 min exposure phase (E), the whale pinger or the seal scarer was placed off the side of the boat into the water at 5 m depth, attached to a rope and buoy similar to Harcourt et al (2014). The breaths, dives, angles, and distances of the focal whale were then recorded in Logger 2010 in the same manner as in PrE phase. After the 15 min E phase ended, the alarm was removed from the water and the boat was positioned approximately 100 m from the focal whale to follow it and record the same data for an additional 30 mins for the post-exposure phase (PoE).

Behavioural response variable calculation and analysis

Five response variables were used to analyze the behavioural reaction of the individual humpback whales to the acoustic alarms: surface feeding, swimming speed, breathing rate, dive time and directness index. The number of surface feeding events observed in each phase of each behavioural trial was determined from the video recordings. For each time the whale surfaced, surface feeding behaviour was categorized as yes (Y), no (N), or not able to determine (NA). Surface feeding behaviour was recognized by observing surface lunging behaviour or expanded throat pleats indicating the whale had a full mouth (Figure 9). The data recorded in Logger 2010 allowed us to calculate swimming speed, breathing rate (breaths per minute) and dive time (seconds) of each individual in each phase of each trial. In addition, I calculated the directness index, which is a scale from 0-100 indicating how linear the animal’s swimming pattern was (Williams et al. 2002). A result of 0 indicated swimming in a complete circle and a result of 100 indicated swimming in a straight line.

Linear mixed effects models were used to analyze the whales’ overall response to exposure to both acoustic alarms in terms of swimming speed, breathing rate, directness and dive time. Separate models were set up for each acoustic alarm and each response variable. The phase of the trial (PrE, E, PoE) was the fixed effect predictor variable and trial-ID was included as the random intercept. Auto-regressive correlation structures of order 1 were specified in the models for $\ln(\text{speed})$, $\ln(\text{breathing rate})$ and dive time to account for autocorrelation.

Since previous studies suggest that an animal’s individual response to sound can depend on behavioural state (Southall et al. 2019), individual-specific response variation was incorporated into the models by adding random slopes for the predictor phase for all response variables. Likelihood ratio tests were used to select the optimal fixed effects structure and determine if the random intercept and slope models fitted the data better than pure random intercept models. For models in which it was determined that phase of the

trial had a significant effect, a post hoc pairwise comparison with Bonferroni correction was used to infer between which phases significant changes in the response variable occurred.

Surface feeding behaviour was modelled with a binary generalized linear mixed effects model. The feeding behaviour at the previous surfacing event (*lag1_feeding*) was included as a fixed effect to account for temporal autocorrelation. Surface feeding behaviour was only analyzed for whale pinger trials, because very little surface feeding was observed in seal scarer trials.



Figure 9 Photos showing lunge feeding behaviour (left) and expanded throat pleats (right) which were used to determine feeding behaviour from the video recording of the humpback whale experimental exposure trials.

3.5.3 Capelin purse seine trial

In addition to the individual experimental exposure trials, I collaborated with the capelin fishing industry to try the Future Oceans whale pingers in a practical application fitted on the purse seine net of a capelin purse seine vessel (Börkur NK122) operating out of Neskaupstaður in east Iceland during the 2018 season (January-March). Ten pingers were attached to the float line of the purse-seine net at a distance of 30-40m from each other, complying with the manufacturer's recommendations (Figure 10). The captain of the vessel kept record of any issues they encountered with the use of the pingers, and any incidences of whales inside the net. In addition, one researcher (C.J.B.) joined as an onboard observer for one trip (February 24-28, 2018). During onboard observations, the track of the vessel and whale sightings were recorded in the SpotterPro app (Conserve.IO) during all transit and active fishing days. If whales were encircled in the net, the event was video recorded for documentation using a hand-held video camera (Sony HDR-CX160E handycam).

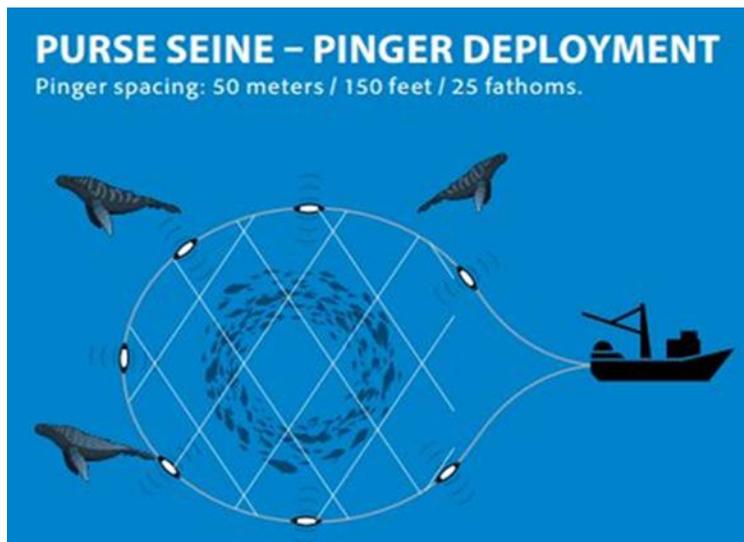


Figure 10 Schematic of the whale pinger attachment to a capelin purse seine net (©Future Oceans).

3.6 Fisher questionnaires and interviews

In order to collect more detailed information about cetacean sightings and whale entanglements in, or interactions with, fishing gear in Iceland and the issues this causes for fishers, an anonymous questionnaire was distributed to fishers and fishing companies all around Iceland (**Paper V**). The questionnaire was translated from English and distributed in Icelandic through personal contact, email, post and an online survey link (Appendix 1). The questionnaire was designed to gather answers from any fisher, not just those that had whales interact with or become entangled in their gear. Experience of the fishers and job onboard was not considered. A list of companies with active fishing vessels was compiled using Marine Traffic and Skipaskrá (the Icelandic ship list) and questionnaires were sent to companies operating all types of vessels in all parts of the country. Contact about the questionnaire was attempted with all companies identified as operating two or more vessels ($n = 25$) and 15 single-boat companies for which contact information could be found either through contacting the company office or making contact directly with fishers working for the companies. In addition, in-person contact requesting participation in the questionnaire was made with seasonal fishers and an online link to the survey was available, both of which did not provide information about which companies the participants worked for. Through the mail, 158 questionnaires with a pre-paid and pre-addressed envelope were sent to 24 companies. The number of blank surveys sent to a company corresponded with the number of active fishing vessels the company had (2 per vessel). The companies to which the questionnaires were mailed included those which did not respond to the initial email contact within one year. Phone contact was attempted with companies which did not answer through email or post, in order to assess if they would be willing to answer the questionnaire if it was sent to them again.

The questionnaire used Likert-type scales for frequency, yes-no, multiple choice and open-ended questions to ask the respondent about cetacean sightings and entanglements in general and specifically about humpback whales. For humpback whales specifically, the

questionnaire asked the respondent to provide details of entanglement incidences such as date, location, gear type, target fish species and damage sustained to their gear. Finally, the questionnaire inquired about what reason (if any) a fisher would not report an incident of a whale entangled in their gear. The data collected from the questionnaires were compiled and visualized for the results. Statistical comparisons between answers were conducted using Wilcoxon Rank Sum tests in the statistical software R (version 3.6.1).

In addition to the questionnaire, I conducted semi-directed interviews with five capelin purse seine vessel captains, four who were current captains and one who was retired. These interviews served in gathering more in-depth information about issues with humpback whales interacting with capelin purse seines in Iceland, since most reports of humpback whale entanglements in Iceland come from the capelin fishery. The five captains were chosen based on the criteria that they had prior incidences with humpback whales in their nets and they were willing to be interviewed in-person or over the phone with the conversation being audio recorded. Three interviews were conducted in English and two in Icelandic. The interviews were later transcribed, and the responses were compiled.

4 Results and Discussion

4.1 Paper II: Bycatch and entanglement under-reporting case studies

For **Paper II**, I initially compiled the first comprehensive list and description of countries which have cetacean bycatch/entanglement reporting legislation. The laws differed between the countries and ranged from very minimal (e.g., only harbour porpoises seemingly covered by law in Sweden and Finland) to well established (e.g., clear legislation and logbook reporting including all species in the USA and New Zealand). I then compared cetacean bycatch/entanglement recorded in fisher logbooks to estimates calculated from observer data for several fishing gear types and species in New Zealand, Iceland and the USA in order to quantify under-reporting in these case study countries. Due to the difficult nature of accessing and/or compiling datasets for countries as a whole, under-reporting of cetacean bycatch/entanglement has not been investigated in this manner previously. In addition, I calculated the cetacean CPUE two gear types in Norway for vessels greater than 15 m (those covered under the reporting legislation) for the first time.

When combining the case study data, reported cetacean bycatch/entanglements in observer data were on average 774% higher than fisher reported bycatch in trawls, 7348% higher in nets and 1725% higher in hook and lines, clearly demonstrating the issue of under-reporting in fisher logbooks, despite this reporting being mandatory by law (See **Paper II**, Table 1).

In New Zealand, nine cetacean species were reported in fisher logbooks between 2009-2019 in six different gear types (trawl, passive netting, lining, other lining, potting, and seine). There were seven cetacean species reported in the observer data, six of which were also reported in the fisher data and one of which was not (see **Paper II**, Table 2). The observer data only consistently covered trawls (25.9-56.1% coverage per year), passive netting (0-10.2% coverage per year), and lining (1.8-11% coverage per year), and therefore these gear types could be analyzed. Fisher logbook CPUE for trawl gear was significantly lower than observer CPUE for all years combined ($p = 0.028$, $t = -2.16$) (see **Paper II**, Table 3), and for the early time period (2009-2014) ($p = 0.004$, $t = -4.16$); however, not for the late time period (2015-2019) ($p = 0.68$, $t = -4.16$). There was no significant difference between early and late time period fisher logbook CPUEs ($p = 0.65$, $W = 18$) (see **Paper II**, Table 4). Comparison of the CPUEs for passive netting yielded similar results, with fisher logbook CPUE being significantly lower than observer CPUE for all years combined (2009-2019, excluding 2011 when there was no observer coverage) ($p = 0.0071$, $t = -3.03$), fisher logbook CPUE being significantly lower than observer CPUE in the earlier time period (2009-2014, excluding 2011) ($p = 0.003$, $t = -5.34$), and there being no significant difference between the CPUEs in the later time period (2015-2019) ($p = 0.22$, $t = -0.86$). There was again no significant difference when comparing fisher logbook CPUEs from the early and late time periods ($p = 0.72$, $t = -0.38$). The CPUEs for lining were not significantly different for all years combined (2009-2019, excluding 2010 and 2013 when

there was no observer coverage) ($p = 0.43$, $V = 15$). It was not possible to compare the CPUEs for the early time period due to little observer data; however, fisher logbook CPUE was significantly lower than observer CPUE for the late time period (2015-2019) ($p = 0.021$, $t = -2.95$). It was also possible to compare the CPUEs for three species of dolphin: common dolphins (*Delphinus delphis*, Linnaeus, 1758) in trawl gear, Hector's dolphins (*Cephalorhynchus hectori*, Van Bénédén, 1881) in passive netting gear, and dusky dolphins (*Lagenorhynchus obscurus*, Gray, 1828) in passive netting gear. The fisher logbook CPUEs were significantly lower than the observer CPUEs for common dolphins in trawls and Hector's dolphins in passive netting ($p = 0.011$, $t = -2.70$; $p = 0.018$, $t = -2.46$ respectively), but were not significantly lower for dusky dolphins ($p = 0.28$, $V = 10$).

In Iceland, there were eight cetacean species reported as bycatch in Icelandic fisher logbooks in the years where reporting could be considered complete (2014-2019) in three different gear types (trawl, passive netting, and lining). There were only two cetacean species reported in the observer data (harbour porpoise and white-beaked dolphin) (See **Paper II**, Table 2). Cetacean bycatch/entanglement was only observed by inspectors in two gillnet categories: lumpfish gillnetting (0.74-2.82% coverage per year, 2014-2019), and cod and other (cod+) gillnetting (0.15-0.25% coverage per year, 2016-2019). The fisher logbook CPUE for the lumpfish gillnet fishery was significantly lower than the inspector reported CPUE for all years combined (2014-2019) ($p = 0.003$, $t = -4.67$), as well as for the early time period (2014-2016) ($p = 0.006$, $t = -9.27$), but not the later time period (2017-2019) ($p = 0.10$, $t = -1.94$). There was no significant difference between the fisher logbook CPUEs in the early time period versus the late time period ($p = 0.14$, $t = -2.17$) (See **Paper II**, Table 4). The fisher logbook CPUE was also significantly lower than the inspector reported CPUE for the cod+ gillnet fishery for all years combined (2016-2019) ($p = 0.001$, $t = -9.29$) (See **Paper II**, Table 3). There were not enough years of data to compare an early and late time period of the fisher and observer CPUEs or to compare the fisher CPUE over time.

In Norway, there were six cetacean species reported by Norwegian fishing vessels 15 m or greater (15m+) between 2011-2019 in five gear types (Danish seine, purse seine, trawl, trap, and gillnet). There were only two species reported as bycatch by the 15m+ reference fleet (harbour porpoise and minke whale) in two gear types: hook and line and gillnet (See **Paper II**, Table 2). There was no available data on the effort of the 15m+ reference fleet, therefore it was not possible to statistically compare the fisher logbook CPUEs to the reference fleet CPUEs for these gear categories. However, it could be noted that there was cetacean bycatch reported in the fisher logbook data in the seine, trawl, and trap gear categories that were not detected by the reference fleet, though the fleet is covering these gear categories (Norway Marine Research Institute, pers. comm.). Fisher logbook CPUEs for gillnet and trawl gear did not significantly differ between the early (2011-2015) and late (2016-2019) time periods ($p = 0.08$, $W = 3$; $p = 0.90$, $W = 9$ respectively) (See **Paper II**, Table 4).

In the USA, there were 21 different cetacean species reported as bycatch/serious injuries in fisher logbooks between 2009-2017 in four broad gear categories (trawl, pot and trap, hook and line, and net). There were also 21 species reported as bycatch between 2009-2017 in observer data reported in the NOAA Marine Mammal Stock Assessment Reports (<https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-stock-assessment-reports-species-stock>). However, in the fisher logbook data, pilot whales were not split into the two known species (*Globicephala melas*, Traill, 1809 and

Globicephala macrorhynchus, Gray, 1846) so these species were also combined in the observer data (taking the total down to 20) (See **Paper II**, Table 2). In order to compare the logbook data to the observer data in these reports, mean annual number of individuals reported were calculated for five five-year time blocks (2009-2013, 2010-2014, 2011-2015, 2012-2016 and 2013-2017). The mean number of cetaceans reported as bycatch annually in the fisher logbook data was significantly lower than the observer estimates for the net, trawl and hook and line gear categories ($p = 0.009$, $t = -3.9$; $p = 0.006$, $t = -4.4$; $p = 0.005$, $t = -4.6$ respectively) (See **Paper II**, Table 3). Comparisons were also made for individual species reported in five or more years in the fisher logbook data. In the net category, harbour porpoise, common dolphin, and bottlenose dolphin mean annual number of individuals reported as bycatch/serious injury were significantly lower in the fisher logbook data when compared to the estimated annual means from the observer data ($p = 0.008$, $t = -4.9$; $p = 0.0004$; $t = -14.0$; $p = 0.04$, $t = -2.6$ respectively). There was no significant difference between the mean annual number of pilot whale spp. In fisher logbooks versus observer data ($p = 0.32$, $t = 1.17$). The mean annual number of humpback whales calculated from fisher logbook data was significantly greater than the mean annual number estimated from observer data ($p = 0.00002$, $t = 20.7$). In the trawl category, the mean annual numbers of individuals reported as bycatch/serious injury in the fisher logbook data were significantly lower than the estimated annual means from the observer data for all three species (Atlantic white-sided dolphin (*Lagenorhynchus acutus*, Gray, 1828): $p = 0.02$, $t = -2.9$; bottlenose dolphin: $p = 0.002$, $t = -16.4$; common dolphin: $p = 0.00007$, $t = -24.6$). In the hook and line category, the mean annual numbers of individuals reported as bycatch/serious injury in the fisher logbook data were significantly less than the estimated annual means from the observer data for both species (false killer whale (*Pseudorca crassidens*, Owen, 1846): $p = 0.009$, $t = -7.3$; pilot whale spp.: $p = 0.0002$, $t = -17.8$) (See **Paper II**, Table 5). There were no significant differences between fisher logbook CPUEs in the early time period (2009-2014) versus the late time period (2015-2019) for the net, trawl, or hook and line gear types ($p = 0.59$, $t = -0.55$; $p = 0.11$, $t = 1.93$; $p = 0.17$ $W = 7$ respectively) (See **Paper II**, Table 4).

The logbook data from fishers could be a very valuable tool for gaining insight into cetacean bycatch/entanglement in fishing gear; however, given the overall stark differences in reporting in logbooks versus estimations of bycatch calculated from observer data shown in our results, it is clear that there is vast room for improvement in logbook reporting. Even though the three countries for which these comparisons could be made differ in geographic location, cetacean species and size of exclusive economic zone, the analysis of the countries yielded similar under-reporting results, suggesting these cases are likely comparable to many other countries with well-developed commercial fishing industries, particularly using trawl, passive netting, and hook and line gear.

One of the most likely causes of under-reporting of cetacean bycatch, even in mandatory logbooks, is the concerns fishers have of punishment or negative consequences to the fishing industry. This was determined to be one of the reasons given by fishers in Iceland (see **Paper V**). Concern over strict consequences, such as closures (e.g., Marrick et al. 2001), or negative publicity from catching a rare/endorsed species in particular could be an additional reason for fishers to not report. I quantified significant under-reporting in logbooks for several individual species in separate gear types in both New Zealand and the USA, ranging from having an IUCN list of threatened species status of least concern (e.g., common dolphin) to endangered (Hector's dolphin) (www.iucnredlist.org). Given all

species examined except for Dusky dolphins in passive netting (New Zealand) and pilot whale spp. and humpback whales in net gears (USA) were significantly under-reported, there was no evidence that rarer/endangered species are reported less than common species when they are in fact reported at all; however, there were cases where species were somewhat suspiciously not reported at all (e.g. North Atlantic right whale and sei whale). These concerns over consequences, paired with the fact that filling out bycatch reports is extra work, usually with no reward, gives fishers very little incentive to report. Differing legislature and different interpretations of the laws by fishers may also influence under-reporting of cetacean entanglement or bycatch. For example, the Icelandic law lacks clarity on what should be reported, leading fishers to believe they should only report deceased animals (see **Paper V**), while fisheries scientists believe all catches, even if released alive, should be reported (Iceland Marine Research Institute. pers. comm. 03 December 2020). In New Zealand, 19.6% percent of individual cetaceans reported were categorized as uninjured or injured but released alive, and in the USA 24.0% were reported as injured but released alive, suggesting that the logbook data from Iceland likely represents an even smaller fraction of the number of cetaceans caught than the other two countries. Based on this, I suggest a first step to improving accuracy of cetacean bycatch/entanglement reporting should be clarification of existing reporting laws.

Though bycatch/entanglement under-reporting is likely an issue for virtually all cetacean species, it has been noted that it is particularly an issue for large whale entanglements given their rare and difficult-to-observer nature, since these whales are more likely to be able to break away from entangling gear (Robbins and Mattila 2001; IWC 2011). This is particularly true for gillnet and pot/trap gears which are left in the water, unattended, for longer periods of time and are well known for entangling whales (Johnson et al. 2005). The majority of reports from all four case study countries involved dolphins and porpoises. Given that these species are the most likely to drown when they are caught in fishing gear, it can be suspected that fishers may be the most inclined to report these events. Also, given the possible misinterpretations of the laws, it is even less likely that large whales will be reported particularly in countries with ambiguous laws like Iceland. For example, **Papers III and V** provide evidence of humpback whale entanglement in Iceland; however, there was only one humpback whale reported as bycatch in the Icelandic fisher logbooks between 2009-2019 (Iceland Marine Research Institute, unpub. data).

Given the issues with under-reporting of cetacean bycatch/entanglement, observer programs have been needed; however, they can be costly (National Marine Fisheries Service 2020) and generally require a high effort in order to produce accurate bycatch estimates (20% for common species and 50% for rare species (Babcock et al. 2013)). Observer coverage in Iceland, for example, only averaged 2% for the lumpfish gillnet fishery and 0.2% for the cod+ gillnet fishery meaning that the observer coverage is likely not enough to accurately estimate bycatch of cetaceans. Given the costs of observer programs making them unfeasible for many fisheries, improvements to the accuracy of fisher self-reported logbook data would be of great benefit. In all four case study countries, fisher logbooks contained more cetacean species than observer data which may be an indicator that fishers have more information, particularly about rare events, than observer programs can detect without very high coverage. However, there is currently no system in place to verify the reports in fisher logbook data.

Standardization and simplification of reporting could improve bycatch/entanglement reporting. I suggest that simple reporting of cetacean bycatch/entanglement using a mobile

phone app could be a viable option. Fishers could pre-fill their vessel and fishing gear information and the app could track the GPS position of the vessel. In the case of cetacean bycatch/entanglement, the app could have the option to submit photo and video reports, in addition to the more traditional “written” reports, which would be uploaded to an online database to which the relevant ministry would have access. A similar type of app exists for recreational fishers to voluntarily report lost and found fishing gear or bycatch in Norway (Fiskeridirektoratet 2020) and could be streamlined to suit the needs of simple mandatory reporting. Pilot projects of such a system could be put in place in countries such as New Zealand and the USA where there are already mandatory logbooks and a well-developed observer program from which data could be used to verify the progress of the app reporting. I also suggest that further effort is put on implementing bycatch monitoring cameras, which have already been tested in the USA and New Zealand, as well as other countries with bycatch reporting legislation (Australia, Canada and Sweden), and could lower the costs of monitoring while simultaneously improving logbook reporting by having the “observer effect” (e.g. Burns and Kerr 2008; Porter 2010; van Helmond et al. 2019), where the accuracy of fisher-reported data greatly increases when there is a way to verify it. Therefore, some of the footage could be used only to verify logbook data, and if bycatch/entanglement reporting closely matched the video, then the vessel could be compensated in some way, while if the reporting did not match, the vessel could be penalized.

4.2 Paper III: Entanglement Scar Analysis

In **Paper III** I calculated the first scar-based estimate of frequency of prior entanglement in fishing gear and entanglement rate per year for the Icelandic humpback whale population, which can be compared to other areas. Approximately half of the individuals analyzed ($n = 189$) were scored as low probability of prior entanglement (LP) and approximately one-quarter each were scored as uncertain (U) and high probability of prior entanglement (HP) ($n = 96$ and $n = 94$ respectively). Based on this, we estimated a minimum of 24.8% and a maximum of 50.1% of the Icelandic humpback whale population has had a least one prior entanglement in fishing gear (see **Paper III**, Table 1).

There were 33 individuals which were scored HP in at least one year and had comparable resightings in consecutive years to be included in entanglement rate analysis based on increased scarring (*Es*). The average *Es* rate for 2011-2017 was 16.3% (see **Paper III**, Table 2). In addition, there were 3 individuals with comparable resightings in which the entanglement-related scarring had healed beyond recognition within one year, and three individuals that had increased scarring that indicated the individual had been entangled at least twice. There were 15 individuals with unhealed entanglement related injuries, indicating an entanglement likely within the past year, that were included in the entanglement rate analysis based on unhealed injuries (*Eu*). For the similar time period as the *Es* rate (2012-2017) the average *Eu* entanglement rate was 1.9%. The estimates calculated by these two metrics were not significantly different ($p = 0.49$). For the earlier time period, the average *Eu* rate was 7.7% (see Paper II, Table 3). This was not significantly greater than the later time period ($p = 0.39$).

Seven individuals photographed in this study had fishing gear still attached to the body (Figure 11). Based on what was visible in the photographs, two had monofilament line

(one with hooks attached to the line), two had rope and netting, one had a single rope, and two had just netting. Two individuals picked up entangling gear or acquired new injuries between sightings in the same year. One was photographed gear-free in Skjálfandi Bay and was then resighted entangled in Eyjafjörður three months later. Another individual was photographed in Eyjafjörður with new entanglement injuries that it had acquired within nine days of first being sighted in Skjálfandi Bay.

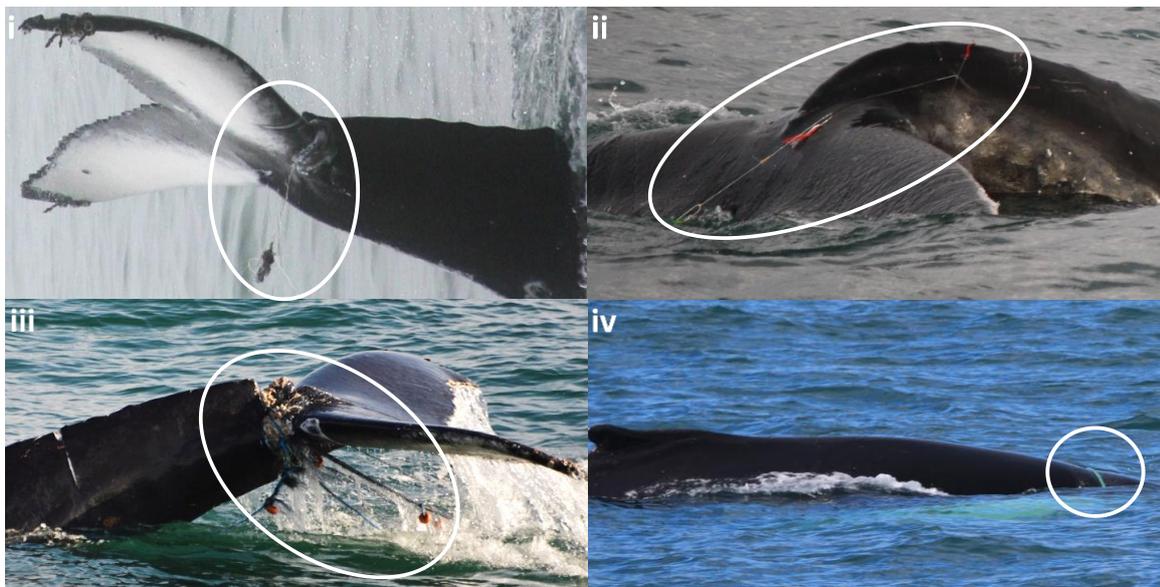


Figure 11 Photos showing four examples of humpback whales photographed with entangling gear attached to the body (indicated by ellipses) both within and outside the coding areas. i) monofilament line, ii) monofilament line and hooks, iii) rope and netting, iv) rope.

Our results show that entanglement is a prevalent issue in the Icelandic humpback whale population. As none of the entanglement rate estimates differed significantly, this suggests that the non-lethal entanglement rate has remained fairly steady over the study period. Since humpback whales are seasonal migrants, it is not possible to say where many of these entanglement events took place, however the individuals that were seen both without and then later with entangling gear or injuries in the same year provide evidence for at least some entanglements occurring locally.

Entanglement estimates calculated in this study are lower than those obtained in the Gulf of Maine and Alaska using the same assessment methods (Robbins and Mattila 2004; Robbins 2009; 2012; Neilson et al. 2009). The reason for the lower incidence of entanglement in this study is not definitively known, but may relate to differences in fishing gear types, potentially lower fishing effort in Iceland than in larger countries, and the extent of the overlap between the whales and the fishing activity. For example, Iceland does not have a commercial fishery using traps/pots, which are implicated in many large whale entanglements in the USA (Johnson et al. 2005; Neilson et al. 2009). In addition, juvenile whales are known to become entangled most often in the Gulf of Maine (Robbins 2011), and therefore the demographic of Iceland's whale population may affect the

entanglement frequency (i.e. if the Icelandic population has fewer juvenile whales, there may be fewer entanglements overall).

The scar-based minimum frequency of prior entanglement calculated for this study is considered to be conservative. Although this is a systematic method, it does not include entanglements that do not involve the peduncle or detect injuries that heal over time or resulted in the death of the whale before it could be studied (Robbins and Mattila 2004). There were a small number of cases in this study where entanglement evidence was opportunistically photographed outside of the peduncle region, suggesting some entanglements of Icelandic whales are occurring on body parts not included in the coding areas. Furthermore, three individuals in our study with comparable resightings in consecutive years exhibited entanglement scar healing beyond recognition, and there are reported entanglement-related humpback whale deaths in Iceland (Víkingsson and Ólafsdóttir 2003; Víkingsson et al. 2004; 2005; Víkingsson 2011). Despite this, our study provided evidence that entanglements off Iceland can be reliably detected based on scarring/injuries in the caudal peduncle areas and entanglements are occurring at a steady rate in this population.

4.3 Paper IV: Acoustic Alarm Trials

Paper IV represents the first in situ experiments testing behavioural response of humpback whales in their North Atlantic feeding grounds to commercially available acoustic alarms, and the first study to consider feeding as a behavioural response variable. In 2017-2018, 14 successful research trips resulted in 9 whale pinger (WP) and 7 seal scarer (SS) experimental exposure trials (EETs) using 15 individual humpback whales (see **Paper IV**, Table 1).

Averages of the behavioural response variables for the pre-exposure (PrE), exposure (E) and post-exposure (PoE) phases of each WP EET can be seen in Figure 12. The model for dive time was the only case in which a random slope model fitted the data significantly better than a random intercept model ($p < 0.001$) providing individual- or behavioural state-specific, divergent responses in terms of dive time. Phase of the trial (the fixed effect variable), however, had no significant effect on dive time ($p = 0.79$), providing no evidence for a consistent response across individuals. Phase of the trial did have a significant effect on both speed ($p = 0.006$) and surface feeding ($p = 0.019$) (see **Paper IV**, Table 2), providing evidence for a consistent response. Humpback whale speed during the E phase was 1.7 times higher than during the PoE phase ($p = 0.0024$) and 1.4 times higher than during the PrE phase, though this was not significant at the 0.05 alpha level ($p = 0.11$) (see **Paper IV**, Table 3). No significant differences in humpback whale speed were observed between the PrE and PoE phases ($p = 0.62$). The probability of surface feeding was significantly lower during the E phase than during the PoE phase ($p = 0.026$) and was marginally lower during the E phase than during the PrE phase ($p = 0.099$) though this difference was not significant at the 0.05 alpha level (see **Paper IV**, Table 4). Rates of surface feeding amounted to 11% in the PrE phase, dropped to 4% in the E phase, and then rose to 13% in the PoE phase (Figure 13).

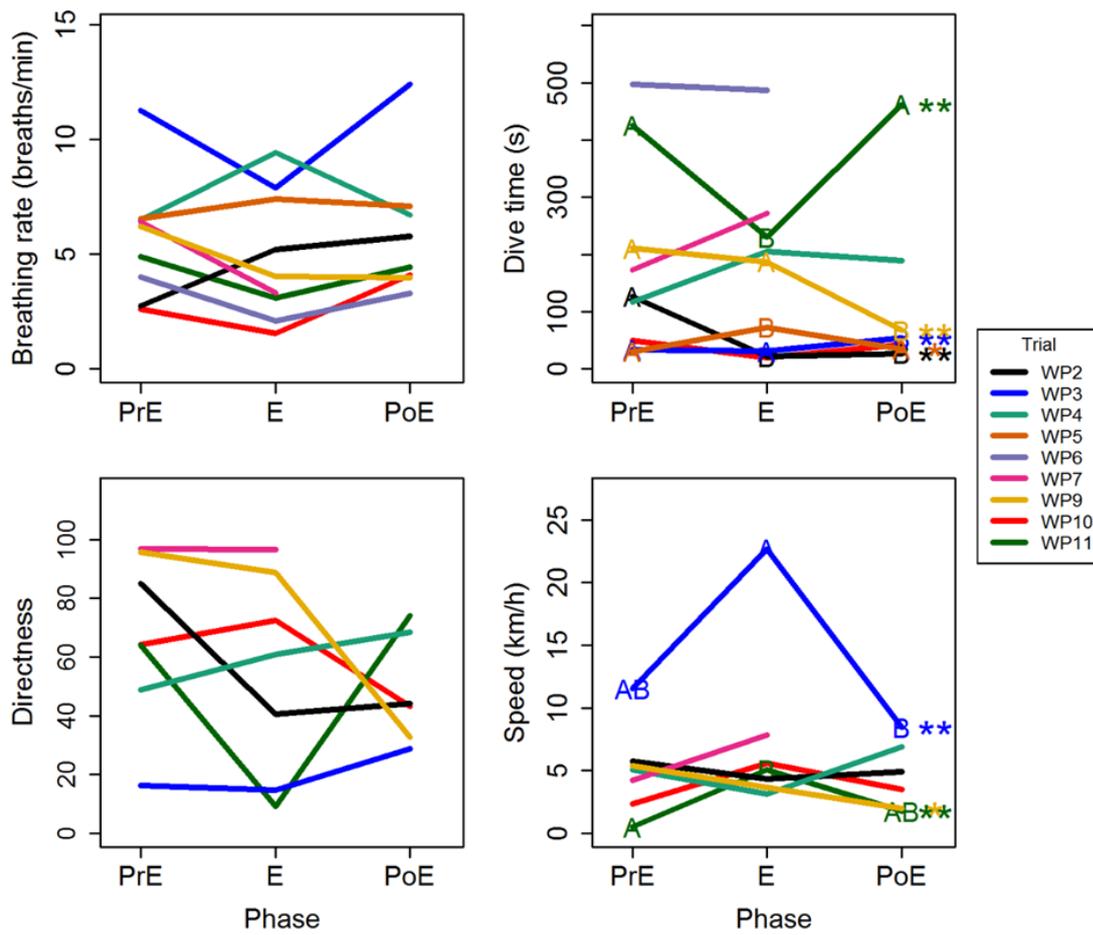


Figure 12 Averages of the behavioural response variables breathing rate, dive time, directness and speed for the pre-exposure (PrE), exposure (E) and post-exposure (PoE) phases of each whale pinger (WP) trial. Stars highlight individual whale pinger exposure trials in which the response variable differed significantly between the phases (* uncorrected $p < 0.05$; ** Bonferroni-corrected $p < 0.05$). Letters indicate between which phases significant differences occurred. Models for individual whale pinger exposure trials were only calculated for response variables for which overall models found a significant effect of phase or random slope.

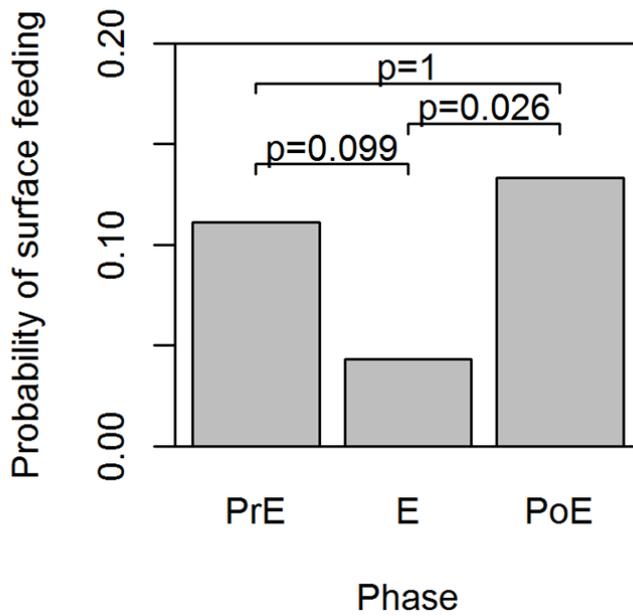


Figure 13 Graph showing the probability of surface feeding during whale pinger trials for each phase (PrE = pre-exposure phase, E = exposure phase, PoE = post-exposure phase).

The averages of the behavioural response variables for the PrE, E and PoE phase of each SS EET can be seen in Figure 14. Again, dive time was the only case in which a random slope model fitted the data significantly better than a random intercept model ($p = 0.002$) providing evidence for significant individual- or behavioural-state responses. However, there was no consistent response across individuals for any of the response variables (phase of the trial did not have a significant effect). Thus, there was no evidence for a shared response of humpback whales to seal scarer alarm (see **Paper IV**, Table 5).

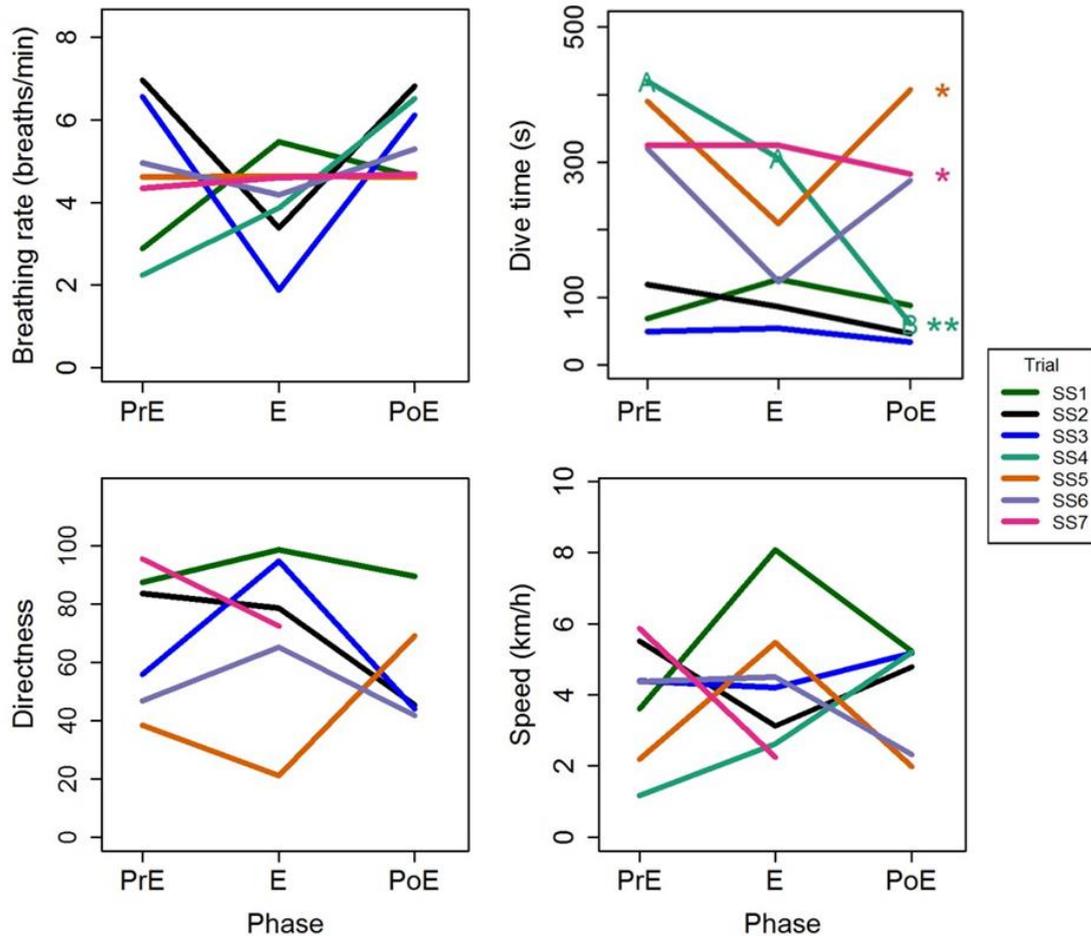


Figure 14 Averages of the behavioural response variables breathing rate, dive time, directness and speed for the pre-exposure (PrE), exposure (E) and post-exposure (PoE) phases of each seal scarer (SS) trial. Stars highlight individual seal scarer exposure trials in which the response variable differed significantly between the phases (* uncorrected $p < 0.05$; ** Bonferroni-corrected $p < 0.05$). Letters indicate between which phases significant differences occurred. Models for individual seal scarer exposure trials were only calculated for response variables for which overall models found a significant effect of phase or random slope.

In addition to experimental exposure trials, in **Paper IV** I conducted the first testing of WPs on a capelin purse seine net for the duration of a fishing season. This served to provide us with information about how the pingers would perform in their intended application and insight into how fishers, who have issues with humpback whales, perceive the usefulness of the pingers. During the 2018 capelin fishing season, the onboard observer recorded 34 individual humpback whale sightings at 7 locations during 16 hours of observation with 70.6% ($n = 24$) occurring while the boat was in the capelin fishing grounds off the south/southwest coast of Iceland (see **Paper IV**, Table 6). When setting the net, whales at the surface near the vessel were noted to swim away from the area, with one whale specifically observed turning 180 degrees to swim in the opposite direction of where the seine net was being set into the water. There were two incidents where humpback whales were encircled in the net fitted with WPs during 2018 (Figure 15), once when the onboard observer was present and once when they were not. In both incidents, two humpback whales appeared at the surface inside the net once the bottom of the net was

being closed, indicating the whales entered from the bottom. During the observed incident, it was noted the whales were “trumpeting” and showed signs of being distressed by the encirclement in the net. In an attempt to release the whales in both cases, the extra line attaching the end of the net to the vessel was not brought in towards the boat, while the net was closed at the bottom, creating an approximately 100 m wide opening in the side of the net towards the stern where there were no WPs, as well as no floats, on the line. During the observed encirclement, the two whales spent approximately 5 minutes inside the net before locating the opening and escaping without causing any damage and without any apparent consequences to the animals. According to the captain, the second incident occurred in the exact same manner. The captain and crew reported that whales rarely, if ever, find this opening and escape without further action or damage to the net in previous seasons when the WPs were not in use.



Figure 15 Video still showing one of two humpback whales going down for a dive while encircled in the capelin purse seine net.

Our modelling results showed that there was no consistent significant behavioural response of humpback whales to WPs in terms of breathing rate, dive time, or swimming directness, which is consistent with experiments conducted during whale migration in Australia (Harcourt et al. 2014; How et al. 2015; Pirota et al. 2016). There was also no evidence for individual- or behavioural state-specific responses in terms of breathing rate or swimming directness, thus there is no evidence that individuals reacted to the whale pinger significantly in terms of these variables. However, our results suggest that humpback whales reduce or stop surface feeding in response to WPs. Previous studies have found that humpback whales cease feeding in response to sonar sound (Sivle et al. 2015), decrease side roll feeding in response to ship noise (Blair et al. 2016), and decrease detectable lunge feeding behaviour during approaches of whale watching vessels in one of the study sites for this experiment (Skjálfandi Bay) (Ovide 2017), suggesting reduction in feeding may be a common response when whales are exposed to anthropogenic noise.

Whales reducing or stopping their feeding in response to the pinger could lead to lower incidence of humpback whale encirclement and entanglement in Icelandic fisheries since the whales are likely feeding when these incidences occur. During the feeding season, humpback whales spend the majority of their time foraging (Friedlaender et al. 2013;

Ovide 2017), and entanglement of humpback whales has been observed to coincide with spawning of one of their main prey species, capelin, in Newfoundland Canada (Perkins and Beamish 1979). Similarly, humpback whales that were evidently feeding on capelin were observed being encircled by a purse seine during the present study. I therefore hypothesize that if the whales stop feeding in the vicinity of fishing gear with active pingers they may be more likely to take notice of the gear and less likely to become entangled or encircled. This indicates pingers may be a useful mitigation tool.

This is the first time a reduction in feeding behaviour has been documented in response to a WP with only hypothetical reasons offered as to why the whales reacted as they did. One possibility is that they are simply distracted by or curious about the sudden introduction of an unnatural and unfamiliar sound in their environment as suggested by Lien et al. (1990). It has been suggested that target fish species are not affected by pinger alarms (Lien et al. 1992). Furthermore, generally fish species have the highest sensitivity to sounds below 0.5-1 kHz (Whalberg and Westerberg, 2005) and humpback whale prey species, such as capelin and krill (*Euphausia spp.*), are hypothesized to have low sensitivity to sound and little behavioural reactions to sound exposure (Brierley et al. 2003; Jørgensen et al. 2004). Therefore, it is unlikely that the pinger sound affected the prey that the whales were feeding on during the EETs and more likely that the whales were responding directly to the WP itself.

Disruption of humpback whale feeding behaviour is cause for concern for potential negative impacts on the individual, and possibly the population, if pinger use becomes widespread in the fishing industry, given humpback whales need to acquire a large energy storage during the feeding season for their migration and winter breeding season (Sigurjónsson and Víkingsson 1997; Butterworth et al. 2012). However, it is important to note that exposure to the whale pinger during the E phase was only for 15 mins, so it is unknown if the whales would habituate to the sound and continue feeding normally after a longer exposure. No lasting effect of the whale pinger on surface feeding was observed, given that there was no significant difference between the PrE and PoT phases. The whales that were encircled in the purse seine net using the pingers in this study were not surface feeding and entered the net from deeper than 120 m while the pingers were near the surface of the water. This may indicate the whale pingers were not in the correct position to cause the whales to stop feeding and avoid entering the net, suggesting the importance of positioning pingers strategically on gear to obtain the desired result. Further experimentation with pingers at different depths and tagging of whales to gather information about their underwater feeding activity could provide valuable information to further explain how a change in feeding behaviour or increased awareness of the nets could lead to lower incidence of entanglement or encirclement.

It was also determined that humpback whales significantly increased their swimming speed during exposure to the whale pinger. An increase in humpback whale swimming speed has not been reported in previous studies investigating behavioural responses to pingers; however, Todd et al. (1992) reported that humpback whales exposed to 4 kHz alarm prototypes made significantly more abrupt turns towards an active alarm, and abrupt turns have been associated with higher swimming speeds (Edel and Winn 1978). Further investigation into the whales' swimming behaviour is required to infer how this response may relate to entanglement mitigation.

Response to sound may differ between individuals and may depend on behavioural state (Southall et al. 2019). The results from the dive time models for both the whale pinger and

the seal scarer showed no consistent change in dive time across individuals or exposure trials and the random slope models that account for individual-specific responses fit the data best. While dive time during the E phase significantly increased for some individuals, it significantly decreased for others, which suggests support for individual-specific, divergent responses. An alternative explanation is that individuals may have been naturally switching between a behavioural state of long dive times and a state of short dive times, and this change coincided with the phases of some of the EETs. Given that there was evidence for individual-specific response in dive time for both ADDs, despite there being no consistent response in dive time to either device, and furthermore no other significant responses to the seal scarer for any variable, a natural change in behavioural state is considered the most likely explanation of these findings.

There was no evidence for a consistent significant effect of the seal scarer on humpback whale breathing rate, dive time, swimming speed, or swimming directness. The seal scarer had a source level 51 dB re 1 μ Pa louder than the whale pinger and therefore it was hypothesized humpback whales would have some reaction to the high-powered sound even though the frequency of the device is at the top or slightly above their modelled hearing range (Houser et al. 2001). Results from the present study are consistent with findings of Henderson et al. (2016) in which it was also concluded humpbacks did not react to high frequency pingers (though the pinger used in their study was 17-35 kHz higher in frequency than the seal scarer used in this study) and with Lien et al. (1990) in which it was determined that high-frequency alarms (7-30 kHz higher in frequency than the seal scarer used in this study) did not significantly lower the incidences of humpback whales colliding with gear. It is possible that the frequency of the seal scarer was just too high for humpback whales to hear the device well enough to exhibit a significant response, confirming that ADDs need to target the best-estimated hearing range of the whales.

During the pinger trial on the capelin purse seine net, on two occasions, a pair of whales entered the purse seine fitted with the whale pingers from the bottom before it had been closed. Since the whale pingers were attached along the float line at the top of the net, it is possible that they were not in the correct position to prevent whales from entering the gear through the bottom opening (below 120 m depth). Despite the whale pingers not deterring the whales from entering the purse seine from the bottom, the whales were able to find their way out through an approximately 100 m wide (at the surface) opening where there were no whale pingers in both cases. The whales escaped without causing any damage to the purse seine and without further intervention methods from the captain (such as putting the boat into reverse to sink the float line). The captain and crew reported that whales escaping the net on their own was a very rare occurrence. This led to an overall positive view of the whale pingers and an increased interest in further trials for use in the Icelandic capelin purse seine fishery to prevent net damage. The observations of humpback whales finding an opening in the net free of pingers in the present study provides insight into the currently unknown directional hearing capabilities of humpback whales. If the whale pingers were truly guiding the humpback whales to the opening, as was suggested based on the captain and crew's several years of experience with whales becoming encircled by the purse seine, then possibly the whales were able to acoustically detect this pinger-less space, given it was possibly devoid of detectable sound and discernible. If further trials can confirm that humpback whales can be guided to a net opening by pingers, this would not only indicate that pingers can reduce the risk of net damage, but also that humpback whales have good directional hearing capabilities.

4.4 Paper V: Fisher Questionnaires and Interviews

For **Paper V** I distributed anonymous questionnaires to gather the first insights into whale sightings and interactions with fishing gear, and resulting damage, from fishers in Iceland. In addition, I conducted semi-directed interviews with five capelin purse seine captains to gain further insight into the issues this fishery has with humpback whales.

A total of 59 complete questionnaires could be used for analysis. The majority of questionnaire respondents reported seeing whale spp. (whales of any species) “often” or “very often” while fishing in Iceland (57.6%) (Figure 16). Nearly half (47.5%) also reported seeing specifically humpback whales “often” or “very often”. Over one-quarter (30.5%) of respondents reported that they had observed whale spp. interact with their fishing gear at least once, and 13.6% reported this happening more than once (Figure 17). In addition, 47.5% of respondents reported having dolphins and/or porpoises in their gear at least once, and 18.6% reported this happening more than once. Ten observed whale-gear interactions involved humpback whales (55.6%), two involved orcas, and there was one report each of minke whale, sperm whale and blue whale interactions (Figure 18). There were an additional four reports where the species were not reported and listed as unknown. Of the ten humpback whale entanglements, six occurred in capelin purse seine nets, one occurred in a cod set net, two occurred in cod/haddock hooks-and-lines, and one report had no details (see **Paper V**, Table 1). There was location information reported for eight of the ten witnessed humpback whale entanglements. The majority of incidences occurred in coastal waters in the southwest ($n = 3$) and northeast ($n = 4$). (Figure 19).

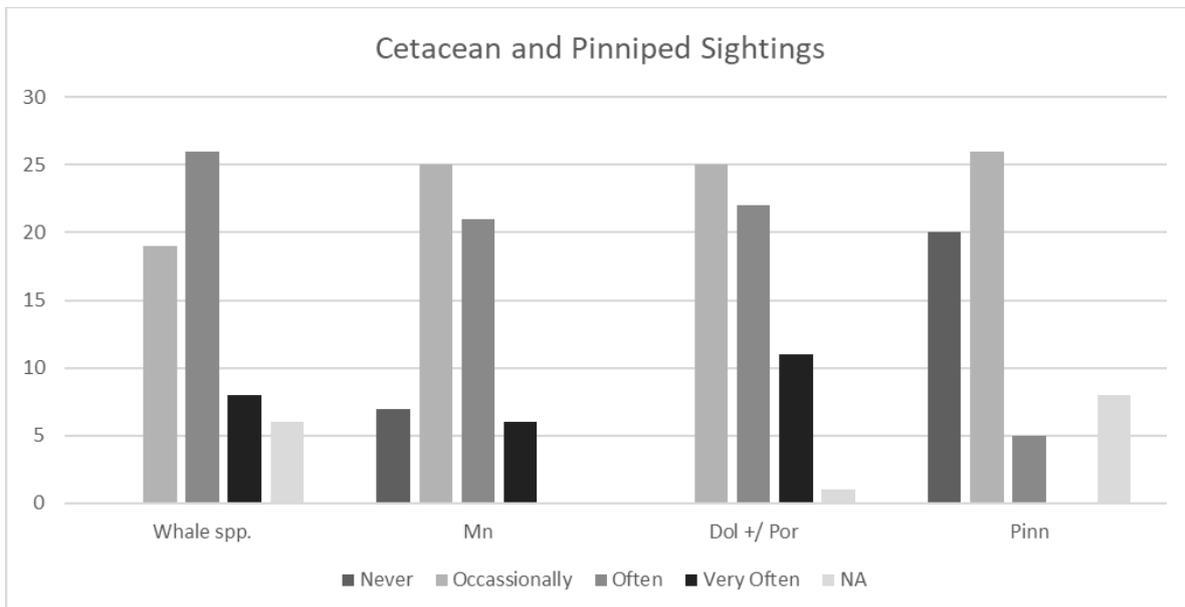


Figure 16 Graph showing how often questionnaire respondents reported seeing whales of any species (Whale spp.), humpback whales (Mn), dolphins and/or porpoises (Dol +/- Por) and pinnipeds (Pinn) while fishing in Iceland.

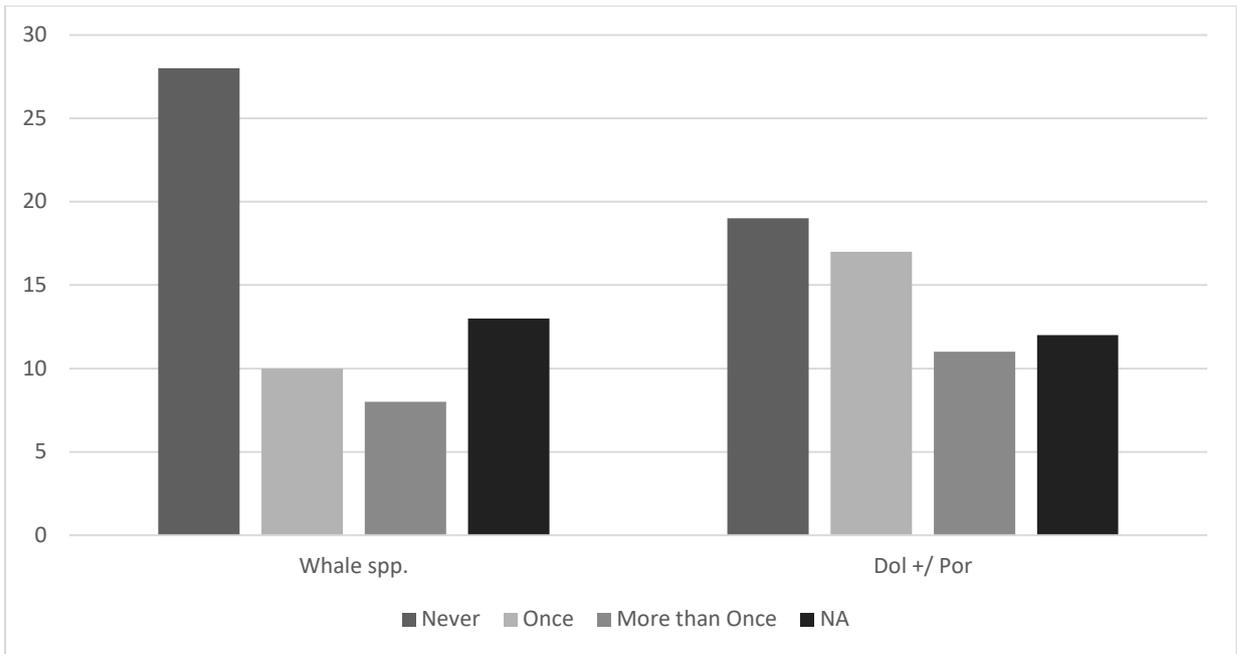


Figure 17 Graph showing how often questionnaire respondents witnessed whales of any species (Whale spp.) and dolphins and/or porpoises (Dol +/- Por) in their fishing gear while fishing in Iceland.

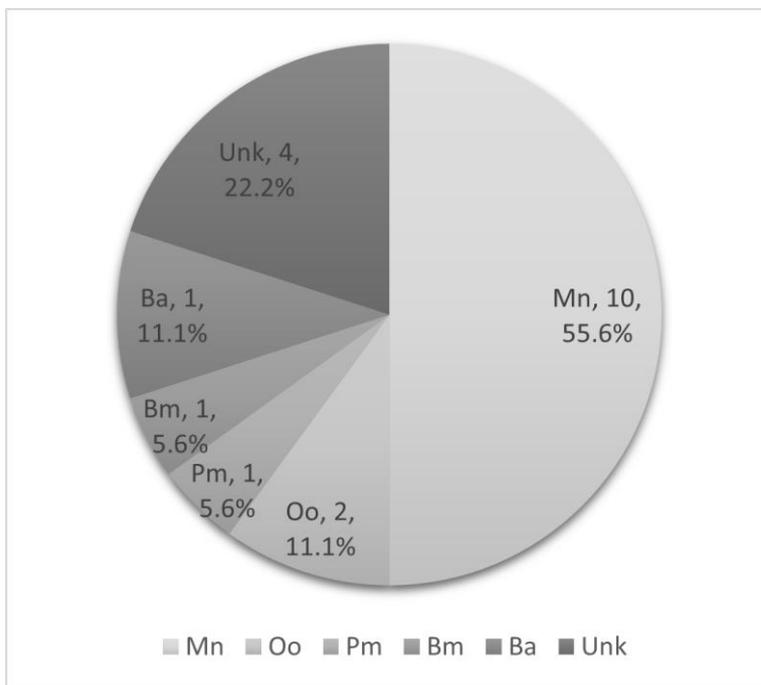


Figure 18 Graph showing the number of each species of whale, and the percent of the total that each species represents, that questionnaire respondents reported witnessing interacting with their fishing gear while fishing in Iceland. Mn = humpback whale, Oo = orca, Pm = sperm whale, Bm = blue whale, Ba = minke whale, Unk = unknown.

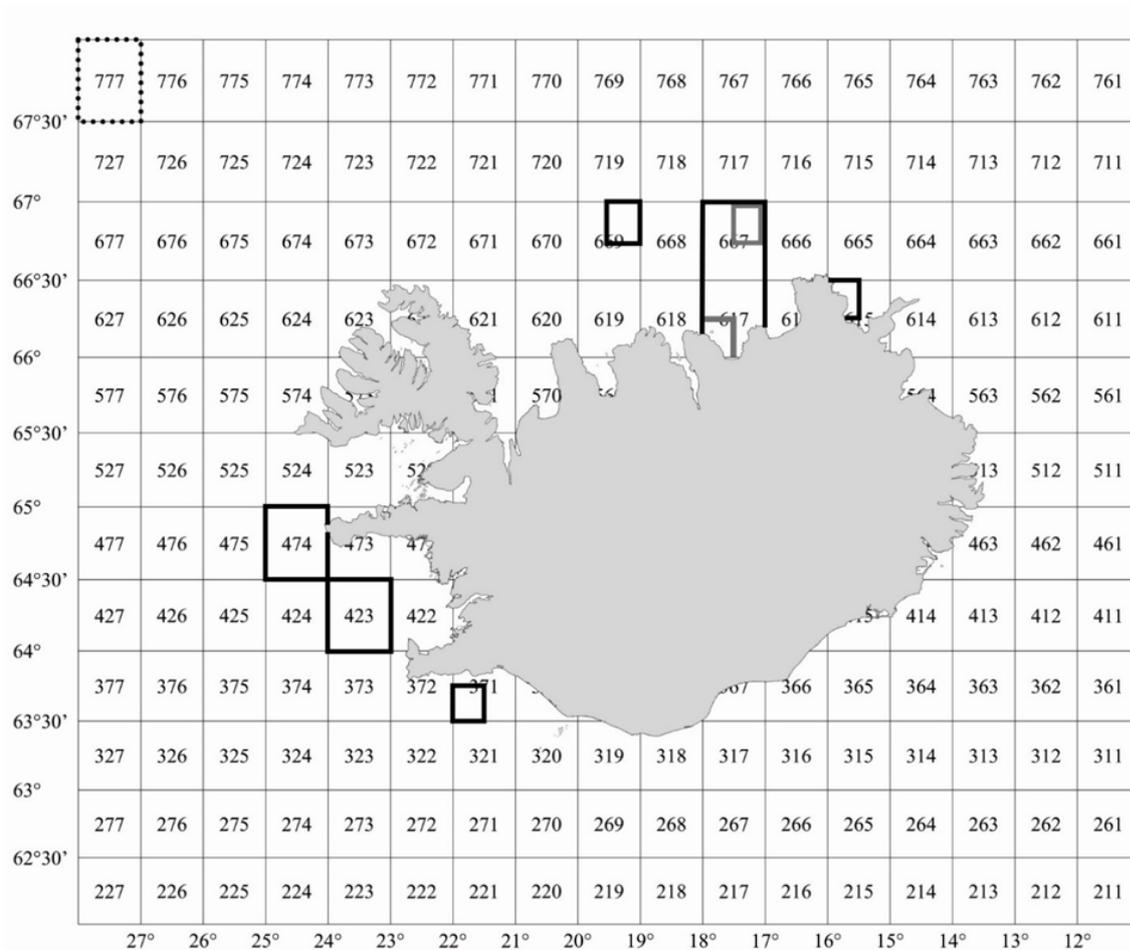


Figure 19 Map showing the eight locations in the fishing grounds where respondent reported witnessing humpback whales in their fishing gear around Iceland. Solid black boxes indicate reported locations, solid grey boxes indicate two locations given in the same report, however the report was counted as one witnessed entanglement since it was unclear if they were reporting two incidences or estimating where one incident occurred. The dotted box indicates a report of an incident “southeast of Scoreby Sound” only indicating that this would be in open ocean to the far northwest of Iceland.

There were twelve reports of whale species (spp.) damaging fishing gear between 2010-2018 (see **Paper V**, Table 2). Of these, seven (58.3%) were humpback whales, two were orcas, one was a minke whale, and one species unknown. The question specifically asked about whales, but in one questionnaire damage due to a white-beaked dolphin was included and this report was included. Five reports of damaged gear involved purse seines (four humpback whale and one orca), three involved net (one humpback whale, one white-beaked dolphin and one unknown), three involved hooks-and-lines (two humpback whale and one minke whale) and one involved a trawl (orca). Those that reported monetary loss due to damage in the continued questionnaire (damage occurring between 2010-2018) estimated monetary damage and losses caused by whales ranged from only 10.000 (for broken leader lines) up to 10.000.000 (for torn purse seine nets) Icelandic krona (ISK) (approximately \$80 up to \$80,000 USD).

Those respondents who had observed whale spp. interacting with their fishing gear (at any time) ($n = 16$, mean rank (MR) = 22.22) did not significantly differ in their responses to how often they observed whale spp. while fishing compared to those who had not observed an interaction ($n = 25$, MR = 20.22) ($p = .578$, $W = 180.5$). Similarly, those who reported having their gear damaged by whale spp. between 2010-2018 ($n = 9$, MR = 12.94) did not differ in their responses to how often they observed whale spp. while fishing compared to those who reported no gear damage ($n = 17$, MR = 13.79) ($p = .793$, $W = 81.5$). However, those respondents who had observed humpback whales interacting with their gear ($n = 10$, MR = 40.5) reported seeing humpback whales significantly more often while fishing than those who had not observed humpback whale interactions ($n = 46$, MR = 25.89) ($p = .006$, $W = 110$). Those respondents who had not observed a humpback whale interaction more often reported they saw humpback whales “never” or only “occasionally” while fishing. There was a trend in the data that suggested that respondents who reported having their gear damaged by whales between 2010-2018 ($n = 10$, MR = 19.1) also reported seeing humpback whales more often than those who reported no gear damaged in the past between 2010-2018 ($n = 20$, MR = 13.7), however this difference was not significant ($W = 64$, $p = .096$). Those respondents who reported having their gear damaged between 2010-2018 ($n = 9$, MR = 19.11) reported observing an interaction (at any time) significantly more often than those who reported no gear damage ($n = 16$, MR = 9.56) ($W = 17$, $p = .0004$). Only two (12.5%) of the respondents who reported observing a whale interact with their fishing gear “once” or “more than once” reported that they had no gear damage.

Over one-third of respondents (35.1%) did not answer the question asking about why they would not report catching a whale in their net. Furthermore, 16.2% of respondents answered that they would not report their incident(s) with whales since they believed the animal was released or escaped alive, and 10.8% answered they would not report their incidence(s) with whales for fear of negative consequences to the fishing industry. (Figure 20).

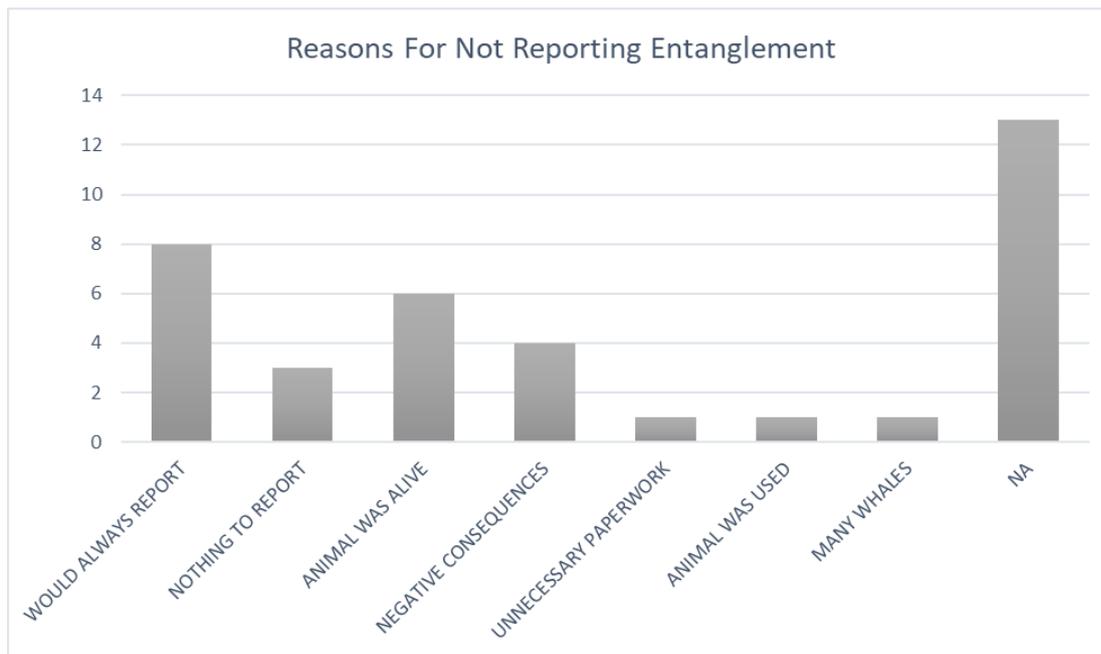


Figure 20 Graph showing responses that questionnaire respondents provided for why they would or would not report whales in their fishing gear in Iceland.

Five capelin captains (four current and one retired) were interviewed about their experiences with humpback whales in their purse seine nets (see **Paper V**, Table 3). All the captains reported that the number of incidences of encircling humpback whales in the capelin purse seine has been increasing over the years. All four current captains also reported having incidences with humpback whales in their fishing nets within the past five years, with one captain estimating having “five or six” incidences, one estimating having ten incidences, and two stating they have just had “many” incidences including nine whales in the net at one time (though this was more than 5 years ago) and 17 whales in the net in one fishing season. All five captains discussed the measures they take to try to remove the whales the net. Four of the five reported that, ideally, they would leave the net partially open to let the whale(s) find their way out on their own (as described in section 4.2), though they report this is rare, with one captain saying it is a “30:70” percent chance that they would be able to do this versus tearing a hole in the net.

Three out of the five captains estimated that gear damage and losses due to humpback whale(s) in their purse seine net costed them 10.000.000 to 55.000.000 Icelandic krona (approximately \$80,000 to \$450,000 USD). Two out of the five captains report that a humpback whale had drowned in their net at least once, with one of them reporting that this happened in their net twice. A third captain reported that whales sometimes had injuries to their pectoral fins or tail, likely caused by the fishing gear. All five captains also reported they were aware of acoustic alarm devices known as pingers (as described in section 3.4.1) and the four current captains were willing to try these and had in fact previously experimented with different pingers. However, they were not pingers that were designed specifically for humpback whales, and they did not find them to be useful in mitigating humpback whales becoming encircled in and damaging their nets, further supporting our results from the SS trials in **Paper IV** (section 4.3).

Questionnaire results showed that cetaceans are seen in Icelandic waters often by fishers, including nearly half of respondents reporting seeing humpback whales specifically. Statistical comparison of the questionnaire responses determined that those respondents who observed humpback whale(s) interact with their gear reported that they saw humpback whales significantly more often than those that did not observe an interaction. This supports the view that those fishers who are seeing humpback whales frequently, while fishing in the humpback whale feeding habitat, have an increased chance to observe a whale-gear interaction and therefore an increased chance of having their gear damaged. Humpback whales are the third most abundant baleen whale species in Icelandic waters (Pike et al. 2019); however, these results support that humpback whales are the most commonly entangled large whale species in Iceland and are most commonly causing damage and issues for fishers. This is likely due to their preference for coastal habitat which overlaps with commercial fishing, as shown by the reported locations where humpback whales were observed interacting with fishing gear. The reports from the questionnaire reflect areas where it would be predicted humpback whales and commercial fishing are overlapping the most both spatially and temporally based on whale sightings and fishing effort (Pike et al. 2019; Pike et al. 2009; Hafrannsóknastofnun 2017). In addition, the estimated summertime subpopulation of humpback whales around Iceland increased by approximately 12% per year between 1987-2001 (Pike et al., 2009) and has remained generally stable since (Víkingsson et al. 2015). This increase in the Icelandic subpopulation is reflected in the interview responses from the capelin purse seiner captains and is likely another large contributing factor to humpback whales being the most reported species observed interacting with fishing gear. This is further confirmed by the scar analysis conducted in **Paper III** (section 4.2).

Eight of 14 respondents who reported observing whale(s) interact with their fishing gear (57.1%) saw humpback whales in their gear within five years of completing the questionnaire (between 2010-2018), or an average of at least one observed humpback whale interaction per year since 2010. In actuality, there are likely more observed interactions between humpback whales and fishing gear within that timeframe, exemplified by one respondent who wrote in his answer that he sees this “every year” but did not provide more specific details on year and month. In addition, one capelin purse seiner captain stated in his interview that he had observed 17 humpback whales in his net in one season. Though considered rare, two out of five capelin purse seiner captains said they had observed at least one humpback whale accidentally drown in their purse seine net. Humpback whale incidental mortality in purse seines has also been reported in the Atlantic tuna fishery off Western Africa (Escalle et al. 2015). All of these events went unreported (Marine and Freshwater Research Institute, unpub. data), as discussed in **Paper II** (section 4.1). The capelin purse seine industry has been recognized in Icelandic media as having issues with humpback whales in their gear (pers. obs.). The questionnaire responses reflect this observation, with six out of ten observed reports of humpback whales interacting with gear occurring in the capelin purse seine industry. This could be expected given the capelin purse seine fishery is directly targeting humpback whale prey (Sigurjónsson and Víkingsson 1997). This phenomenon was witnessed first-hand during data collection for the pinger trial in the capelin purse seine industry for **Paper IV** (section 4.3). Other large whale species reported interacting with fishing gear in the questionnaires included a sperm whale, orcas, minke whales and a blue whale, exemplifying that this is at least occasionally an issue for a wide range of Icelandic whale species.

Gear damage caused by whales was reported in all the general gear-types used in Iceland. As suspected, those who reported that they had observed a whale interact with their fishing gear also reported that their gear had been damaged by whales significantly more often than those who had not observed whales interact with their gear. This is confirming that when whales interact with fishing gear, they are causing damage the majority of the time; however, the damage can range anywhere from minimal to severe in terms of financial costs. Damage to hooks-and-lines caused little financial loss to the fishers, with the report stating two broken leader lines (broken by a minke whale) costed the fishers ca. 10.000 ISK (ca. \$80 USD). However, a whale entanglement in fishing line can be serious for the animal if the line ends up wrapping tightly around the body, which has been seen in Skjálfandi Bay, Iceland previously (University of Iceland's Húsavík Research Centre unpub. data) (Figure 21). Damage to a purse seine net, including loss of catch and downtime, caused by humpback whale(s) was reported to cost up to 10.000.000 ISK (ca. \$80,000 USD) in the questionnaire and up to 55.000.000 ISK (ca. \$450,000 USD) in the interviews of captains. In the majority of cases, humpback whales likely escape from purse seines without serious injury or long-term consequences to the animal, but these events can have serious impacts on the profits of the fishers. The capelin fishing season in Iceland is currently only approximately three months long (from January through March) (Síldarvinnslan hf. n.d.) and purse-seining is weather (sea state) dependent (NOAA 2003) meaning gear damage due to humpback whales and loss of fishing time to repair this damage can in some cases cost up to an estimated 11% of the revenue of an average fishing season (Geir F. Zoega pers. comm. 20 January 2020).



Figure 21 Image showing a humpback whale in Skjálfandi Bay, Iceland with monofilament line (possibly long-line fishing gear) wrapped tightly around the tail stalk causing deep lacerations. (©Húsavík Research Centre).

5 Conclusions

In **Paper II** I quantified cetacean bycatch/entanglement under-reporting in fisher logbooks by comparing catch per unit effort (CPUE) or mean annual number of individuals reported in fisher logbooks and observer reports for passive netting, trawl and hook and line gear in New Zealand and the USA and lumpfish gillnets and cod (and others) gillnets in Iceland. This represents the first quantification of cetacean under-reporting in logbooks versus observer data for several gear types and species. Additionally, I calculated CPUEs for Norwegian vessels greater than 15 m for trawl and gillnet gear for the first time. These are all countries where cetacean bycatch reporting is mandatory by law. Fisher logbook estimates were significantly lower than observer estimates for all gear types that could be examined, except for lining in New Zealand. The observer estimates were on average anywhere from 52-26920% greater than the fisher logbook estimates, with the greatest difference being in the cod (and others) gillnet fishery in Iceland, which has very low (0.2%) observer coverage. It is likely that results would be similar for other countries with comparable, well-developed fishing industries given that the case study countries differed in location and cetacean species but all yielded similar results. Though all species are likely under-reported, large whale entanglements appeared to be minimal in both fisher and observer data, likely due in part to their rare and difficult-to-observer nature. This is an issue that is a detriment to fisheries and cetacean population management. Given the high costs of observer programs, putting more focus on improving self-reporting and electronic monitoring could be a simple way to eliminate the need for many observers onboard vessels and build trust between government, scientists and fishers, in addition to gathering more data in an unbiased manner. By quantifying under-reporting in the manner conducted in this study, this data can be used as a baseline in which to verify if different approaches have improved the accuracy of fisher logbook reporting.

Given the issues with observing and reporting large whale entanglements in particular, in **Paper III** I estimated Icelandic humpback whale entanglement based on scarring. I estimated that a minimum of one-quarter of the Icelandic humpback whale population has been entangled in fishing gear at least once, and our most reliable metric estimates acquisition of entanglement-related injuries occurs at a rate of 2% of the population per year. This represents the first study of humpback whales using systematic scar-analysis outside of the United States and allows for the Icelandic population to be compared to other areas being studied using the same method previously and in the future. Though these estimates are lower than other studied humpback whale populations in the United States, they still suggest that entanglement is a persistent issue in this population, and data showed that at least some incidences were occurring locally in Icelandic waters. The use of whale watching boats as a research platform was essential to the data collection, however dedicated surveys in the future could improve the relatively low resightings in consecutive years obtained in this study used to calculate annual entanglement rate. Some of the whales that feed off Iceland are known to belong to a small breeding stock occurring around the Cape Verde Islands. It has been previously suggested that this breeding stock is distinct and endangered (NOAA Department of Commerce 2016) and therefore negative impacts of entanglement on even a relatively small number of these humpback whales could have serious implications for the Cape Verde stock. The implications of the impacts of non-

lethal entanglements on individuals and populations are not well understood. The majority of the entanglement injuries observed on Icelandic humpback whales were not considered severe, suggesting the impacts on these animals may be minor. However, the long-term outcome for any of the animals, particularly those that had more severe injuries or were last photographed carrying gear attached to the body, is not known. Given the minimum entanglement estimate of 25% of the Icelandic humpback whale population and the fact these whales are contributing to the endangered Cape Verde stock, precautionary entanglement mitigation measures should be considered, particularly for gear that could be causing the most severe injuries. Based on the limited number of cases in this study where an animal was observed with moderate-to-severe injuries and gear still attached to the body, I hypothesize set nets and hand/long lines have the highest potential for negative impacts on the animal. Continued entanglement monitoring and assessment of severity of entanglement-related injuries would aid in more clearly understanding the long-term effects of entanglement on humpback whales off Iceland and more clearly identifying where mitigation efforts are most warranted.

Since I determined that entanglement is an issue for Icelandic humpback whales, and at least some entanglements occur in Icelandic fisheries, I tested acoustic alarms as a potential mitigation tool for this issue in **Paper IV**. This was the first testing of the “whale pinger” alarm in the humpback whales’ North Atlantic feeding grounds. Through experimental exposure trials it was determined that humpback whales significantly increased their swimming speed and significantly decreased their surface feeding behaviour in response to the whale pinger alarm. This was the first time a reduction in feeding behaviour has been observed in response to a low frequency whale pinger. When the whale pingers were fitted on a capelin purse seine net, whales entered the net from the bottom on two occasions but were able to find their way out of the net through an approximately 100 m pinger-less opening left for them to escape both times. This led to the hypothesis that humpback whales may have directional hearing capabilities which they used to find the opening left for them in purse seine net. The capability of baleen whales to hear directionally is currently unknown, and this provides some first evidence to suggest this can be explored further using low frequency pingers. Primarily based on the results of the surface feeding behaviour model, I concluded that low frequency whale pingers may be a useful tool in preventing humpback whale entanglement, encirclement and fishing gear damage in their feeding grounds off Iceland. The implications of the significant increase in swimming speed in terms of entanglement reduction are unknown. Further research into humpback whale response to low frequency sound would help to clarify these initial results, especially tagging of the whales in order to obtain behavioural data from when the whale is under the water. In particular, I recommend further investigation into the humpback whale’s feeding response in order to determine if this response is consistent within larger sample sizes and if it is detected in other humpback whale feeding grounds. It is also advisable to investigate what the response of the whales is to longer exposure to the alarms to determine if reduction in feeding is only a short-term consequence or is a longer response. Given the uncertainty of the effects of long-term use, the whale pingers may be particularly advisable for fishing methods in which the gear is not in the water for long periods of time such as attached to purse seine nets or suspended in the water from long-line vessels.

To better understand details and consequences surrounding the issue of whale entanglement in Icelandic fisheries from the fishers’ perspective, I conducted anonymous questionnaires and interviews for **Paper V**. This was the first effort to gather fisher

knowledge on large whale entanglement in Iceland including details such as exact location of entanglement incidences and monetary loss estimates due to damage caused by whales. The data showed that the humpback whale is the large whale species that is most often becoming entangled in fishing gear and causing damage, however on occasion other large whale species are becoming entangled as well. Entanglement of humpback whales appears to be primarily concentrated in the north/northeast and southwest of the country where there is high fishing effort and known humpback whale feeding habitat. The majority of the reported incidences occurred in the capelin purse seine fishery, which is directly targeting humpback whale prey and therefore conflict is likely increased. Responses indicated encirclement of humpback whales in a purse seine (as witnessed during onboard observation in **Paper IV**) can cause high monetary losses to fishers, and also be detrimental to the animal in some cases. Therefore, further research into mitigation measures, such as the acoustic alarms tested in **Paper IV**, could benefit both the Icelandic fisheries and the whales. Of the 40 companies that were contacted, 37.5% provided at least one completed questionnaire; however, the actual total number of questionnaires collected was low. The majority of fishing companies were contacted through more than one method (email, post, phone) and never provided any response. This may be reflecting an unwillingness to provide details about a negative consequence of fishing, potentially due to concerns over the possibility of this leading to fishing restrictions, a view that the issue of whale entanglement is not of high importance or interest, or simply that the companies or fishers could not spare the time to participate. Given that 35% of respondents did not answer the question about what their reason would be to not report whale entanglement and 11% answered that they were concerned about negative consequences to the fishing industry, this further suggests that this is an issue that some fishers are not willing to talk about openly, despite their answers being anonymous. I suggest that long-term use of fisher questionnaires and interviews, paired with onboard observation, to gather data about large whale entanglement in Icelandic fisheries could be used to inform best management practices on the specific issues each fishery faces.

Overall, I was able to provide the first quantified estimates of under-reporting of cetacean bycatch/entanglement in fisher logbooks in case study countries, including Iceland. This provides necessary baseline data to investigate how to improve logbook reporting accuracy for scientific use and minimize the need for expensive observer programs. I then focused the further studies on the understudied topic of humpback whale entanglement in Iceland. These studies provided the first research on this topic in the country, for which future research can be built upon. The scar-analysis provides the necessary entanglement frequency baseline data to continue monitoring this issue over time in the Icelandic population and to begin to assess the implications entanglement might have, particularly in terms of Icelandic whales' contribution to the Cape Verde breeding stock. I found evidence that humpback whales respond to whale pingers and these pingers may reduce gear damage caused by whales that are encircled in nets. These initial findings are applicable to both Icelandic fisheries and likely other fisheries operating in humpback whale feeding grounds. Further testing to obtain larger sample sizes for both individual and onboard fishing vessel observation trials is advisable to determine if whale pingers should be included in fisheries management plans. The questionnaires and interviews provide previously unknown details about humpback whale entanglement in Icelandic fisheries including incidences reportedly resulting in significant monetary losses to the capelin purse seine fishery and unreported fatal entanglements. Continued cooperation and dialogue between fishers and researchers will aid in better management to both conserve the whale population and ensure sustainable fisheries management.

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Appendix 1

Fisher Questionnaire in English

This short survey is being conducted for a biology doctorate thesis at the University of Iceland focusing on whale entanglement/bycatch in fishing gear and fishing gear damage. **This survey will be treated anonymously, therefore no names of individuals or companies will be used in conjunction with the answers.** Thank you for your participation!

Any further questions can be sent to:

Charla Basran – PhD Candidate at the University of Iceland’s Húsavík Research Centre
cjb2@hi.is
(354)868-0609

1. How often do you see marine mammals when you are fishing?

- | | | | | |
|---------------------------------------------|-------|--------------|-------|------------|
| <input type="radio"/> Whales | Never | Occasionally | Often | Frequently |
| <input type="radio"/> Dolphins or Porpoises | Never | Occasionally | Often | Frequently |
| <input type="radio"/> Seals | Never | Occasionally | Often | Frequently |
| <input type="radio"/> Other _____ | Never | Occasionally | Often | Frequently |

2. How often have you seen **humpback whales** in the area where you were fishing?

Never Occasionally Often Frequently

3. Have you ever witnessed whales, dolphins, or porpoises entangled in the fishing gear deployed by your vessel (*Identify species if possible*)?

- | | | | | |
|---------------------------------|----------------|-------|------|----------------|
| <input type="radio"/> Whales | (Species_____) | Never | Once | More than once |
| <input type="radio"/> Dolphins | (Species_____) | Never | Once | More than once |
| <input type="radio"/> Porpoises | (Species_____) | Never | Once | More than once |

4. Have you witnessed a **humpback whale** entangled in or interacting with your fishing gear **in the past 5 years**? YES NO (*If YES, please answer the following questions*)

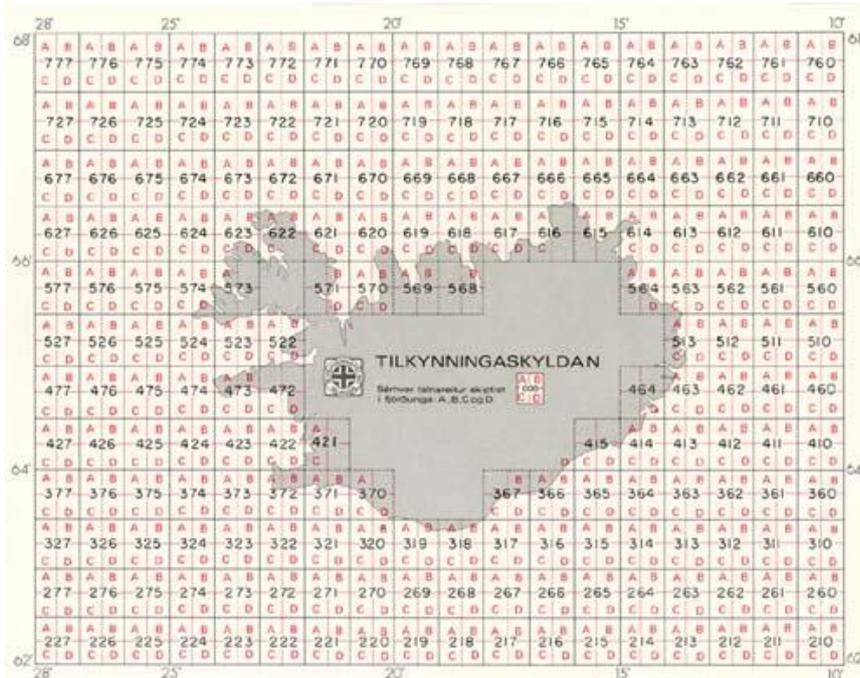
When did this occur? Month_____ Year_____

What type of fishing gear were you using?

What type of fish were you fishing for?

What area were you fishing in (*Please use the reference chart below*)?

Did you take action to free the whale? How?



5. Has your fishing gear been damaged or lost due to what you believe was a whale swimming through it **in the past 5 years**? YES NO (*If YES, please answer the following*)

Do you know what species of whale? YES (species _____) NO

What type of gear was damaged/lost?

How was the gear damaged/lost (broken lines, torn nets etc.)?

Did this result in loss of catch or downtime? YES NO Please explain:

Approximately how much money did this damage/loss cost to repair?

Are you willing to be contacted for interview about the whale entanglement issues you have witnessed/experienced? YES NO

Contact

information: _____

6. For what reasons would you **not** report bycatch of a whale, porpoise, or dolphin? (*Please circle all that apply*)

DO NOT UNDERSTAND/WANT TO USE THE ELECTRONIC REPORTING SYSTEM

THE ANIMAL WAS STILL ALIVE

THE ANIMAL WAS USED (AS BAIT ETC.)

CONCERNED ABOUT NEGATIVE CONSEQUENCES TO FISHING

OTHER

Paper I

Paper I

Conflicts Between Arctic Industries and Cetaceans

Charla J. Basran and Marianne H. Rasmussen

Author contributions. Wrote the paper: CJB, MHR

Conflicts Between Arctic Industries and Cetaceans

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Abstract

As in many oceans around the globe, there is extensive and increasing interactions between cetaceans and industries in the Arctic. The Arctic hosts 16 cetacean species (whales, dolphins, and porpoises), some of which are seasonal visitors while others are year-round inhabitants (CAFF 2017). This chapter focuses on six cetacean species on which extensive research has been conducted, exemplified by: baleen whales; blue whale (*Balaenoptera musculus*) and humpback whale (*Megaptera novaeangliae*), large toothed whales; sperm whale (*Physeter macrocephalus*) and orca (*Orcinus orca*), and small toothed whales; white-beaked dolphin (*Lagenorhynchus albirostris*) and harbour porpoise (*Phocoena phocoena*). These and can be used as representatives of Arctic cetacean species. The industries which have the most interaction with cetaceans in the Arctic include shipping, oil exploration, and commercial fisheries. This chapter will explore the interactions between the six example species and these industries, and the impacts these interactions can have on both. It will also touch on some further conflicts between Arctic activities and cetaceans as industries expand and human presence in the Arctic Ocean increases.

Key Words: Arctic, cetaceans, conflicts, shipping, oil-exploration, entanglement

1. Arctic Cetaceans

1.1 Baleen whales: Blue Whale (*Balaenoptera musculus*) and Humpback Whale (*Megaptera novaeangliae*)

Baleen whales are generally characterized by the hundreds of baleen plates they have along their upper jaw and two blowholes on the top of their head. In addition, they are known to be primarily solitary animals that are communicating over long distances using low frequency sounds, and many are making long migrations between summer feeding grounds and winter breeding grounds. There is a total of seven baleen whale species which can be found in the Arctic seasonally or year-round: blue whale (*Balaenoptera musculus*),

humpback whale (*Megaptera novaeangliae*), fin whale (*Balaenoptera physalus*), gray whale (*Eschrichtius robustus*), bowhead whale (*Balaena mysticetus*), sei whale (*Balaenoptera borealis*), and minke whale (*Balaenoptera acutorostrata*).

The blue whale (Figure 1) is the largest baleen whale and largest animal on the planet, growing up to a maximum of 33 meters long and weighing up to 150 tonnes (Wilson and Mittermeier 2014). The blue whale communicates with the lowest frequency of any cetacean, with a range of 16-100 Hz (Cummins and Thompson 1971). The North Atlantic blue whale song consists of a single tonal unit around 19 Hz (Mellinger and Clark 2003). Source levels of blue whale moans measured by Akamatsu et al (2014) in Icelandic waters were between 159-169 dB re 1 μ Pa rms from tagged animals. The hearing of blue whales is unknown, but it is assumed that they can hear at least the same frequencies as their vocalizations. Some blue whale populations are seasonal migrators to Arctic waters, where they spend the summer-time feeding primarily on krill. Their habitat range in the Arctic extends from northern Norway (up to Svalbard), north of Iceland, and east and west Greenland (Wilson and Mittermeier 2014).



Figure 1. A blue whale (*Balaenoptera musculus*), the largest cetacean in the Arctic and on the planet

The humpback whale (Figure 2) is another member of the baleen whale group, growing up to a maximum of 17 meters long and weighing up to 34 tonnes (Wilson and Mittermeier 2014). They produce different kinds of sounds such as grunts and groans, mostly in a wide frequency range of 10 Hz to 10 kHz (Thompson et al. 1979; Cerchio et al. 2001). In Alaskan feeding grounds moans were recorded with dominant frequency at 300-500 Hz and source levels of 175-192 dB re 1 μ Pa @ 1m (Thompson et al. 1986). Humpback whales are famous for their songs, first reported by Payne and McVay (1971), and they are reported singing in the tropical breeding grounds and recently also in sub-Arctic waters during the Icelandic winter (Magnúsdóttir et al. 2014; 2015). The hearing of humpback whales has been modelled based on anatomical data which indicates that humpback whales have maximum hearing sensitivity between 2 to 6 kHz, and good sensitivity between 700 Hz to 10 kHz, resembling their vocalizations (Houser et al. 2001). They are also seasonal migrators, spending their summer feeding season both in sub-arctic and Arctic waters, where they range from northern Norway (including north of Svalbard), north of Iceland, east and west Greenland, and northern Canada and Alaska. Here, they are feeding on krill and small schooling fish species (Wilson and Mittermeier 2014).



Figure 2. A humpback whale (*Megaptera novaeangliae*) breaching out of the water

1.2 Toothed Whales: Sperm Whale (*Physeter macrocephalus*), Orca (*Orcinus orca*), White-beaked Dolphin (*Lagenorhynchus albirostris*) and Harbour Porpoises (*Phocoena phocoena*)

Toothed whales are generally characterized by having true teeth, a single blowhole, and using echolocation to hunt prey and for orientation. This group includes sperm whales, beaked whales, dolphins, and porpoises and therefore is comprised of a large range of species. Unlike the baleen whales, they are known to live in social groups and communicate with higher frequency whistles and calls. There is a total of nine toothed whale species found living in the Arctic: sperm whale (*Physeter macrocephalus*), beluga whale (*Delphinapterus leucas*), narwhal (*Monodon monoceros*), northern bottlenose whale (*Hyperoodon ampullatus*), orca (also known as killer whale) (*Orcinus orca*), white-beaked dolphin (*Lagenorhynchus albirostris*), Atlantic white-sided dolphin (*Lagenorhynchus acutus*), long-finned pilot whale (*Globicephala melas*), and harbour porpoise (*Phocoena phocoena*).

Sperm whales (Figure 3) are the largest of the toothed whales, with the males growing up to 19 meters in length and weighing up to 70 tonnes (Wilson and Mittermeier 2014). They are deep diving specialists, with a maximum dive depth of 3000 meters, feeding on squid and deep-sea fish. Sperm whales echolocate using clicks with a center frequency of 15 kHz (Møhl et al. 2003) and they produce the loudest sound of all cetaceans with source level of their clicks up to 236 dB re 1 mPa peRMS (Møhl et al. 2003). The hearing of sperm whales is unknown, but as other species, it is assumed they can at least hear the same frequency range as the sounds they produce. Different from all other cetaceans found in the Arctic, only male sperm whales are seen in Arctic waters. Their known range in the Arctic spreads from northern Norway, north of Iceland, and the east coast of Greenland; all the way up to the southern ice edge (Wilson and Mittermeier 2014).



Figure 3. A sperm whale (*Physeter macrocephalus*), the largest toothed whale in the Arctic and on the planet: fluking (lifting the tail) and resting at the surface

Orcas (Figure 4) are the largest dolphin species in the world, with females growing up to 8 meters in length and weighing up to 5 tonnes and males growing up to 10 meters in length and weighing up to 7 tonnes (Wilson and Mittermeier 2014). The orca's echolocation clicks have a center frequency between 45-80 kHz (Au et al. 2004), and the average source level varies from 173-202 dB re 1 μ Pa peak-to-peak @ 1 m (Simon et al. 2007). Orcas communicate with calls and whistles, and different pods have different dialects of calls (Strager 1995). Whistles have been reported to include high frequencies with a fundamental frequency up to 40 kHz (Samara et al. 2010). From studies of captive orcas, they are known to have best hearing between 18–42 kHz, but they reliably responded to 100 kHz tones at ca. 95 dB (Szymanska et al. 1999). Orcas are found all around Arctic waters, extending as far as the sea ice allows, and therefore with diminishing sea ice their range is expanding. Here they are feeding on a variety of fish and other marine mammal species (Wilson and Mittermeier 2014).



Figure 7.4. Orcas (*Orcinus orca*), also known as killer whales

White-beaked dolphins (Figure 5) grow up to 3 meters in length and weigh up to 350 kilograms (Wilson and Mittermeier 2014). They produce broadband echolocation clicks with very high frequencies: up to 250 kHz (Rasmussen and Miller 2002), and source levels up to 219 dB re 1 mPa (Rasmussen et al, 2002). White-beaked dolphins communicate with whistles with a fundamental frequency up to 35 kHz (Rasmussen and Miller 2002) and harmonics up to 65 kHz (Rasmussen et al. 2006). Source levels of the whistles are up to 160 dB (Rasmussen et al. 2006). White-beaked dolphins hear in the frequency range from 1-150 kHz (Nachtigall et al. 2008). They are found only living in the temperate to arctic waters of the North Atlantic Ocean and up into the Arctic Ocean, where they range from north of Norway and Iceland, and along eastern Greenland. All year round they can be spotted in pods usually up to 50 individuals, feeding on a variety of small schooling fish (Wilson and Mittermeier 2014).



Figure 5. A pod of white-beaked dolphins (*Lagenorhynchus albirostris*)

Harbour porpoises (Figure 6) are the smallest Arctic cetacean species, growing up to 1.6 meters in length and weighing up to 65 kilograms (Lockyer 2003). They produce narrow band clicks centered around 130 kHz (Au et al. 1999) with source levels up to 160-205 dB re 1· μ Pa pp @ 1·m (Au et al. 1999; Villadsgaard et al. 2007). Harbour porpoises do not whistle but communicate with high-rate clicks only (Clausen et al. 2011). It is known that harbour porpoises hear best between 16-140 kHz (Kastelein et al. 2002). They are widely distributed from temperate to Arctic waters, where they range from northeastern Russia, north of Norway and Iceland, along eastern and western Greenland, northeastern Canada, and Alaska. Throughout their range they are most often found in shallow waters, though some populations are known to travel large distance to deep waters, feeding on a wide variety of fish and cephalopods depending on location and season (Wilson and Mittermeier 2014, Nielsen et al. 2018).



Figure 6. Harbour porpoises (*Phocoena phocoena*), the smallest cetacean in the Arctic

2. Conflicts with Arctic Industries

2.1 Ship Strikes

One of the major threats that the baleen whales face all along their migration route, including into the Arctic, is that of ship strikes from both large shipping vessels and cruise ships, as well as fishing vessels and whale watching vessels. These ship strikes are known to lead to both serious injury and/or death of the whale, particularly if the ship is 80 meters or longer or when the ship involved is travelling at a speed of 14 knots or greater (Laist et al. 2001). The other major factor in ship strike occurrence is where shipping routes are overlapping with areas that have high densities of whales. This will likely be of greatest risk in areas which are narrow passages, where the ship traffic and whales in the area would be highly concentrated (Williams and O'Hara 2010).

Research on blue whales has found that they make little-to-no lateral movement to swim out of the way of an oncoming ship, but they performed slow-decent shallow avoidance dives in 55% of studied cases (McKenna et al. 2015). These factors make blue whales particularly vulnerable to ship strikes. Though ship-strikes may not be a large contributing factor in the recovery of blue whale populations in post-whaling times (Monnahan et al. 2015), it is still considered a serious concern in order to ensure their recovery.

Humpback whales are also considered as commonly struck by ships (Laist et al. 2001) and are actually one of the most reported species involved in a ship strike incident, though this is likely due in-part to the coastal habitat of humpback whales and therefore higher chance of detectability of ship-struck animals in coastal waters compared to other species that are struck further away from the coast (Jensen and Silber 2004). In addition to increasing ship traffic world-wide, humpback whale populations have recovered well in post-whaling times and therefore their increase in numbers around the world has also likely been a factor in increasing ship strike risk.

The question is, why do these whales not swim out of the way? Modelling suggests that baleen whales at the surface may have difficulties acoustically detecting oncoming ships (Allen et al. 2012). Ship noise has been found to have lower source level sound at the surface of the water, and ships tend to have an “acoustic shadow” caused by the bow of the boat, lowering the detectable noise directly in front of the ship. These factors mean that baleen whales may not be able to detect the ship until it is too late for them to swim out of the way (Allen et al. 2012). Research also suggests that the likelihood of a ship strike may also be dependent on what the whale is doing at the time of approach. When whales are sleeping or feeding there is evidence they are much less responsive to the noise of an approaching vessel (Laist et al. 2001). Other factors may also increase some whales’ vulnerability to ship strikes, such as parasites, illness, or entanglement in fish gear which may cause some animals to spend more time than usual at the surface.

From the other side of the issue, whale collisions can cause ship damage. This is unlikely to be an issue for the large cargo ships and cruise ships, but can occur for smaller vessels such as fishing boats or whale watching boats. In addition, there are cases where deceased whales have actually been brought to port on the front of large vessels that struck them. This is generally a negative situation that companies would like to avoid and therefore mitigation measures have been explored and adopted in some areas. Shipping lane changes have been proposed, and even some lanes have been rerouted, in order to reduce the risk of ship strike (Redfern et al. 2013). In addition, speed restrictions have been put in places in some areas with high whale densities near shipping lanes (van der Hoop et al. 2015). The use of forward-facing sonar has also been proposed as a way for ships to see large whales in their path in time to change course (Miller and Potter 2001).

The decrease in Arctic sea ice has opened up the possibility for increased shipping, new shipping routes, and an increase in Arctic tourism via cruise ships. Shipping time between Europe and Asia is estimated to be reduced by up to 50% by using the Northern Sea Route during the summertime now, with thinning ice conditions (Aksenov et al. 2017). It is predicted that by 2020 65 million tonnes of cargo will be shipped through the Bering Strait along the Northern Sea Route, compared to just 1.36 million tonnes in 2013 (Huntington et al. 2015). Marine spatial planning measures should be taken into account to minimize the impacts that increased traffic can have on Arctic cetaceans.

2.2 Response to Oil Exploration

A major source of loud sounds in the ocean that can cause communication masking and behavioural disruptions to cetaceans is that of seismic airgun surveys used for oil exploration (DiLorio and Clark 2010). An airgun is towed behind a ship and emits high-powered blasts of air causing a seismic wave to penetrate deep into the seabed in order to find oil deposits. These loud blasts can travel great distances through the ocean, and in some cases are picked up by hydrophones over 3000 km from the source (Nieukirk 2004), and therefore may affect a wide range of ocean species.

Seismic survey blasts are believed to “mask” blue whale communication, making it more difficult since the loud, low frequency signals from the airgun are produced in the same frequency range as blue whale calls (DiLorio and Clark 2010). Research has also found that blue whales significantly increase their calling rate during seismic survey days. This is hypothesized to be compensating for the increased noise in the ocean by increasing the chance that their message is received by other members of the species. One observation showed that a blue whale within 10km of a ship with an active airgun array stopped calling

for an hour and moved away from the vessel, showing potential avoidance behaviour (McDonald et al. 1995).

Research on humpback whale response to oil exploration has found different responses, with some showing avoidance, some showing approach, and some showing little reaction (Malme et al. 1985). Some humpback whales show a “startle response”, meaning the animal quickly changes direction or behaviour in direct response to the sound. Trials conducted during humpback whale migration found that animals avoided the vessel with the airgun in operation when it was within 1.2-4.4 km away (McCauley 2000). It was also noted that some animals spend an unusually long time at the surface. This could be related to the fact that the sound level is lower at the surface of the water, in the same way that was described for ship noise in section 7.2.1, and could be considered a “vertical avoidance response” (Weir 2008). This response could potentially make the animals more vulnerable to a ship strike. Interestingly, some humpback whales have been observed having the opposite response, actually approaching the vessel with an active airgun within 100-400m. This is hypothesized to be male humpback whales that are responding to the airgun sound believing it is that of a competitor breaching (jumping out of the water) (McCauley 2000). This could potentially be dangerous for these whales, since it is considered plausible that baleen whales may experience at least temporary hearing impairment when exposed to the airgun at close range (Gedamke et al. 2011).

Just as is the case with baleen whales, some toothed whales are also known to respond to airguns used for oil exploration since they are believed to be audible to all species of cetacean due to the wide bandwidth of sound (Goold and Coates 2006). Interestingly, research has found that sperm whales do not detectibly or significantly react to or avoid airguns in use (Miller et al. 2009; Stone and Tasker 2006; Madsen et al. 2002), though there is some evidence that they may decrease their foraging during airgun activity due to longer periods spent at the surface. Orcas have been found to show “localized avoidance” to active airguns, where the animals distanced themselves from the source (Stone and Tasker 2006), also suggesting behavioural change.

There has currently been little scientific research on white-beaked dolphin response to airgun oil exploration specifically. This is problematic since they are an abundant sub-Arctic and Arctic species which is likely sensitive to this type of noise, based on the information known about other small cetacean species. One study found that white-beaked dolphins were observed moving away from a vessel with an operating airgun in 26.5% of sightings versus only 4.8% of sightings when the airgun was not operating (Stone and Tasker 2006), suggesting an avoidance response to the sound.

Harbour porpoises are thought to be one of the most sensitive cetaceans to airgun noise. Apparent avoidance of a vessel with an active airgun has been observed when the animals were upwards of 70 kilometers away (Bain and Williams 2006). They are also considered to be the most sensitive to having temporary hearing impairment caused by seismic surveys than any other cetacean (Lucke et al. 2009). Other research showed that even without an apparent avoidance response, there appears to be other changes in behaviour. Harbour porpoises were found to produce 15% less “buzzing” sounds when within 25 kilometers of a vessel with an active airgun (Pirodda et al. 2014). This buzzing is associated with either prey capture or communication (Verfuß et al. 2009, Clausen et al. 2011) meaning a reduction is indication of behavioural disruption.

From the other perspective, the oil industry faces increasing public and scientific pressure in regards to environmental impacts. For example, the United States has tried to pass legislation in order to be allowed to explore and drill oil within the current Arctic National Wildlife Refuge. This was met by opposition from 37 leading Arctic scientists, stating "...the cumulative impact of many seemingly small changes is significant. New development on the coastal plain of the Arctic Refuge, one of the nation's and planet's premier protected areas, will only contribute to these harmful impacts on wildlife. For all these reasons, we oppose oil and gas exploration, development and production on the coastal plain of the Arctic Refuge." (Bowyer et al. 2017). In Norway, a public opinion poll conducted in 2017 found that the majority of Norwegians would choose to minimize oil industry activity to protect the environment (P. Wijnen August 4 2017). There is even opposition from other Arctic industries, such as the fishing and tourism sectors in Norway which have spoken out against negative impacts of oil exploration (G. Fouche March 20 2009). Based on this type of opposition, the industry as a whole has a need to look for new technologies for less invasive surveys or turn their focus to alternatives to oil. One such technology is the marine vibrator. These have been developed by the industry and produce a lower sound source than an airgun, while working in much the same way. Preliminary tests of the impact of the marine vibrators on blue whales and humpback whales have been conducted in Iceland, and found that animals, which were tagged with acoustic behavioural recorders, were constantly feeding and not seemingly interrupted by the marine vibrator sound (Akamatsu et al. 2014; Schnitzler et al. 2018). These marine vibrators have yet to be tested on toothed whales.

Arctic oil exploration has been expanding and is likely to continue with the decreasing sea ice opening up new exploration possibilities. The Arctic continental shelf is now one of the world's largest oil prospect areas remaining (Gautier et al. 2009). Large oil companies in Russia have been exploring their Arctic shelf and believe 20-30% of Russia's oil production will come from that area by 2050 (T. Paraskova October 19 2017). Norway is considered another major leader in the Arctic oil industry and there are 93 oil exploration blocks located in the Barents Sea (R. Milne June 21 2017). The increasing interest in oil exploration in the Arctic could have serious impacts on Arctic cetaceans. Precautionary research needs to be conducted in order to minimize seismic survey impacts on these animals.

2.3 Entanglement and Bycatch

Entanglement (when a cetacean gets caught up in fishing lines or netting), and bycatch (when a cetacean is caught in fishing gear and drowns) are some of the leading causes of human-induced injury and mortality to whales. This is likely to be an issue anywhere that there is an overlap between fishing activities and cetaceans. Entanglement and bycatch is known to be increasing over the years as fishing industries develop and broaden, especially as the ice cover decreases in the Arctic (Meyer et al. 2011). For the large baleen whales, becoming entangled in fishing gear often does not lead to immediate drowning, and can last for hours, days, or even months, causing a wide range of potential impacts on the animal. Impacts on the animals in addition to the possibility of drowning include rope lacerations and infection risk, and inability to feed/starvation (Cassoff et al. 2011). Furthermore, dragging entangling gear can lead to a disruption in the whale's energy budget which could affect their ability to migrate (Moore and van der Hoop 2012; van der Hoop et al. 2013). Entanglement is also a stressful event for an animal, leading to an increase in stress hormones being released, which has been linked to compromising the

immune system and lowering reproductive success (Robbins and Mattila 2001; Rolland et al. 2017). Entanglement and bycatch is known to occur in all types of fishing gear to some extent, with set nets, long-lines, traps/pots, and purse seines, as well as “ghost gear” (ie. fishing gear that has been lost at sea) being the main contributors (Butterworth et al. 2012).

Blue whales sometimes become entangled in fishing gear, though seemingly to a lesser extent than humpback whales. There is little information about blue whale entanglement other than news reports of disentanglement efforts off California, USA. This may be attributed to the blue whale’s extremely large size and tendency to spend less time in shallow coastal waters, where the majority of entangling gear is used. It may also be due to their elusive nature and generally small populations, making them much less sighted and studied than the humpback whale.

Conversely, entanglement of humpback whales has been extensively studied in some populations, and they are known to be one of the most vulnerable species to this issue (Cole et al. 2006; Benjamins et al. 2012). Scarring studies estimating non-lethal entanglement rates found that 29-50% of humpback whales in North Pacific populations (Robbins et al. 2007; Neilson et al. 2009), 48-65% of humpback whales in the western North Atlantic (Robbins and Mattila 2004; Robbins 2009), and 25% of humpback whales around Iceland (Basran et al. 2019) have been previously entangled in fishing gear at least once in their lifetime. This is likely to be an underestimation and is not taking into account whales that died as a result of an entanglement. Due to their large size, humpback whales often free themselves from all or part of the entangling gear, but this is not always the case. In the western North Atlantic, 16% of reported entangled humpback whale cases were fatal to the animal (Benjamins et al. 2012).

Both sperm whales and orcas come in contact with fisheries, particularly long-line fisheries. They can become entangled in fishing line and occasionally net, just as baleen whales, though it is generally less of an issue for large toothed whales and there is little scientific information on this. There are a few reports of orcas being hooked in the back and bearing line scars consistent with previous entanglement (Visser 1998; 2000). Furthermore, there are some first-hand accounts of orcas being encircled in, and even sometimes drowning in herring purse seines (H. Hjallason, pers. comm. 2018). Studies on sperm whales found that six out of eight animals that were studied post-mortem after stranding in Ecuador had gillnet gear still attached to the body or bared clear entanglement injuries (Felix et al. 1997). Furthermore, sperm whales have been reported trapped and entangled in drift nets (Pace et al. 2008), and carrying long-line (Purves et al. 2004). In addition to becoming entangled in these nets, sperm whales are also known to ingest the nets by mistake (Jacobsen et al. 2010). One type of entanglement that seems to be unique to sperm whales is entanglement in deep sea cables. Since sperm whales are an extremely deep-diving species, they encounter these deep sea cables used for telecommunication, unlike most other cetacean species. This issue dates all the way back to 1953 when 14 sperm whales were reported entangled in cables (Heezen 1953). Though little is known about large toothed whale entanglement, it is an issue that likely goes hand-in-hand with the learned behaviour of associating fishing boats and gear with an easy meal (see section 7.2.4.3 Depredation).

Due to the small size of dolphins and porpoises, getting caught-up in fishing gear and drowning is a major issue all over the world. White-beaked dolphins can sometimes be subject to bycatch, though it seems to be less of an issue for this species than it is for harbour porpoises. Despite this, they were assessed as being at “high-risk” of bycatch in

setnet fisheries, just as the harbour porpoise (Brown et al. 2013). In Iceland white-beaked dolphins are the third most common bycatch species in the lumpfish (*Cyclopterus lumpus*) gillnet fishery, with 54 animals caught in 2013 (Palsson et al. 2015). Further bycatch evidence is reported from England and Wales where four white-beaked dolphins washed up on shore and the cause of death was determined as bycatch (Kirkwood et al. 1997). There are even small numbers reported caught in other types of gear, such as mid-water trawls, where they made up 1.5% of total dolphins caught (n=71) around Ireland (Couperus 1997). White-beaked dolphin bycatch does not appear to be an issue that would be damaging populations in general, though it may be having an impact on localized individuals or small populations (MacLeod 2013).

Harbour porpoises are known to be extremely vulnerable to bycatch, particularly getting caught in gillnets (Brown et al. 2013) which are used extensively in sub-Arctic and Arctic waters to catch species such as cod (*Gadus morhua*), monkfish (*Lophius piscatorius*), and lumpfish. In Norwegian gillnet fisheries alone, it is estimated that 6900 harbour porpoises die as bycatch every year (Bjorge et al. 2013). In Iceland, just the lumpfish gillnet fishery accounts for an estimated annual bycatch of 551 harbour porpoises (Iceland Marine and Freshwater Institute 2018), and an estimated additional 1450-1650 end up as bycatch in the cod gillnet fishery (Palsson et al. 2015). Other sub-Arctic and Arctic fisheries, such as the salmon gillnet fishery in Alaska and many Greenlandic fisheries, are understudied in terms of bycatch. Harbour porpoise bycatch is likely high in understudied fisheries as well, though it is currently not properly documented (Moore et al. 2009). These high numbers of bycatch mortalities can mean that the deaths exceed the calculated “acceptable take” from the populations. In Norway for example, the aforementioned estimated annual bycatch would need to come from a population of over 400,000 individuals in order to be within sustainable limits, but it is considered unlikely that the population is that large (Bjorge et al. 2013).

Entanglement and bycatch of cetaceans not only causes several issues for the animals, but for the fishermen or fishing companies as well. Large whale collisions with fishing gear often lead to extensive gear damage, which in-turn leads to downtime for repairs, new investments, and loss of catch. In some cases, such as with set-net or traps/pots which are left in the water unattended for some time, the gear is just lost completely since it was carried away by the whale. This all equals a financial burden to the fishing companies. In the Canadian western North Atlantic alone, reported gear loss due to whales has been estimated to cost hundreds of thousands of dollars per year and could be upwards of one million dollars when including down-time losses* (Lien 1979; Lien and Aldrich 1982). From the fishermen perspective, bycatch of smaller cetaceans is generally less of an issue than that of the large whales. Even so, both harbour porpoise and white-beaked dolphin bycatch causes some net damage and potential downtime for repairs. Severely entangled animals, particularly dolphins, may need to be cut out of the net causing more extensive damage. Large, unrepairable holes cause the loss of approximately 2-3 lumpfish gillnets per season (March-April) in north Iceland alone (S. Karlsson, pers. comm. 2018). As one can imagine, due to these issues fishing companies then find it in their best interest to avoid cetacean entanglement or bycatch. Several mitigation methods have been developed in attempt to minimize the conflict between cetaceans and fishing, and the impacts on both parties. There are several mitigation methods already in use in some places. One such measure is the use of “pingers”: devices that make a noise in the best-known hearing range of the target cetacean species in order to alert them of fishing gear in the water (Harcourt et al. 2014). Porpoise/dolphin “pingers” have even been made mandatory in some fisheries

around the world in attempt to reduce bycatch (Europa 2010; NOAA 2010) and are known to have some experimental and “real-world” success in reducing porpoise and dolphin bycatch (Cox et al. 2007). “Weak links” have also been developed for set-nets: links designed to break under the force of a large whale in order to avoid both entanglement and gear damage (Consortium for Wildlife Bycatch Reduction, n.d.). In addition, in some places area closures have been put into effect, often limiting the time of year and type of fishing gear that is allowed to be used in certain areas that are considered important cetacean habitat, such a crucial feeding or calving areas (Vanderlaan et al. 2011).

With the changing Arctic environment and the warming of the Arctic Ocean, fish species are moving poleward, and therefore expanding the fishery possibilities. Currently the majority of commercial fishing takes place in sub-arctic waters and “arctic corridors”, and targets mainly sub-arctic/boreal fish species (Christiansen et al. 2014), but as these target species move further northwards into the Arctic, Arctic fishing is expected to expand. Modelling has predicted that the annual landed fish catch in the Arctic will increase by 39% by 2050 compared to the year 2000 (Lam et al. 2016). The expanding fishing industry in the Arctic potentially means greater risk to Arctic cetaceans with respect to entanglement and bycatch and therefore mitigation measures should be implemented to avoid increasing conflict.

*converted into current dollar estimates to account for inflation

2.4 Other Conflicts between Arctic Industries and Cetaceans

2.4.1 Ship Noise

An increase in ship traffic in Arctic waters means more noise pollution in the ocean. Different types of vessels make different kinds of underwater noise, with most engines producing noise in low frequencies from 20-1000 Hz (Richardson et al. 1996). Therefore, animals communicating in this frequency range will be most affected in terms of masking of their communication. Masking is defined by Erbe et al (2016) as: “The process by which the threshold of hearing for one sound is raised by the presence of another (masking) sound; and the amount by which the threshold of hearing for one sound is raised by the presence of another (masking) sound, expressed in dB”. Communication masking is therefore depending on the hearing of the animals (their audiogram), the loudness of the signal, the frequency of the signal, the distance to the source (since sound attenuates with increasing distance), and the frequency of the signals the animals are using. Of the six example species, communication masking by ship noise is most relevant for blue whales, humpback whales, sperm whales, killer whales, and white-beaked dolphins, but it is even recently believed to interfere with harbour porpoise communication as well (Hermansen et al. 2014). It is likely that ship noise can cause masking and communication difficulties for all 16 of the Arctic cetacean species, and therefore shipping routes through important habitat should be avoided where possible.

2.4.2 Whale Watching

Whale watching is an increasing industry around the world, including in sub-Arctic and Arctic waters. In general, whale watching can be considered a positive for the whales, increasing the general public’s knowledge and the push to protect the whales and the ocean ecosystem by connecting people with them. With diminishing Arctic sea ice and shifts in species distribution, most likely due to climate change, whale watching in the sub-Arctic and Arctic is likely to continue to grow and evolve. Despite the positive image, there can

be some negative consequences of this industry if not operated with care. Just as with increased shipping, increased whale watching also means more ship engine noise in the ocean and potential masking of whale communication for all types of whales, as well as potentially leading to more collisions between vessels and cetaceans (Parsons 2012). Behavioural changes around whale watching boats have also been noted, including changes in diving, breathing rate, swimming direction, swimming speed, feeding, and resting. In terms of the six example species, these behavioural changes have been specifically noted for humpback whales (Corkeron 1995), sperm whales (Richter et al. 2006), and orcas (Noren et al. 2009). To combat the impacts of whale watching, voluntary, or in some cases mandatory, whale watching code-of-conducts have been put in place, often limiting the distance a boat can get to the animals, the speed they can go, and the time they can spend there (Garrod and Fennell 2004).

2.4.2 Offshore Wind Development

Plans for offshore wind farms, to produce clean renewable energy by harvesting the Arctic's windy conditions, are underway in several sub-Arctic/Arctic countries including Russia, Norway, and Finland. These developments are being designed to withstand ice and harsh Arctic conditions. Of particular concern for marine mammals is the loud noise from pile-driving required to construct the wind turbines in some cases. This noise presents much of the same issues as seismic surveys: behavioural changes, potential communication masking (particularly of blue whale calls), and potential hearing impairment at close range (Bailey et al. 2010). Since windfarms are often constructed in shallow, coastal waters, the harbour porpoise is thought to be one of the more effected species. Research found they would likely show "minor disturbance" at a sound level of 90 dB re 1 μ Pa (or estimated to be 70km away from the source), and "major disturbance" at a sound level of 155 dB re 1 μ Pa (or estimated to be 20km from the source) (Dähne et al. 2013). As with other underwater noise issues, it is likely that most other Arctic cetaceans could be affected by offshore wind farm construction depending on location, construction method, sound levels, and distance to the source. One way to eliminate the issues with construction is the planning of floating wind farm platforms that are just anchored to the sea floor (Roddi et al. 2010). This development also allows for turbines in deeper waters, to potentially choose sites with less impact on marine mammal habitats.

2.4.3 Depredation

Both sperm whales and orcas have a unique interaction with fisheries known as depredation. Depredation is when the whales specifically target the fishing boats as a food source, and essentially steal the fish off the lines or damage the fish that have been hooked. This is a learned behaviour that appears to be an issue all over the world, including in sub-Arctic and Arctic waters, as both species have a large distribution range. In Alaska, fish damage due to depredation by sperm whales has been found to occur in 46-65% of long-line sets when sperm whales are known to be present (Hill et al. 1999; Sigler et al. 2008). The target species of the long-line fishery is sablefish (black cod) (*Anoplopoma fimbria*). Similarly, orcas in Alaska and surrounding waters are depredating sablefish, as well as arrowtoothed flounder (*Atheresthes stomias*), Greenland turbot (*Reinhardtius hippoglossoides*) and several other long-line fished species.

Depredation has an effect on the catch of these long-line fisheries, and therefore there are cost implications to the companies. Where sperm whale depredation was recorded, there was an estimated 2% loss of sablefish catch in Alaskan waters (Sigler et al. 2008). Due to

depredation from orcas, there is a predicted annual loss of 11-29% of sablefish, 10-22% of arrowtoothed flounder, and 22% of Greenland turbot in Alaska and surrounding waters (Peterson et al. 2013). The fact that sperm whale and killer whale depredation is overlapping in these areas means the accumulative impacts of this issue are even larger. These two species seem to be the only culprits of this in Arctic waters. In response to these losses, fisheries have changed their methods, moving away from long-lines towards pot gear or trawls, or altered their fishing season in order to try to mitigate depredation (Peterson et al. 2013). In addition to the loss of catch, depredation can also have an impact on fish stock assessments used to set fishing quotas, since depredation is causing unrecorded fish removal (Purves et al. 2004). Depredation is known to have been increasing in the past decade and should be considered an important issue in the aforementioned expanding Arctic fisheries.

Overall, there is a lot of interaction and potential conflicts between human industrial activity in the Arctic and cetacean species living there seasonally or year-round. As discussed, human presence in Arctic waters is likely to continue to expand to new locations, and generally increase. Continuous research, monitoring, and impact mitigation plans will be needed to maintain sustainable development in the Arctic that is taking into account the impacts industries can have on Arctic flora and fauna, with cetaceans being an example of just one group of animals that are known to be widely affected by industries and industrial development.

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Paper II

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Using case studies to investigate cetacean bycatch/interaction under-reporting in countries with reporting legislation

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Using case studies to investigate cetacean bycatch/interaction under-reporting in countries with reporting legislation

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Abstract

A great hurdle to both fisheries and cetacean population management globally is the ability to accurately estimate cetacean bycatch. Accurate reporting of cetacean bycatch in/interactions with fishing gear in fisher logbooks would be of immense scientific value; however, despite some countries having mandatory reporting laws, logbook reporting is widely considered unreliable and cetacean catches are thought to be under-reported. This has led to the use of onboard observer programs, which are effective if coverage is high enough, but are also costly and therefore likely not feasible for many fisheries. Despite this widespread notion of logbook unreliability, under-reporting has rarely been quantified. For this study, initially we compiled the first comprehensive legislation summary of countries who have cetacean reporting laws (11 out of the top 30 countries with the largest fishing industries). We then used data provided by government and research agencies in three case study countries to test for differences between logbook and observer cetacean catch per unit effort (CPUE) (New Zealand and Iceland) and average number of individuals (USA) in trawl, net and/or hook and line gear types. Data was requested from 2009-2019, though not all fisheries had data available for all years. Fisher logbook CPUEs per gear type were calculated based on kgs of catch (New Zealand, USA), number of trips (Iceland lump sucker gillnets), and number of net-nights (number of nets x soak time) (Iceland cod and other gillnets). Observer data CPUEs were calculated in the same manner except for the USA, where observer bycatch/interaction estimates were available in the form of estimated average number of individuals caught per year, based on 5-year time blocks, so this data was compared to the average number of cetaceans caught per year in the fisher logbook data, based on the same 5-year time blocks. Additionally, CPUEs or average number of individuals were also compared for individual cetacean species in New Zealand (n = 3) and USA (n = 7, three of which were analyzed in two separate gears) in different gear types. When data was sufficient, fisher logbook CPUEs were compared over time periods to investigate changes in reporting. Comparisons were made using paired t-tests and Wilcoxon tests with a set alpha of 0.05. Overall, cetacean bycatch recorded by observers was higher than that from fisher logbooks by an average of 774% in trawls, 7348% in nets and 1725% in hook and line gears. When combining all years of data, fisher logbook CPUE or average number of individuals were significantly less than those from observer data for all gear types that could be examined in all countries, except for lining in New Zealand. Logbook CPUE/average number of individuals were also significantly lower for 2/3 species in New Zealand (1/1 in trawls and 1/2 in net), and 3/3 species in trawl, 3/5 species in net, and 2/2 species in hook and line in the USA. There was similar under-reporting in the case study countries despite differences in geographic location, cetacean species and EEZ size, suggesting these results would likely be similar in many countries

with comparable, well-developed fishing industries. Under-reporting in logbooks, despite laws, was clearly quantified and it is known that fishers have little incentive to report and have concerns over negative repercussions to the industry over bycatch issues. We suggest a first step to improving fisher reporting is implementation of clear and simple legislation, which is lacking, for example, in the Nordic countries. To make reporting as simple and least time consuming for fishers as possible, we suggest greater focus on the development of logbook smartphone apps with the possibility of easily submitting photos and videos as well as “written” reports, which would automatically upload to an online database that the relevant governing body could access. Finally, we suggest more trials using onboard camera monitoring of bycatch in place of onboard observers. The cameras are likely to improve logbook reporting since fishers know there is a way to verify their compliance, and a subset of the video footage could be used for reporting compliance verification each year. If reporting was verified to be accurate within a certain range, we suggest that fishers are compensated in some way in order to build a better relationship between fishers and scientists. These possible improvements to the accuracy of logbooks could start to minimize the need for expensive observer programs and increase cetacean bycatch data from diverse countries and fisheries. The quantified baseline data on under-reporting in different gear types calculated in this study can be used to verify improvements in reporting as new management practices are put in place.

Key words: cetacean, bycatch, logbook, CPUE, under-reporting

Introduction

Cetacean bycatch in or interaction with a wide array of fishing gear types is a global issue which is difficult to quantify and manage. Bycatch is defined as the capture of non-target species in fishing gear which died or were likely fatally injured (Hall, 1996). This is more often the case for small cetaceans that cannot free themselves from gear. Bycatch is considered one of the main causes of anthropogenic mortality in cetaceans and it was previously estimated that over 300,000 cetaceans are killed or seriously injured annually in fisheries world-wide (Read et al., 2006). Entanglement, or interaction, is defined as when an individual is caught in fishing gear but then escapes or is released alive (Moore, 2014). This is more often the case for large cetaceans who are strong enough to carry or break-free from gear. (Read et al. 2006). Despite their different biological adaptations, both odontocetes and mysticetes continue to suffer from bycatch and interact with fishing gear. Much of the fishing gear that has been implicated in such incidents, such as gillnets, is set in shallow waters with low visibility or deep waters with low light where it is very unlikely for cetaceans to see the gear in time to avoid it (Kastelein et al. 2000). Though odontocetes use echolocation, the acoustic reflectivity of nets is relatively weak, meaning the animals also have difficulty detecting them with their echolocation (Au and Jones 1991; Mooney et al. 2007). Though not using echolocation, hearing and interpretation of sounds is likely an important method for mysticetes to orient themselves and navigate in their environment (Lien et al. 1990) and it is hypothesized that they may not be able to acoustically detect fishing gear in such a way that they can avoid colliding with it.

Due to the detectability issues for the cetaceans, bycatch and interaction with fishing gear poses the serious threat of extinction to several small, vulnerable cetacean populations, such as the vaquita (eg. Taylor et al. 2017) and the North Atlantic right whale (eg. Moore et al. 2021), by causing unsustainable mortality. Even when not fatal, entanglements can potentially have negative impacts on the individual, such as lowered reproductive success (Robbins & Mattila, 2001; Rolland et al., 2017), which can then impact the recruitment rate of the population.

It is imperative to understand the magnitude of cetacean bycatch and interaction issues in fisheries in order to implement sustainable fishing practices and conserve cetacean populations. Having fishers log all cetacean bycatch and interactions would be of immense scientific value, and therefore some countries have developed logbook reporting systems for their respective fisheries and have made this reporting mandatory by law; however, accurate and reliable reporting is rare and few countries have systematically reported data (Read et al., 2006). Even in countries where reporting is mandatory, under-reporting of bycatch and interactions is still recognized as a serious issue (eg. Cornish et al. 2004). This has led to the need for onboard observers to monitor and record bycatch/interactions, but this is a costly solution that is not viable for all fisheries (Reeves et al. 2013). It has proven difficult for many countries to be able to quantify bycatch and under-reporting in their fisheries and in turn make informed management decisions (Young and Iudicello 2007). Understanding and managing cetacean bycatch has become a particularly important issue for governments worldwide since the United States of America (USA) began enforcing a rule in the Marine Mammal Protection Act stating that all imported fish products must come from fisheries that do not cause serious harm to marine mammal populations (NOAA, 2019). This rule came into effect on 1 January 2017 (Federal Register, 2016); however, an exemption period of 5 years was granted for countries to work on implementing proper marine mammal bycatch management (NOAA, 2019), meaning proper management practices need to be adopted by fisheries exporting their products to the USA by 2022.

In this study, we reviewed which countries require fishers to report cetacean bycatch, and then further reviewed the legislation of countries which have mandatory cetacean bycatch and/or interaction reporting. We then used data from four of these countries that have mandatory reporting; New Zealand, Iceland, USA, and Norway, for case studies investigating the amount of bycatch and/or interaction that is reported in different gear categories in each country. We then compared the reported cetacean bycatch/interaction rates reported in fisher logbooks to reported rates calculated from observer programs for three of these countries. Finally, we compared the results of these case studies and discussed strategies to improve cetacean bycatch/interaction reporting and monitoring which could be used to improve upon systems already in place or implemented in countries that have yet to tackle this problem.

Countries with cetacean bycatch/interaction reporting legislation

Twelve countries were identified as having legislation that included mandatory cetacean bycatch/interaction reporting. The laws differ between the countries in terms of what size vessels have to report and what legally has to be included in the details. Below is a summary of the cetacean bycatch reporting laws for each country individually. We acknowledge that this list may not be complete and will update it, once new information is available to us, at this website: heima.hafro.is/~gudjon/marinemammallegislation

USA

The USA has a federal Marine Mammal Protection Act (MMPA) that was established in 1972 (U.S. Fish & Wildlife Service International Affairs, n.d.). This act prohibits any take of marine mammals. Starting in 1994, under code § 1387, it became mandatory for all vessels fishing in a “Category I or II” fishery to apply for a “marine mammal authorization certificate” from the National Oceanic and Atmospheric Administration (NOAA) fisheries department which allows the vessel to incidentally take marine mammals without being in violation of the MMPA, so long as they are abiding to other regulations (Legal Information Institute, n.d.). Category I “designates fisheries with frequent deaths and serious injuries [to marine mammals] incidental to commercial fishing” and Category II “designates fisheries with occasional deaths and serious injuries [to marine mammals]” (NOAA Fisheries, n.d.a). In addition, under this same code, it became mandatory for all fishing vessels to report any death or serious injury of a marine mammal during fishing activities within 48 hours of the incident (Legal Information Institute, n.d.). The reports must include the vessel identification, the information of the owner, the name of the fishery, and the information about the incident including the species of marine mammal, the type of injury, and the date, time, and location. In addition to the mandatory reporting, NOAA has five hotlines for the different regions of the country to report a marine mammal in distress, as well as a smartphone app (NOAA Fisheries, n.d.b).

Canada

Canada’s Fisheries Act, first established in 1985, later included Marine Mammal Regulations in 1993 (Government of Canada, 2020). These regulations govern the protection and harvest of marine mammals in Canadian waters. The regulations were further amended in 2018 to include Accidental Contact with Marine Mammals regulations. These regulations made it mandatory for all interactions between vehicles or fishing gear and marine mammals to be reported to the Minister of Fisheries or reported in a mandatory logbook, even if the animal did not appear to be injured or deceased (Government of Canada, 2018). The incidents should be reported no later than 48 hours after the end of a fishing trip and must include the type of vehicle and/or type of fishing gear involved, the vessel name and owner, and specific information about the incident including species of marine mammal, date, time, location, and condition of the animal (Fisheries and Oceans Canada, n.d.). In addition to this mandatory reporting, Canada has eight hotlines set up in different regions of the country to report incidents of marine mammal entanglement where the animal is in need of professional assistance (Fisheries and Oceans Canada, 2020).

Australia

Australia’s Environment Protection and Biodiversity Conservation Act (EPBC) was implemented in 1999 (Australian Government Department of Agriculture, Water and the Environment, n.d.a). Under this act, all cetaceans are listed as protected species and the rules for all Commonwealth fisheries state “all interactions with EPBC Act-listed species, whether authorized or not, must be reported to the Department of the Environment and Energy” (Australian Government Department of Agriculture and Water Resources, 2018). All Australian Commonwealth fisheries are managed by the government’s Australian Fisheries Management Authority (AFMA) which permits accredited fisheries to incidentally interact with protected species without it being a punishable offence under the EPBC, so long as these interactions are recorded in AFMA fishing logbook (AFMA, n.d.).

An interaction includes “any physical contact a person, boat or gear has with a protected species”. In addition to incident reporting in logbooks, Australia also has nine agencies around the country which can be contacted in the event that a whale is witnessed entangled in fishing gear and is in need of professional assistance (Australian Government Department of Agriculture, Water and the Environment, n.d.b).

New Zealand

New Zealand implemented a Marine Mammal Protection Act, similar to the Act in USA, in 1978. Section 16 of this Act was created in 1996 and covers “Reporting of accidental death or injuries” which states that any person who incidentally kills or injures a marine mammal while fishing must both record the incident in the official logbook and submit a written report to the fishery officer within 48 hours of returning to port (Parliamentary Counsel Office, 1978). The reports must include the location, species or animal description, and the circumstances of the event. Despite the Act covering deaths or injuries, the fisher logbook data collected by Fisheries New Zealand also contains reports of cetaceans caught alive and uninjured (Fisheries New Zealand, pers. comm. 13.05.2020). In addition to this mandatory reporting, the New Zealand Department of Conservation has a hotline to report marine mammals entangled in fishing gear and in distress (Department of Conservation, n.d.).

Sweden

Harbour porpoises (*Phocoena phocoena*) are listed as a protected species in Sweden (Naturvårdsverket, 2016). Any porpoises which are found dead or incidentally killed in Sweden belong to the state and must be reported as stated in Article 33 of the Swedish Hunting Ordinance (1987:905) (Sveriges Riksdag, n.d.). The regulations are specifically in place for harbour porpoises only and do not include any other cetacean species that could be seen in Swedish waters. According to the Swedish Agency for Marine and Water Management (SwAM) it is not mandatory for fishers to report harbour porpoise bycatch in fishing logbooks (Havs- och vattenmyndighetens, 2018), but they are legally required to report this bycatch to the police or directly to the Swedish Museum of Natural History which is commissioned by SwAM to collect such reports (Naturhistoriska riksmuseet – Peter Mortensen, 2020). The reports must include the location (including coordinates), date, length of the animal, estimated weight of the animal (if possible), and optionally the depth of the fishing gear and the type of fishing gear (Naturhistoriska riksmuseet – Katarina Loso, 2020). Upon approval by the Swedish Museum of Natural History, compensation of 1000 Swedish krona (ca. 14000ISK/100USD) is paid to anyone who collects and freezes a deceased harbour porpoise for their research (Naturhistoriska riksmuseet – Katarina Loso, 2019).

Finland

In Finland, Section 62 of the Finnish Fishing Act, first established in 1982, covers reporting of bycatch (Finlex, 2015). The legislation simply states that any bycatch of harbour porpoises must be immediately reported to the Finnish National Resources Centre. No other cetacean species are covered by this legislation, and it is not specified how the reports should be submitted. It is possible for bycatch to be recorded in logbooks and then the logbook information reported to the National Resources Centre, or it is possible to make an online report through the National Resource Centre webpage (Olli Loisa, pers.

comm., 24 June 2020). The online report must include the name of the reporter or vessel, the date, time and location of the incident, the gender and age class of the animal (if known), and whether or not the animal was alive or deceased (Luonnonvarakeskus, n.d.).

Norway

Norway has “Regulations on position reporting and electronic reporting for Norwegian fishing and catching vessels” which state under § 10 and § 12 that vessels with a length of 15 m or more fishing in Norwegian waters must electronically report all catch, including bycatch of marine mammals, to the Norwegian Directorate of Fisheries (Nærings- og fiskeridepartementet, 2009). This mandatory reporting began in 2011 (Fiskeridirektoratet, pers. comm, 15 April 2021). The information required in the reports includes date, time, position, fishing zone, species, gear damage, number of animals, and weight. Most reports also include the gear type (though it is only mandatory to report when using a trawl) and mesh size (though it is only mandatory to report when using a trawl, Danish seine, or seine) (Nærings- og fiskeridepartementet, 2009). For recreational fishers and vessels below 15m in length, they have the option to voluntarily use an app (“fritidsfiskeappen”) to report bycatch to the Directorate of Fisheries, but this is currently not mandatory by law (Fiskeridirektoratet, pers. comm., 09 July 2020).

Iceland

Iceland established the Fisheries Management Act in 1990. Under Article 17 of this Act it is stated that all catch must be recorded in special logbooks which are provided by and submitted to the Directorate of Fisheries (FAOLEX Database, 2006). This must include information about all cetaceans. This logbook reporting system became electronic in 2009 and under Article 3 of the “Regulation on registration and electronic submission of catch information” states that all marine mammal bycatch must be reported in the electronic logbook, including date, ship identification, fishing gear type, location, species and number of animals (Atvinnuvega- og nýsköpunarráðuneyti, 2020).

France

Mandatory reporting of cetacean bycatch is relatively new in France. In 2018, the country passed the “Decree of September 6, 2018 amending the Order of July 1, 2011 setting the list of marine mammals protected on national territory and the terms of their protection” which states that all marine mammal bycatch must be reported in fishing logbooks (electronic for vessels 12 m and larger and paper for smaller vessels) for the purpose of scientific research (Ministère de l'Agriculture et de l'Alimentation, 2018). This came into effect 1 January 2019. The logbook reports must include the date, species, number of animals, estimated weight of each animal, and if the animal was discarded in the sea (Tachaires et al., 2018).

South Korea

The Korean Ministry of Oceans and Fisheries has a “Notice on Conservation and Management of Whale Resources”. This Notice was created in accordance with the Fisheries Act and Fisheries Resource Management Act for the “preservation and management of cetacean resources” in Korean waters (Ministry of Oceans and Fisheries, 2018). This notice states that any capture of a cetacean must be reported to the maritime

police chief, regardless of if the animal was alive or died during the incident. If the bycatch is reported to the maritime police, the fishers can then legally sell the meat (Mills et al., 1997). Due to this, it is possible that “incidental” take in Korean waters may at times actually be intentional capture, which is then reported as bycatch in order to profit from the sales (Baker et al., 2006; Lukoschek et al., 2009). All Korean cetacean bycatch data is first confirmed by an inspector (South Korea Ministry of Oceans and Fisheries, pers. comm. 08 May 2020) and is then reported to the International Whaling Commission (IWC). The available data in the progress reports include year, location, species, number of animals, life status of the animals, and fishing gear involved (IWC, n.d.).

Chile

In September 2012, Article 7 of the Chilean General Law for Fisheries and Aquaculture was amended to include law no. 20.625 “Law on Discards and Bycatch” (Subsecretaría de Pesca y Acuicultura, n.d.). Under this law, fishers are required to report bycatch of all marine mammals in vessel logbooks, which are electronic for commercial fishing vessels over 15 m and paper for artisanal vessels. The logbooks are collected by the National Fisheries and Aquaculture Service. The law states that all marine mammals are released when possible, and all reports of interaction incidents must include details about the vessel, location, date, number of animals caught, species, and life status (dead or alive) (Subsecretaría de Pesca y Acuicultura, pers. comm., 10 November 2020).

Japan

Since 2001, Article 91, Paragraph 2 of the Ministerial Ordinance on Fisheries Permits and Controls (in Ministry of Agriculture, Forestry and Fisheries Ordinance No. 5 of 1963) has included mandatory reporting of “baleen whale, etc.” bycatch in fixed fishing nets (Fisheries Agency Research Management Department, 2020; Institute for Cetacean Research, 2011). The law covers seven species of baleen whale and three species of toothed whale designated by the IWC. A bycatch report should be submitted for all incidents, including releasing the animal alive. A bycatch report must include date and location, species (including a photograph), type of set net fishery and permit number, and length, gender, evidence of lactation, and measurements of foetus (if the animal was deceased) (Institute for Cetacean Research, 2011). It is also required to take a DNA sample and send it for testing to the Institute of Cetacean Research if the animal will be used. Once these actions are completed, it is permitted to sell the whale meat or use it for personal consumption. The Japanese Fisheries Resources Conservation Law also includes an additional three species of baleen whale and one species of toothed whale that must be reported, for which possession and sale are prohibited (Institute for Cetacean Research, 2011).

Methods

The search for countries which have cetacean bycatch/interaction reporting laws was based on the top 30 countries with the largest fishing industries (FAO, 2018). An internet search was used to determine the fisheries governing body in each country and search their fisheries legislature for the keywords “mammal”, “bycatch”, “reporting”, and “log”. For countries where the relevant legislature could not be found or was not clear due to language barriers, the governing body was contacted directly through email to ask for further information.

The governments and relative ministries in each of the countries with cetacean bycatch reporting legislation were contacted directly through email about this study to inquire about available data. For those countries where it was possible, data was requested from 2009-2019. Raw fisher-reported logbook data including year, species, number of animals, and gear type was provided directly from Fisheries New Zealand, National Oceanic and Atmospheric Administration (NOAA) (USA), Fiskistofa (Directorate of Fisheries) and Hafrannsóknastofnun (Marine and Freshwater Research Institute) (Iceland), and Fiskeridirektoratet (Directorate of Fisheries) (Norway). Fishing effort data per year was provided by Fisheries New Zealand, Fiskistofa and Hafrannsóknastofnun (Iceland), and Havforskningsinstituttet (Norway). For the USA, effort data was provided by Pacific Fisheries Information Network, Western Pacific Fisheries Information Network, Alaska Fisheries Information Network, Gulf States Marine Fisheries Commission, and Atlantic States Marine Fisheries Commission, which included data for each state and territory (including Puerto Rico and the US Virgin Islands), except for Alabama, where permission was not granted to release this data. Fisher-reported cetacean bycatch/interactions per unit effort (“catch”) (CPUE) per gear type were calculated based on kgs of catch (New Zealand, Norway, USA), number of trips (Iceland lumpsucker gillnets), and number of net-nights (number of nets x soak time) (Iceland cod and other gillnets). CPUE was also calculated for individual species per gear type category when data were sufficient. All fisher logbook CPUEs were calculated using all reports where gear type was specified, regardless of the reported life-status of the animal.

Cetacean bycatch estimates from observer programs in each of the case study countries were provided directly from the relevant government or research office (New Zealand, Iceland) or gathered from the NOAA official stock assessment reports (USA; <https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-stock-assessment-reports-species-stock#cetaceans>) similar to work conducted by Read et al., 2006 on earlier data. Minimum estimates of cetacean bycatch per year were calculated from the stock reports only considering data coming directly from observer programs and excluding supplementary data that is available in some reports such as from strandings. Norwegian “reference fleet” data, which is used to estimate cetacean bycatch in Norwegian waters, was not available for comparison for this study.

To compare the two methods of quantifying bycatch (logbook vs. observer), pairwise t-test or wilcoxon test comparisons between fisher logbook CPUE and observer CPUE were conducted for each gear category and species, where data were sufficient, for New Zealand and Iceland. Since the USA observer bycatch/interaction estimates were available in the form of estimated average number of individuals caught per year, based on 5-year time blocks, this data was compared to the average number of cetaceans caught per year in the fisher logbook data, based on the same 5-year time blocks, also using pairwise t-tests or wilcoxon tests. T-tests were used to compare “early time period” vs. “late time period” CPUE for each gear category in order to investigate logbook reporting over time in each of the case study countries. All tests were performed using a set alpha of 0.05 in the statistical software R (The R Foundation for Statistical Computing, version 3.6.1).

Results

Reported cetacean bycatch/interactions by observers were on average 774% higher than fisher reported bycatch in trawls, 7348% higher in nets and 1725% higher in hook and lines. When breaking down this data by individual countries, the average annual estimated

CPUE of cetaceans based on observer data in New Zealand was 52% higher in trawl, 779% higher in passive netting, and 754% higher in lining compared to the CPUEs based on fisher logbook data (Table 1). In Iceland, the estimated CPUE based on observer data was 329% higher in the lumpfish gillnet fishery and 26920% higher in the cod and others (cod+) gillnet fishery compared to CPUEs based on fisher logbook data. For the USA, the mean annual number of individuals estimated as bycatch/seriously injured based on observer data pooled into five-year time blocks was on average 2696% higher in hook and lines, 1365% in nets, and 1495% in trawl when compared to the mean annual number of individuals in the same five-year times blocks reported in fisher logbooks (Table 1). For Norway, CPUEs for the 15m+ vessel fishing fleet were calculated based on fisher logbooks for the first time, but there were no available data to compare this to the 15m+ vessel reference fleet. However, for seines (n = 3), trap (n = 1), and trawl (n = 13) gear categories, there were reports in the fisher logbooks that were not detected by the reference fleet (Norway Marine Research Institute, pers comm.). Further results from statistical comparisons between fisher logbook data and observer data for each case study country are detailed below.

Table 1. Average annual number of individual cetaceans reported as bycatch per year, average annual catch per unit effort (CPUE) based on 100kg fish caught (New Zealand, Norway, USA), number of trips (Iceland lumpfish gillnet) or net-nights (Iceland cod+ gillnet), coefficient of variance (CV) and 95% confident intervals (CIs) calculated based on fisher logbook data and observer data CPUEs for each country and each gear type for which the average annual number of cetaceans caught was at least 1 animal.

Country	Gear-type	Group	Average number individuals reported per year	Average CPUE per year	Percent increase (%)	CV	CIs
New Zealand	Passive Netting	Fisher	5.1	1.04E-04		0.67	6.4E-05 - 1.5E-04
		Observer	1.7	9.14E-04	+779	0.87	4.2E-04 - 1.4E-03
	Trawl	Fisher	18.4	5.41E-06		0.54	3.7E-06 - 7.1E-06
		Observer	11.7	8.22E-06	+52	0.77	4.5E-06 - 1.2E-05
	Lining	Fisher	2.1	1.37E-05		1.00	4.6E-06 - 1.8E-05
		Observer	1.1	1.17E-04	+754	1.31	1.7E-05 - 2.2E-04
Iceland	Lumpfish gillnet	Fisher	107.8	2.96E-02		0.92	7.8E-03 - 5.2E-02
		Observer	7.7	1.27E-01	+329	0.51	7.5E-02 - 1.8E-01
	Cod+ gillnet	Fisher	54.0	2.92E-04		0.26	2.2E-04 - 3.7E-04
		Observer	30.3	7.89E-02	+26920	0.22	6.2E-02 - 9.6E-02
Norway	Gillnet	Fisher	1.1	2.87E-06		1.22	5.8E-07 - 5.2E-06
	Trawl	Fisher	1.4	1.74E-07		1.28	2.9E-08 - 3.2E-07
USA*	Trawl	Fisher	23.0	2.60E-06		0.31	16.8 - 29.3
		Observer	368.2	X	+1495	0.49	209.5 - 526.6
	Net	Fisher	26.7	2.78E-06		0.25	20.9 - 32.5
		Observer	391.5	X	+1365	0.54	205.3 - 577.9
	Hook & line	Fisher	6.1	6.76E-06		0.09	5.6 - 6.6
		Observer	170.0	X	+2696	0.47	99.3 - 240.8

*USA CV and CIs are based on average number of individuals reported based on 5-year time block, not CPUE, due to the observer data being available is raised number of individuals per the same time blocks.

New Zealand

There were nine cetacean species reported as bycatch in the New Zealand exclusive economic zone between 2009 – 2019 in fisher logbooks (Table 2). There were also reports of unspecified dolphin/toothed whales, baleen whales, and beaked whales. When grouping all the reports from all years, 90.4% were dolphins/porpoises, 7.0% were small whales, and 2.6% were large whales. New Zealand logbooks specify between the categories of “alive

and uninjured”, “alive and injured” and “deceased”. When combining all reports from all years the percent of individuals reported in each category were 2.1%, 17.5% and 80.4% respectively. Reports came from six different gears (trawl, passive netting, lining, other lining, potting, and seine). There were seven cetacean species reported in the observer data, six of which were also reported in the fisher data and one of which was not (Risso’s dolphin (*Grampus griseus*)). The observer data did not include bycatch records of minke whale (*Balaenoptera bonaerensis*), humpback whale (*Megaptera novaeangliae*) or fin whale (*Balaenoptera physalus*), which were reported in the fisher logbook data, though it did have records of unspecified baleen whales which may account for these species. The observer data only consistently covered trawls (25.9-56.1% coverage per year), passive netting (0-10.2% coverage per year), and lining (1.8-11% coverage per year), and rarely covered the other gears (other lining, potting, and seine). Despite observer coverage in lining, trawl and passive netting, as well as a low coverage in “other lining” and potting, there was no observed cetacean bycatch in any gear type in 2019.

Cetacean catch per unit effort (CPUE) was calculated for trawl, passive netting and lining, as well as for three dolphin species for which the most data were available (common dolphins (*Delphinus delphis*) in trawl gear, Hector’s dolphins (*Cephalorhynchus hectori*) in passive netting gear, and dusky dolphins (*Lagenorhynchus obscurus*) in passive netting gear). The trawl category had the highest total number of individuals reported in fisher logbook data ($n = 202$). The fisher CPUE for trawl fisheries was significantly less than the observer CPUE for all years combined (2009-2019) ($p = 0.028$, $t = -2.16$) (Table 3). Data was also sufficient to split trawl data into an early time period (2009-2014) and a late time period (2015-2019). The fisher logbook trawl CPUE was significantly lower than the observer trawl CPUE for the earlier time period ($p = 0.004$, $t = -4.16$); however, there was no difference between the CPUEs for the later time period ($p = 0.68$, $t = 0.50$). When comparing the fisher logbook trawl CPUE for the early time period to the late time period, there was no significant difference between them ($p = 0.65$, $W = 18$) (Table 4).

Comparison of the CPUEs for passive netting yielded similar results, with fisher logbook CPUE being significantly lower than observer CPUE for all years combined (2009-2019, excluding 2011 when there was no observer coverage) ($p = 0.0071$, $t = -3.03$), fisher logbook CPUE being significantly lower than observer CPUE in the earlier time period (2009-2014, excluding 2011) ($p = 0.003$, $t = -5.34$), and there being no significant difference between the CPUEs in the later time period (2015-2019) ($p = 0.22$, $t = -0.86$) (Table 3). When comparing the fisher logbook CPUE for the earlier time period to the later time period, there was no significant difference between them ($p = 0.72$, $t = -0.38$) (Table 4).

The CPUEs for lining were not significantly different for all years combined (2009-2019, excluding 2010 and 2013 when there was no observer coverage) ($p = 0.43$, $V = 15$) (Table 3). It was not possible to compare the CPUEs for the early time period due to little observer data; however, CPUEs could be compared for the late time period (2015-2019). For the late time period, fisher logbook CPUE was significantly lower than observer CPUE ($p = 0.021$, $t = -2.95$). When comparing the fisher logbook CPUE for the early time period to the late time period, there was no significant difference between them ($p = 0.18$, $t = -1.47$) (Table 4).

The fisher logbook CPUE for common dolphins in trawl gear was significantly lower than the observer CPUE for all years combined (2009-2019) ($p = 0.011$, $t = -2.70$) (Table 5).

The fisher logbook CPUE was also significantly lower in the early time period (2009-2014) ($p = 0.002$, $t = -5.05$), but was not significantly lower in the later time period (2015-2019) ($p = 0.49$, $t = -0.032$). The fisher logbook CPUE for Hector's dolphins caught in passive net gear was also significantly lower than the observer CPUE for all years combined (2009-2019, excluding 2011 when there was no observer coverage) ($p = 0.018$, $t = -2.46$) and significantly lower in the earlier time period (2009-2014, excluding 2011) ($p = 0.012$, $t = 3.59$) (Table 5). There was not enough observer reported bycatch of Hector's dolphins to compare the late time period. Oppositely, there was no significant difference in the CPUEs for dusky dolphins caught in passive netting for all years combined (2009-2019, excluding 2011 when there was no observer coverage) ($p = 0.28$, $V = 10$) and no significant difference between the CPUEs for the early time period (2009-2014, excluding 2011) ($p = 0.10$, $t = -1.54$) (Table 5). There was not enough observer reported bycatch of dusky dolphins in passive net gear to compare the late time period.

Iceland

There were eight cetacean species reported as bycatch in Icelandic fisher logbooks in the years where reporting could be considered complete (2014-2019) (Table 2). There were also reports of an unspecified dolphin and unspecified medium cetacean. When grouping all the reports from all years, 99.2% were dolphins/porpoises, 0.51% were small whales, and 0.31% were large whales. Reports came from three different fishing gear categories (trawl, passive netting, and hook and line). There were 984 individual cetaceans reported as bycatch in all gear combined between 2009-2019; however, 647 of these individuals could be included in this study from the lumpfish gillnet fishery (2014-2019) and 216 of these individuals could be included in this study from the "cod and others" (cod+) gillnet fishery (2016-2019). There were only two cetacean species reported in the observer data (harbour porpoise (*Phocoena phocoena*) and white-beaked dolphin (*Lagenorhynchus albirostris*). Cetaceans were only observed by inspectors in two gillnet categories: lumpfish gillnetting (0.74-2.82% coverage per year), and cod and other (cod+) gillnetting (0.15-0.25% coverage per year). There is also some inspector coverage on bottom trawls and long-lines (ICES, 2020), however there has never been cetacean bycatch reported (Iceland Marine and Freshwater Research Institute, unpub. data).

Cetacean catch per unit effort was calculated separately for each of the two gillnet fisheries that had inspector coverage (lumpfish and cod+). Inspectors started reporting marine mammal bycatch in the lumpfish fishery in 2014 and the cod+ fishery in 2016, therefore only data from these years onwards could be used in CPUE comparisons. The fisher logbook CPUE for the lumpfish gillnet fishery was significantly less than the inspector reported CPUE for all years combined (2014-2019) ($p = 0.003$, $t = -4.67$) (Table 3). Data was also sufficient to split the lumpfish gillnet data into an early time period (2014-2016) and a late time period (2017-2019). The fisher logbook CPUE was significantly lower than the inspector CPUE for the early time period ($p = 0.006$, $t = -9.27$); however, there was no significant difference between the CPUEs for the late time period ($p = 0.10$, $t = -1.94$). When comparing the fisher logbook CPUE for the early time period to the late time period, there was no significant difference between them ($p = 0.14$, $t = -2.17$) (Table 4).

The fisher logbook CPUE was also significantly lower than the inspector reported CPUE for the cod+ gillnet fishery for all years combined (2016-2019) ($p = 0.001$, $t = -9.29$) (Table 3). There were not enough years of data to compare an early and late time period of the fisher and observer CPUEs or to compare the fisher logbook CPUE over time.

Norway

There were six cetacean species reported by Norwegian fishing vessels 15 m or greater (15m+) between 2011-2019 (Table 2). When grouping all the reports from all years, 48.2% were dolphins/porpoises, 14.8% were small whales, and 37.0% were large whales. The reports came from five different gear types (Danish seine, purse seine, trawl, trap, and gillnet). There were only two species reported as bycatch by the 15m+ reference fleet (harbour porpoise and minke whale) and, additionally, reports simply labeled as “dolphin”. The reference fleet reports did not include orca (*Orcinus orca*), beluga (*Delphinapterus leucas*), blue whale (*Balaenoptera musculus*), or bottlenose dolphin (*Tursiops truncatus*) which were included in the fisher logbook data. Reports from the reference fleet were from two different gear categories (hook and line and gillnet). There was no available data on the effort of the 15m+ reference fleet, therefore it was not possible to statistically compare the fisher logbook CPUEs to the reference fleet CPUEs for these gear categories. However, it could be noted that there was cetacean bycatch reported in the fisher logbook data in the seine, trawl, and trap gear categories that were not detected by the reference fleet, though the fleet is covering these gear categories (Norway Marine Research Institute, pers. comm.). Fisher logbook gillnet and trawl CPUEs could be compared between an early time period (2011-2015) and a late time period (2016-2019) for each gear separately. Both the gillnet and trawl CPUEs did not differ significantly between the two time periods ($p = 0.08$, $W = 3$; $p = 0.90$, $W = 9$ respectively) (Table 4).

USA

There were 21 different cetacean species reported as bycatch/seriously injured in fisher logbooks in the USA between 2009-2017, matching the dates for which observer reports were available (Table 2). There were also reports of unidentified baleen whales, small cetaceans (porpoise or dolphin), toothed whales and beaked whales. When combining all reports for all years, 73.3% were dolphins and porpoises, 18.3% were small whales, and 8.5% were large whales. Furthermore, 24.0% were reported as injured, 72.8% were reported as killed, and 3.2% were unknown due to the status being left blank. The logbook reports came from four broad gear categories that were available for the USA data: trawl, pot and trap, hook and line, and net. The net category included all set nets and seine gear. There were 21 species reported as bycatch between 2009-2017 in observer data reported in the NOAA Marine Mammal Stock Assessment Reports (<https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-stock-assessment-reports-species-stock>). However, in the fisher logbook data, pilot whales were not split into the two known species (*Globicephala melas* and *Globicephala macrorhynchus*) so these species were also combined in the observer data (taking the total down to 20). Fisher logbook data included spinner dolphins (*Stenella longirostris*) and Bryde’s whales (*Balaenoptera edeni*) which were not in the observer reports. The observer reports included pygmy sperm whales (*Kogia breviceps*) which were not included in the fisher reports, however, the unidentified toothed whales in the fisher reports may account for this species.

USA observer bycatch data is reported as the mean annual number of individuals of each species caught based on the most recent five years of data. For comparison, the same means were calculated using the fisher logbook data for the same five five-year time blocks (2009-2013, 2010-2014, 2011-2015, 2012-2016 and 2013-2017) for net, trawl, and hook and line, gears. The mean number of cetaceans reported as bycatch annually in the

fisher logbook data was significantly lower than the observer estimates for the net, trawl and hook and line gear types ($p = 0.009$, $t = -3.9$; $p = 0.006$, $t = -4.4$; $p = 0.005$, $t = -4.6$ respectively) (Table 3).

Comparisons were also made between the mean annual number of individuals of the most commonly reported species in the fisher logbook data (species reported in five or more years between 2009-2017), excluding means from time blocks where the observer report was not available. These were bottlenose dolphin (excluding 2012-2016 mean), common dolphin (excluding 2012-2016 mean), harbour porpoise (excluding 2011-2015 mean), humpback whale, and pilot whale spp. (excluding 2011-2015 mean) in the net category; Atlantic white-sided dolphin (*Lagenorhynchus acutus*), bottlenose dolphin (excluding 2011-2015 and 2012-2016 means) and common dolphin (excluding 2012-2016 mean) in the trawl category; and false killer whales (*Pseudorca crassidens*) and pilot whale spp. (excluding 2011-2015) in the hook and line category.

In the net category, harbour porpoise, common dolphin, and bottlenose dolphin mean annual number of individuals reported as bycatch/serious injury were significantly lower in the fisher logbook data when compared to the estimated annual means from the observer data ($p = 0.008$, $t = -4.9$; $p = 0.0004$; $t = -14.0$; $p = 0.04$, $t = -2.6$ respectively) (Table 5). There was no significant difference between the mean annual number of pilot whale spp. calculated from fisher logbook data and the mean annual number calculated from observer data ($p = 0.32$, $t = 1.17$). The mean annual number of humpback whales calculated from fisher logbook data was significantly greater than the mean annual number estimated from observer data ($p = 0.00002$, $t = 20.7$).

In the trawl category, the mean annual numbers of individuals reported as bycatch/serious injury in the fisher logbook data were significantly less than the estimated annual means from the observer data for all three species (Atlantic white-sided dolphin: $p = 0.02$, $t = -2.9$; bottlenose dolphin: $p = 0.002$, $t = -16.4$; common dolphin: $p = 0.00007$, $t = -24.6$) (Table 5).

In the hook and line category, the mean annual numbers of individuals reported as bycatch/serious injury in the fisher logbook data were significantly less than the estimated annual means from the observer data for both species (false killer whale: $p = 0.009$, $t = -7.3$; pilot whale spp.: $p = 0.0002$, $t = -17.8$) (Table 5).

CPUEs were calculated for the fisher logbook data and used to compare reporting over time. Data was sufficient to compare an early time period (2009-2014) with a late time period (2015-2019) for the net, trawl, and hook and line categories. There was no significant difference between the two time periods for any of the categories ($p = 0.59$, $t = -0.55$; $p = 0.11$, $t = 1.93$; $p = 0.17$ $W = 7$ respectively) (Table 4).

Table 2. Cetacean species included in cetacean bycatch/interaction reports from each country, with indication of if they were reported in both fisher logbook and observer data (F+O), fish logbook data only (F), or observer data only (O).

Country	Common name	Scientific name	Reported in
New Zealand	Bottlenose dolphin	<i>Tursiops truncatus</i>	F+O
	Common dolphin	<i>Delphinus delphis</i>	F+O
	Dusky dolphin	<i>Lagenorhynchus obscurus</i>	F+O
	Hector's dolphin	<i>Cephalorhynchus hectori</i>	F+O
	Killer whale	<i>Orcinus orca</i>	F+O
	Pilot whale	<i>Globicephala</i> spp.	F+O
	Fin whale	<i>Balaenoptera physalus</i>	F
	Humpback whale	<i>Megaptera novaeangliae</i>	F
	Minke whale	<i>Balaenoptera acutorostrata</i>	F
Risso's dolphin	<i>Grampus griseus</i>	O	
Iceland	Harbour porpoise	<i>Phocoena phocoena</i>	F+O
	White-beaked dolphin	<i>Lagenorhynchus albirostris</i>	F+O
	Common dolphin	<i>Delphinus delphis</i>	F
	Risso's dolphin	<i>Grampus griseus</i>	F
	Cuvier's beaked whale	<i>Ziphius cavirostris</i>	F
	Northern bottlenose whale	<i>Hyperoodon ampullatus</i>	F
	Fin whale	<i>Balaenoptera physalus</i>	F
	Humpback whale	<i>Megaptera novaeangliae</i>	F
Norway	Harbour porpoise	<i>Phocoena phocoena</i>	F+O
	Minke whale	<i>Balaenoptera acutorostrata</i>	F+O
	Bottlenose dolphin	<i>Tursiops truncatus</i>	F
	Beluga whale	<i>Delphinapterus leucas</i>	F
	Killer whale	<i>Orcinus orca</i>	F
	Blue whale	<i>Balaenoptera musculus</i>	F
USA	Harbour porpoise	<i>Phocoena phocoena</i>	F+O
	Atlantic white-sided dolphin	<i>Lagenorhynchus acutus</i>	F+O
	Bottlenose dolphin	<i>Tursiops truncatus</i>	F+O
	Common dolphin	<i>Delphinus delphis</i>	F+O
	Dall's porpoise	<i>Phocoenoides dalli</i>	F+O
	Northern right whale dolphin	<i>Lissodelphis borealis</i>	F+O
	Pacific white sided dolphin	<i>Lagenorhynchus obliquidens</i>	F+O
	Risso's dolphin	<i>Grampus griseus</i>	F+O
	Rough-toothed dolphin	<i>Steno bredanensis</i>	F+O
	Beluga whale	<i>Delphinapterus leucas</i>	F+O
	Dwarf sperm whale	<i>Kogia sima</i>	F+O
	False killer whale	<i>Pseudorca crassidens</i>	F+O
	Killer whale	<i>Orcinus orca</i>	F+O
	Pilot whale	<i>Globicephala</i> spp.	F+O
	Sperm whale	<i>Physeter macrocephalus</i>	F+O
	Gray whale	<i>Eschrichtius robustus</i>	F+O
	Humpback whale	<i>Megaptera novaeangliae</i>	F+O
	Fin whale	<i>Balaenoptera physalus</i>	F+O
	Minke whale	<i>Balaenoptera acutorostrata</i>	F+O
	Spotted dolphin	<i>Stenella</i> spp.	F
	Bryde's whale	<i>Balaenoptera brydei</i>	F
Pygmy sperm whale	<i>Kogia breviceps</i>	O	

Table 3. p-value results of paired t-test/wilcoxon tests determining if fisher reported CPUE was significantly lower than observer reported CPUE (New Zealand, Iceland) and if fisher reported annual average number of individuals based on 5-year time blocks significantly differed from observer reported annual average number of individuals based on the same 5-year time blocks (USA) for each gear category where enough data were available. Significant p-values are in bold.

Country	Gear category	Time period	Years	p-value
New Zealand	Trawl	All	2009-2019	0.028
		Early	2009-2014	0.004
		Late	2015-2019	0.68
	Passive netting	All	2009-2019 (ex. 2011)	0.007
		Early	2009-2014 (ex. 2011)	0.003
		Late	2015-2019	0.22
	Lining	All	2009-2019 (ex. 2010, 2013)	0.43
		Early	X	X
		Late	2015-2019	0.021
Iceland	Lumpfish gillnet	All	2014-2019	0.003
		Early	2014-2016	0.006
		Late	2017-2019	0.1
	Cod+ gillnet	All	2016-2019	0.001
		Early	X	X
		Late	X	X
USA	Trawl	All time blocks	*	0.006
	Net	All time blocks	*	0.009
	Hook & line	All time blocks	*	0.005

* USA data was based on average number of individuals for the 5-year time blocks 2009-2013, 2010-2014, 2011-2015, 2012-2016 and 2013-2017.

Table 4. Average CPUE and p-value results of t-tests or Wilcoxon tests comparing fisher logbook CPUE over time for all gear types with sufficient data.

Country	Gear-type	Group	Years	Average CPUE	p-value
New Zealand	Passive Netting	Early	2009-2014	9.3487E-05	0.72
		Late	2015-2019	0.000111538	
	Trawl	Early	2009-2014	6.11667E-06	0.65
		Late	2015-2019	0.000004568	
	Lining	Early	2009-2014	6.92333E-06	0.18
		Late	2015-2019	1.63536E-05	
Iceland	Lumpfish gillnet	Early	2014-2016	0.011307951	0.14
		Late	2017-2019	0.047988214	
Norway	Gillnet	Early	2011-2015	9.71898E-07	0.08
		Late	2016-2019	5.23959E-06	
	Trawl	Early	2011-2015	9.75392E-08	0.9
		Late	2016-2019	2.70052E-07	
USA	Trawl	Early	2009-2014	3.1251E-06	0.11
		Late	2015-2019	1.47519E-06	
	Net	Early	2009-2014	2.53633E-06	0.59
		Late	2015-2019	3.06044E-06	
	Hook & line	Early	2009-2014	6.41707E-06	0.17
		Late	2015-2019	9.2772E-06	

Table 5. p-value results of paired t-test/wilcoxon tests determining if fisher reported CPUE is significantly lower than observer reported CPUE (New Zealand) and if fisher reported annual average number of individuals based on 5-year time blocks is significantly lower than observer reported annual average number of individuals based on the same 5-year time blocks (USA) for the most commonly reported species in specific gear categories. Significant p-values are in bold.

Country	Gear category	Species	Time period	Years	p-value
New Zealand	Trawl	Common dolphin (<i>delphinus delphis</i>)	All	2009-2019	0.011
			Early	2009-2014	0.002
			Late	2015-2019	0.49
	Passive netting	Hector's dolphin (<i>Cephalorhynchus hectori</i>)	All	2009-2019 ex. 2011)	0.018
			Early	2009-2014 ex. 2011	0.012
			Late	X	X
	Passive netting	Dusky dolphin (<i>Lagenorhynchus obscurus</i>)	All	2009-2019 ex. 2011)	0.28
			Early	2009-2014 ex. 2011	0.1
			Late	X	X
USA	Net	Bottlenose dolphin (<i>tursiops truncatus</i>)	All (ex. 2012-2016 mean)	*	0.04
		Common dolphin (<i>delphinus delphis</i>)	All (ex. 2012-2016 mean)	*	0.0004
		harbour porpoise (<i>Phocoena phocoena</i>)	All (ex. 2011-2015 mean)	*	0.008
		Humpback whale (<i>Megaptera novaeangliae</i>)	All	*	0.00002**
		Pilot whale (<i>Globicephala</i> spp.)	All (ex. 2011-2015 mean)	*	0.32
	Trawl	Atlantic white-sided dolphin (<i>Lagenorhynchus acutus</i>)	All	*	0.02
		Bottlenose dolphin (<i>tursiops truncatus</i>)	All (ex. 2011-2015 and 2012-2016 mean)	*	0.002
		Common dolphin (<i>delphinus delphis</i>)	All (ex. 2012-2016 mean)	*	0.00007
	Hook & Line	False killer whale (<i>Pseudorca crassidens</i>)	All	*	0.009
		Pilot whale (<i>Globicephala</i> spp.)	All (ex. 2011-2015 mean)	*	0.0002

* USA data was based on average number of individuals for the 5-year time blocks 2009-2013, 2010-2014, 2011-2015, 2012-2016 and 2013-2017.

**p-value showing mean annual humpback whale bycatch/interaction was significantly higher in the fisher logbook data compared to the observer data

Discussion

Out of the 30 countries with the largest fishing industries in the world (FAO, 2018), only 12 were determined to have some form of cetacean bycatch/interaction reporting legislation. The legislation ranged from very minimal (only harbour porpoises seemingly covered by law in Sweden and Finland and very little reporting) to well established (clear legislation and logbook reporting including all species e.g. in USA and New Zealand). Of these 12, nine of the countries were identified as also having some level of onboard observer coverage which they use to calculate cetacean bycatch/interaction CPUE, which varies by percent coverage and fisheries monitored (e.g. Australian Fisheries Management Authority, n.d.; Hanrahand and Melindy, 1997; Muñoz et al., 2018; ICES, 2020; National Marine Fisheries Service, 2020; Ministry for Primary Industries New Zealand, 2020). Finland does not have any form of observer program (ICES, 2020) and no information could be found for South Korea, other than that all landed bycatch is verified by an inspector (South Korea Ministry of Oceans and Fisheries, pers. comm., 08 May 2020).

This study provides a broad, quantitative overview of the global issue of under-reporting of cetacean bycatch/interactions in fisher logbooks compared to observer programs using case studies of entire countries. Due to the difficult nature of accessing and/or compiling datasets for countries as a whole, under-reporting of cetacean bycatch/interactions has not been investigated in this manner previously. When looking generally at the differences between fisher logbook and observer data from New Zealand, USA, and Iceland, the average bycatch of cetaceans per year (dead or alive) was underestimated by anywhere between 52-26920% for the three major gear types which could be examined (trawl, net, and hook and line). The differences were significant when combining data for all available years for all gear types that could be examined in each country, except for the lining category in New Zealand, despite an over 750% increase in CPUE calculated from observer data. Low observer coverage and zeros in the data may have affected the results in this case. Under-reporting of harbour porpoise bycatch in the gillnet fishery in Iceland was quantified previously through a questionnaire, which determined logbook data underestimated bycatch by a ratio of approximately 1:26 (Ólafsdóttir, 2010). Quantified cetacean under-reporting in logbooks has not been published for fisheries in the other case study countries. In addition, CPUE of cetaceans in Norway's 15m+ fishing fleet, though small, was quantified using logbook data for the first time. This determined that there is some amount of cetacean bycatch in Norway going unaccounted for that is likely underestimated given the trend in the other countries with well-developed fishing industries.

For cases where it was possible to split data into both early and late time periods for separate comparisons (trawl and passive netting in New Zealand, lumpfish gillnet in Iceland), the fisher logbook CPUEs were significantly lower than the observer CPUEs for the early time period but there were no significant differences between them in the late time period for all cases. We considered if this could be an indication that fisher reporting was increasing over time in these fisheries; however, when we compared the fisher logbook CPUEs from the early time period to the late time period there was no significant differences and therefore no evidence that fishers increased reporting over time. The most likely explanation is that small sample sizes and zeros in the data from late time periods affected the results; however, we cannot rule out that even though fishers did not report significantly more bycatch/interactions in recent years, there may be less to report overall, decreasing the gap between fisher and observer CPUEs. The logbook data from fishers

could be a very valuable tool for gaining insight into cetacean bycatch and interaction with fishing gear; however, given the overall stark differences in reporting in logbooks versus estimations of bycatch calculated from observer data, it is clear that there is vast room for improvement in logbook reporting.

The fact that the three countries for which comparisons could be made between cetacean bycatch/interaction data reported in fisher logbooks and bycatch estimates calculated from observer data differ in geographic location, cetacean species and size of exclusive economic zone (New Zealand: 1.2 million square nautical miles (Sea Around Us, 2016), US: 3.4 million square nautical miles (NOAA, 2011), Iceland: 0.22 million square nautical miles (FAO, 2011)), the analysis of the countries yielded similar under-reporting results, suggesting these cases are likely comparable to many other countries with well-developed commercial fishing industries, particularly using trawl, net, and hook and line gears.

One of the most likely causes of under-reporting of cetacean bycatch, even in mandatory logbooks, is the concerns fishers have of punishment or negative consequences to the fishing industry. For example, in Atlantic Canada, one-quarter of target participants for interviews discussing long-line bycatch refused the interview based on concerns of consequences and general distrust of the researchers (Carruthers and Neis, 2011), and similarly, in Iceland, nearly half of questionnaire respondents refused to answer a question about why they would not report cetacean bycatch or responded they were concerned about the potential negative consequences (Basran & Rasmussen, 2021, in press). Particularly when endangered or critically endangered species are involved in bycatch incidents (such as the North Atlantic right whale), changes to or closures of fisheries can occur due to the serious implications to the stock if even one individual is removed (e.g. Merrick et al. 2001). Significant under-reporting in logbooks was also demonstrated for several different individual species in separate gear types in both New Zealand and the USA. The species that could be examined ranged from having an IUCN list of threatened species status of least concern (e.g. common dolphin) to endangered (Hector's dolphin) (www.iucnredlist.org). Given all species examined (net: n = 7, trawl: n = 4; hook and line: n = 2) except for Dusky dolphins in passive netting (New Zealand) and pilot whale spp. and humpback whales in net gear (USA) were significantly under-reported, there was no evidence that rarer/endangered species are reported less than common species when they are in fact reported at all; however, there were cases where species were somewhat suspiciously not reported at all (eg. North Atlantic right whale and sei whale (*Balaenoptera borealis*)). Concern over strict consequences or negative publicity from catching a rare/endangered species could be an additional reason for fishers to not report. These concerns over consequences, paired with the fact that filling out bycatch reports is extra work, usually with no reward, gives fishers very little incentive to report. Though in the aforementioned 11 countries, not reporting cetacean bycatch is a punishable offense by law, violations are virtually impossible to track without independent observers and inspections.

Differing legislature and different interpretations of the laws by fishers may also influence under-reporting of cetacean entanglement or bycatch. The laws in New Zealand clearly state that all interactions causing injury or death to cetaceans should be reported (Parliamentary Council Office, 1978), however the mandatory logbooks also include an uninjured category. Similarly in the USA, the law states that all serious injuries and mortalities must be reported, however this is complicated with a lengthy list of "serious injury" categorizations (Legal Information Institute, n.d.). However, the wording of the law

in Iceland lacks clarity on this matter. Results from a questionnaire targeting Icelandic fishers revealed that those reporting cetaceans in their logbooks are only doing so if the animal is dead (unpub. data), though fisheries scientists believe all catches, even if released alive, should be reported (Iceland Marine Research Institute. pers. comm. 03.12.2020). A similar issue arises in Norway, where the logbooks are designed to report landed catch, including bycatch of cetaceans, but it is not required for fishers to land cetacean bycatch (Norway Directorate of Fisheries. pers. comm. 14.07.2020). This suggests that even though the law states fishers should report all cetacean bycatch, not only will they not report injured animals, but they are also unlikely to report all deceased animals if they did not land them. In New Zealand, 19.6% percent of individual cetaceans reported were categorized as uninjured or injured but released alive, and in the USA 24.0% were reported as injured but released alive, suggesting that the logbook data from Norway and Iceland likely represents an even smaller fraction of the number of cetaceans caught than the other two countries. It is safe to assume that at least some portion of animals released injured did not survive, particularly those released with serious injuries or with entangling gear attached to the body (eg. Moore et al., 2006).

Though bycatch/interaction under-reporting is likely an issue for virtually all cetacean species, it has been noted that it is particularly an issue for large whale entanglements given their rare and difficult-to-observe nature (IWC 2011). Most of the reports from all four case study countries involved dolphins and porpoises. Given that these species are the most likely to drown when they are caught in fishing gear, it can be suspected that fishers may be the most inclined to report these events. Both small whale and, particularly, large whale interactions with gear are less likely to be witnessed given that these species may be able to break away from entangling gear, meaning many incidents will go unreported (Robbins and Mattila 2001; IWC 2011). This is particularly true for gillnet and pot/trap gears which are left in the water, unattended, for longer periods of time and are well known for entangling whales (Johnson et al. 2005). Also, given the possible misinterpretations of the laws, it is even less likely that large whales will be reported, particularly in countries with ambiguous laws like Iceland and Norway. For example, in Iceland a study based on scarring estimated that a minimum of 25% of humpback whales have been entangled previously (Basran et al. 2019) and additionally 15% of questionnaire respondents witnessed humpback whales interact with their fishing gear (Basran & Rasmussen, 2021, in press). Furthermore, there have been reports of humpback whale deaths due to entanglement in interviews with fishing vessel captains (Basran & Rasmussen, 2021, in press), and based on examination of stranded animals (Vikingsson et al. 2004, 2005, Vikingsson 2011). Despite this evidence, there was only one humpback whale reported as bycatch in the Icelandic fisher logbooks between 2009-2019 (Iceland Marine Research Institute, unpub. data). Similarly in the Gulf of Maine, USA, it was estimated based on scarring that a minimum of 50% of humpback whales (Robbins & Mattila 2004, Robbins 2009) and 83% of North Atlantic right whales have been entangled previously (Knowlton et al., 2012); however there were only 32 humpback whales (averaging 2.9 individuals reported per year) and no North Atlantic right whales reported in the logbooks (2009-2019) despite the law being clear about reporting all interactions leading to injury or death, and the injury category including a sub-code “released trailing gear”. Though many of the incidents may have gone unwitnessed, it is likely some of them were witnessed but unreported, as demonstrated by the questionnaires and interviews previously conducted in Iceland.

Based on the strong evidence for under-reporting in logbooks, observer programs are needed in order to estimate cetacean bycatch and interaction with fishing gear more accurately; however, there are several reasons why improvements to logbook reporting could be favoured over observer programs. Firstly, observer programs can be very costly, with the latest report from the USA observer program stating it costed 79.5 million USD for observer coverage in 54 fisheries (National Marine Fisheries Service, 2020) and therefore it is unlikely that they can be implemented in all fisheries that are high-risk of catching cetaceans. Additionally, sufficient observer effort must be used in order to produce accurate estimates. The observer coverage calculator ObsCovgTools for R (Curtis & Carretta, 2020) can calculate coverage levels required to meet user-defined bycatch estimation objectives that can include estimating bycatch to a desired precision level and estimating the probability of observing bycatch if there is some in a fishery. Necessary coverage will depend on total fishing effort, bycatch per unit effort and variance in the sampling process. The level of observer coverage needed to accurately estimate cetacean bycatch varies largely between fisheries and ideally individual simulations for each fishery should be conducted to determine this (Babcock et al. 2013). However, a simulation, assuming unbiased observer programs and requiring 90% of the simulated observer samples to estimate bycatch within 10% of the actual number, estimated that coverage must be at least 20% to accurately estimate bycatch of common species and 50% to accurately estimate bycatch of rarer species (Babcock et al. 2003). The observer coverage in New Zealand was an average of 44% per year for trawl gear, which should be sufficient for accurate estimates; however, averaged 5% for both passive netting gear and lining gear, suggesting the observer estimates could be under-representing the total catch of cetaceans, particularly for cases involving large whales or rare species (Read et al. 2006), given the low coverage. This could be of particular concern for the endangered Hector's dolphin which was most reported in passive netting gear. Observer coverage in Iceland only averaged 2% for the lumpfish gillnet fishery and 0.2% for the cod+ gillnet fishery meaning that the observer coverage is likely not enough to accurately estimate bycatch of cetaceans. Given the vast expanse, complicated management, and diversity of the USA fishing industries, estimating the overall observer coverage for each gear category was not possible in this study. Individual fisheries have anywhere from zero observer coverage (such as several gillnet and seine fisheries that are classified as low incidence of cetacean mortality ("Category III", see: <https://www.fisheries.noaa.gov/national/marine-mammal-protection/list-fisheries-summary-tables#table-1-category-iii>) to 100% observer coverage (such as the shallow-set longline fishery in Hawaii (NOAA, 2018)). In Norway, a "reference fleet" is used for bycatch estimation, where vessel operators are paid a small fee for accurate reporting (Clegg and Williams, 2020). In addition, the Norwegian Directorate of Fisheries maritime service has onboard inspectors which assess bycatch among other things (Fiskeridirektoratet, 2017). Cetacean bycatch has not been investigated or publicly reported on for the Norway large vessel/high seas reference fleet (for which it is mandatory for all vessels to report cetacean bycatch), and neither these data, nor data from maritime service inspectors, were available for this study. There were 16 vessels in the large vessel reference fleet in 2019 using bottom gillnet, longline, demersal seine, purse seine, bottom trawl and shrimp trawl gear types (Clegg and Williams, 2020).

Improvements to the accuracy of fisher self-reported logbook data would be of great scientific benefit in terms of accurately assessing the impacts fisheries are having on cetacean populations and finding best management practices. Observer programs can be difficult to establish for various reasons and fishers possess key information that could be

collected using more economic methods. In all four case study countries, fisher logbooks contained more cetacean species than observer data, which may be an indicator that fishers have more information, particularly about rare events, than observer programs can detect without very high coverage. However, there is currently no system in place to verify the reports in fisher logbook data.

A first step to improving accuracy of logbook data should be clarification of laws and standardization and simplification of reporting. New Zealand adopted a straight-forward reporting system that requires all cetacean interactions with fishing gear to be logged and categorized as released uninjured, released injured, or deceased (Fisheries New Zealand, pers. comm., 13 May 2020). The simplicity and clarity of what should be reported in New Zealand, versus Iceland which has unclearly worded legislature, Norway that has logbook requirements not matching the cetacean bycatch reporting law, and the USA which has a relatively long list of injury categories, should be considered by countries looking to implement cetacean bycatch reporting. However, despite the clear reporting requirements, cetacean bycatch and interaction was still significantly underreported in trawl and passive netting gears in New Zealand.

Through building a trusting relationship with fishers, simple reporting of cetacean bycatch/interactions using a mobile phone app could be a viable option. Fishers could pre-fill their vessel and fishing gear information and, in the case of cetacean bycatch/interaction, open the app and take a picture or video of the event. Additionally, bycatch/interaction events could be added manually into the app if no photo or video were available. A survey study in Iceland determined that fishers often misidentify cetacean species from photographs (Stoller, 2020), therefore it would be advisable to have basic species identification photos that could be selected in the app to aid in correct reporting. The app could automatically record the GPS position of the vessel and data would be uploaded to an online database accessed by the relevant ministry or research institute. A similar type of app exists for recreational fishers to voluntarily report lost and found fishing gear or bycatch in Norway (Fiskeridirektoratet, 2020) and could be streamlined to suit the needs of simple mandatory reporting. Pilot projects of such a system could be put in place in countries such as New Zealand and the USA where there is already a well-developed observer program. By piloting this in countries with a well-developed observer program, observer data from the recent past could be used as a comparison to determine if fishers are reporting accurately or not, in a similar manner to what was done in this study. If reporting was not accurate, further investigation would be warranted by an onboard observer and potentially further action could be taken, such as the vessel receiving a fine.

Another option is to equip more fishing vessels with bycatch monitoring cameras, as has already been tested in the USA and New Zealand, as well as other countries with bycatch reporting legislation (Australia, Canada and Sweden), which could lower the cost and improve the coverage of bycatch observation (van Helmond et al. 2019; Course et al., 2020). Additionally, the use of monitoring cameras is likely to have the “observer effect” (eg. Burns and Kerr, 2008; Porter, 2010; van Helmond et al. 2019), where the accuracy of fisher-reported data greatly increases when there is a way to verify it. Therefore, even if the cameras were to malfunction or not have the ability to identify all bycatch, or if only some of the footage is reviewed as verification, the fisher reports should be a more reliable source of information (Course et al., 2020). Using electronic monitoring cameras for harbour porpoise bycatch was shown to be effective and reliable in trials in gillnet fisheries in Denmark, where it was noted that the cameras were able to capture bycatch that fell out

of the net before it made it onboard (Kindt-Larsen et al., 2012). Furthermore, in Australia, logbook reporting of marine mammal bycatch significantly increased in the gillnet hook and trap sector of a scalefish and shark fishery after implementation of camera monitoring (Emery et al. 2019). Offering some compensation to fishers for turning in accurate reports could also be considered in conjunction with camera monitoring to provide incentive to fishers to support the program. If an annual check of cetacean bycatch from the video footage closely matched the logbooks, then the vessel could be compensated in some way, while if the reporting did not match, the vessel could be penalized. This could be another way to build a better relationship between fishers and scientists and gather accurate bycatch information. In Norway, “reference fleet” vessels are compensated for reporting, and fisheries scientists in Norway believe their reference fleet program yields them accurate bycatch data (Norway Marine Research Institute., pers. comm., 11 December 2019); however, biases in data from a select set of vessels should be considered before choosing to use a reference fleet opposed to focusing on improving reporting accuracy from fishing fleets as wholes.

Under-reporting of cetacean bycatch/interactions in fisher logbooks, despite reporting legislation, was clearly quantified in the case studies presented here by comparing this data to data from established observer programs. This is an issue that is a detriment to fisheries and cetacean population management. Given the high costs of observer programs and the suggestion that some fishers/fisheries express concerns for having an observer on board for health, safety and financial reasons (eg. Hulac, 2020; Moore - National Fisherman - 25 February 2020), putting more focus on improving self-reporting and electronic monitoring could be a simple way to eliminate the need for many observers onboard vessels and build trust between government, scientists and fishers, in addition to gathering more data in an unbiased manner. By quantifying under-reporting in this manner used in this study, this data can be used as a baseline in which to verify if different approaches have improved the accuracy of fisher logbook reporting.

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Paper III

Paper III

First estimates of entanglement rate of humpback whales (*Megaptera novaeangliae*) observed in coastal Icelandic waters

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**First estimates of entanglement rate of humpback whales
(*Megaptera novaeangliae*) observed in coastal Icelandic waters**

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ABSTRACT

Entanglement in fishing gear is a significant anthropogenic source of large whale injury and mortality. Although entanglements have been reported in the eastern North Atlantic, their frequency has not been previously estimated. This study used systematic scar-analysis to estimate the frequency of non-lethal entanglements among individual humpback whales off coastal Iceland, from 2005 through 2017. Images of the caudal peduncle and fluke insertions of 379 individuals were analyzed for wrapping injuries and notches known to be indicative of entanglement. The results indicated that at least 24.8% (n = 94 CI: 20.5-

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29.1%) of individuals had a history of prior entanglement when first encountered. Depending on the metric used, the whales subsequently acquired new entanglement-related injuries at an average rate of 1.9% (95%CI: 0.6-3.2%) or 16.3% (95%CI: 3.0-29.3%) per year, with no statistical change over time. Furthermore, evidence suggests at least some entanglements occurred locally. When whales were observed with gear still entangling the body, they confirmed the patterns of injury studied here. These results are lower than scar-based estimates from other parts of the world, but the cause of this difference requires further study. Scar-based methods underestimate the frequency of prior entanglement because some injuries heal beyond recognition, do not involve the caudal peduncle, and whales may die before they are studied. Long-term monitoring of humpback whale entanglement in Icelandic coastal waters is important for evaluating the local effects of fisheries, as well as the viability of the Endangered Cape Verde breeding population.

Key words: Entanglement, Humpback whales, Scar-analysis, Iceland, *Megaptera novaeangliae*, North Atlantic

INTRODUCTION

Entanglement in fishing gear has been identified as one of the major anthropogenic issues marine mammals face, with global bycatch estimated to be in the hundreds of thousands (Read et al. 2006). Most types of fishing gear (e.g., gillnets, long lines, and pot/trap lines) are known to cause entanglements (Baird et al. 2002, Johnson et al. 2005, Read et al. 2006, Song et al. 2010, Benjamins et al. 2012) and these can lead to serious consequences for both individuals and populations. At an individual level, entanglement can cause behavioral impairment (Kot et al. 2009), disruptions in energy budget (van der Hoop et al. 2013), an increase in stress-induced hormones potentially causing weakening of the immune system (Hunt et al. 2006, Rolland et al. 2017), a higher chance of predatory attacks (Mazzuca et al. 1998, Moore et al. 2012), injuries and infections (Moore et al. 2013, Cassoff et al. 2011, Knowlton & Kraus, 2001), emaciation, and/or drowning (Cassoff et al. 2011, Moore et al. 2013). At a population level, entanglement can increase the overall mortality (Volgenau et al. 1995, Robbins et al. 2015) and potentially decrease recruitment rates, given a higher incidence of juvenile entanglement (Lien 1994, Mazzuca et al. 1998, Robbins 2011, Knowlton et al. 2012).

Dedicated surveys, stranding records, and eye-witness reports of whales observed with attached gear have been used to assess entanglement in cetacean populations (e.g., Felix et al. 2006, Lien 1994, Benjamins 2012, Volgenau et al. 1995, van der Hoop et al. 2013). Large whale entanglements present a particular challenge because the animals may carry away some or all of the gear and can either shed the gear or die before the event has been detected. Given the challenge of detecting these events in progress, injury-based studies have been used as a method of systematically assessing the frequency of entanglement interactions (i.e. used to identify whales which have had fishing gear attached to the body previously). Cetacean species in these studies include common minke whales (*Balaenoptera acutorostrata*) (Held-Wirz 2008), North Atlantic right whales (*Eubalaena glacialis*) (Kraus 1990, Knowlton et al. 2012), bowhead whales (*Balaena mysticetus*) (George et al. 2017), gray whales (*Eschrichtius robustus*) (Bradford et al. 2009) and humpback whales (*Megaptera novaeangliae*) (Robbins & Mattila 2001, 2004, Neilson et al. 2009, Robbins 2009, 2011). The most detailed scar-based humpback whale study has been conducted in the Gulf of Maine (GoM) where the majority of individuals have scarring indicative of at least one prior entanglement in fishing gear and the frequency of

non-lethal events over time has been estimated by monitoring injury acquisition and healing (Robbins & Mattila 2004; Robbins 2009, 2011, 2012).

In Iceland, humpback whales are regularly sighted in coastal shelf waters from the spring through the fall, and occasionally in winter months (Víkingsson et al. 2004, Magnúsdóttir et al. 2014). Photo-identification data collected in Icelandic coastal shelf waters during opportunistic boat surveys found that humpback whales show a certain degree of site fidelity to areas in the northeast, but also demonstrate exchange with areas to the southwest (Klotz et al. 2017, Bertulli et al. 2018). Data also suggest that humpback whales are abundant in the waters north and northwest of Iceland (Pike et al. 2019 submitted). Icelandic humpback whales migrate seasonally to breeding grounds in the Caribbean Sea (Martin et al. 1984, Katona & Beard 1990, Stevick et al. 2003) or off of the Cape Verde Islands (Jann et al. 2003, Wenzel et al., 2009). The latter area hosts a small and distinctive breeding population (Ryan et al. 2014, Punt et al. 2006, Bettridge et al. 2015, Stevick et al. 2016) which could be negatively impacted by human activities in Icelandic waters.

Significant longline and gillnet effort occurs in both the northeast and south of Iceland (Hafrannsóknastofnun 2017), suggesting potential entanglement issues due to overlap with the areas the humpback whales are frequenting. However, limited information is available on the nature and frequency of interactions between fisheries and whales. Anthropogenic scarring and injuries related to fishing activities have been observed in Iceland in common minke whales, white-beaked dolphins (*Lagenorhynchus albirostris*) (Bertulli et al. 2012, 2015, 2016), and humpback whales (Basran 2014). Fishermen eye-witness reports of humpback whale entanglements in Iceland date back to 1979 (Basran 2014), and entanglement mortalities have been reported (Víkingsson & Ólafsdóttir 2003, Víkingsson et al. 2004, 2005, 2011).

Whale entanglement studies can provide valuable support to resource management by identifying the need for mitigation measures and evaluating effectiveness after implementation. In order to assess and manage humpback whales in Icelandic waters, it is important to obtain information on the entanglement rates and impacts. This information can then aid in assessing impacts on the breeding stocks that these whales contribute to, such as the Endangered population around the Cape Verde Islands. In this study, a scar-based photograph assessment of entanglement injuries on free-ranging humpback whales was performed to provide the first estimates of non-lethal entanglement rate for the whales in Icelandic coastal waters.

MATERIALS AND METHODS

Study area

This study focuses on three main areas in the nearshore waters off Iceland: Faxaflói Bay, Skjálfandi Bay (hereafter referred to as Faxaflói and Skjálfandi), and Eyjafjörður. These sites were chosen for the predictable numbers of humpback whales arriving during their feeding season, and the accessibility to data collection on-board whale watching vessels operating tours multiple times a day in all three locations. Faxaflói (64° 24'N23°00'W) is a 50 x 105 km bay (approximately 4,400 km²) located off of the country's capital city Reykjavík on the southwest coast. Skjálfandi (66°05'N17° 33'W) is a 10-50 x 25 km bay (approximately 1,100 km²) on the northeast coast harbouring the fishing and whale-watching village of Húsavík situated on its southeast shore (Stefánsson & Guðmundsson 1978, Stefánsson et al. 1987, A. Gíslason unpubl. data, Einarsson 2009). Eyjafjörður (65°50'N18° 07'W) is a 5-15 x 60 km fjord (approximately 440 km²) also located on northeast coast of Iceland, hosting the second-largest Icelandic city, Akureyri, at the southern end and the fishing and whale watching villages of Dalvík and Hjalteyri along the

western shore (S. Jónsson unpubl. data). Skjálfandi and Eyjafjörður are ca. 80 km apart, while Faxaflói is ca. 600km to the southwest from Skjálfandi (Fig. 1).

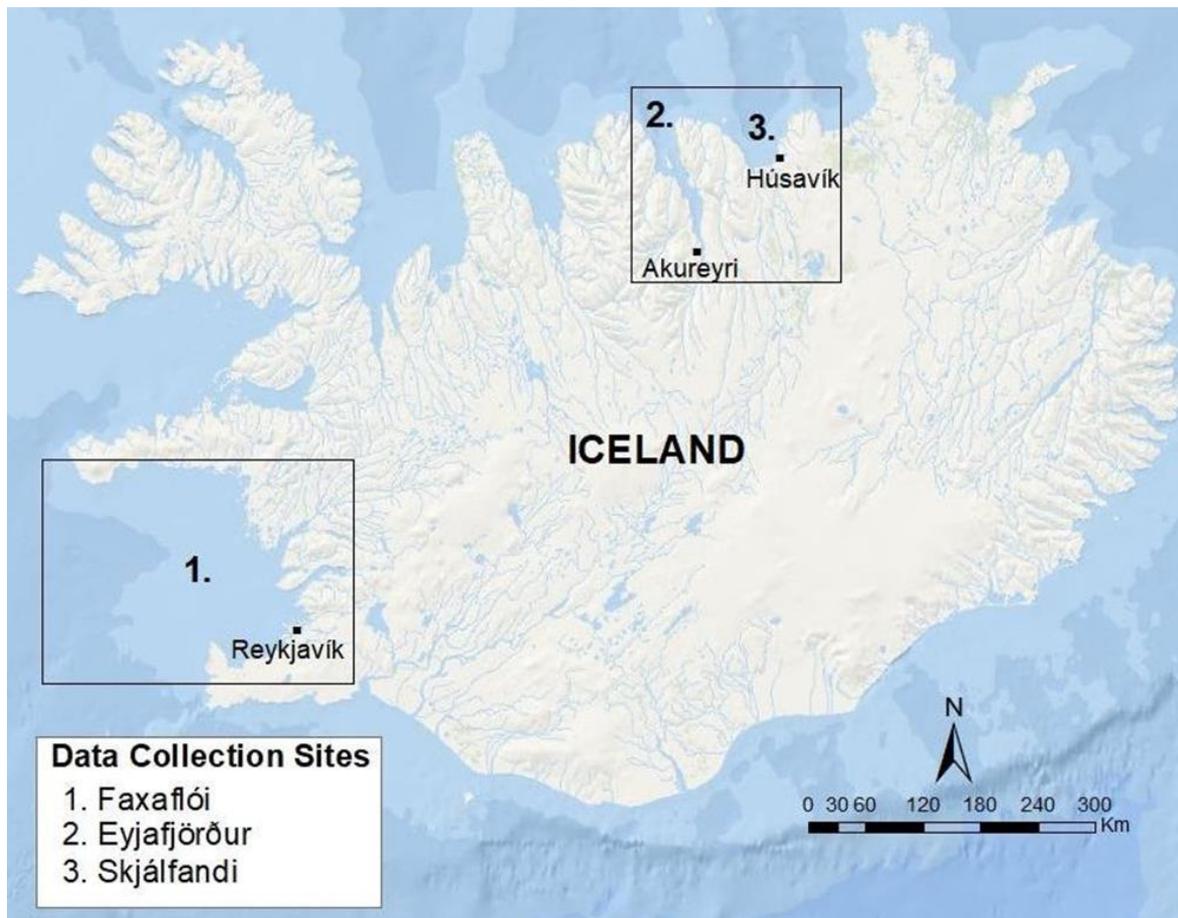


Fig. 1. Map of Iceland showing the three photograph data collection field sites.

Data collection

Photographs of humpback whales were primarily collected from April to November onboard whale-watching vessels operating out of Faxaflói (FB, 2007-2017), Skjálfandi (SB, 2001-2017), and Eyjafjörður (EyF, 2015-2017). Each boat survey lasted approximately 3 hours and covered morning, afternoon and/or evening times. All photographs used in this study were taken with dSLR cameras with zoom lenses (between 55-400mm). The photographs were taken mainly by researchers and students associated with the University of Iceland (HI), though some photographs were contributed by whale watching guides and tourists. Photo-identification images were taken of the pigmentation pattern on the ventral side of each individual humpback whale fluke (Katona & Whitehead 1981). Whenever possible, researchers photographed the caudal peduncle and insertion point of the flukes from parallel to, or in front of the animal while it took a terminal dive. These features are frequently involved in entanglements and are known to acquire injuries that can be used to determine the entanglement history of the individual (Robbins & Mattila, 2001, 2004). To minimize bias, photos were taken regardless of if the whale appeared to have any injuries or scarring.

Image Selection and Peduncle Scar Analysis

The only images selected for analysis were of individuals which were photo-identifiable by the unique pigmentation pattern on the underneath side of the fluke. All images used had

high enough resolution to be zoomed in without losing detail, were in good light conditions, and were taken from the correct angle (following Gowans & Whitehead 2001, Robbins & Mattila 2001). The image interpretation and coding were originally defined by Robbins and Mattila (2001, 2004). Specifically, images which showed at least two of six predetermined coding areas were examined for wrapping scars and notches indicating a previous entanglement and were scored accordingly. The six coding areas were i) left flank, ii) dorsal peduncle, iii) ventral peduncle, iv) left insertion point and leading edge of fluke, v) right insertion point and leading edge of fluke, vi) right flank (Fig. 2). Each individual whale then received a likelihood of prior entanglement score taking into account all usable images spanning all available coding areas. The likelihood of prior entanglement score was assigned as follows: *HP*) high probability of prior entanglement, if evidence was found in two or more coding areas, *U*) uncertain, if evidence was only found in one coding area, or *LP*) low probability of prior entanglement, if no clear evidence was found in any coding areas (Fig. 3). Image analysis was conducted by one researcher (CJB) for consistency, and then whales assigned *HP* underwent expert consultation (JR) to ensure accuracy. The minimum scar-based *frequency of prior entanglement* was calculated as *HP* divided by the total sample, while the maximum was calculated as *HP+U* divided by the total sample. Individuals were only included in this estimate once, based on the score they were assigned the first year they were recorded in the study.

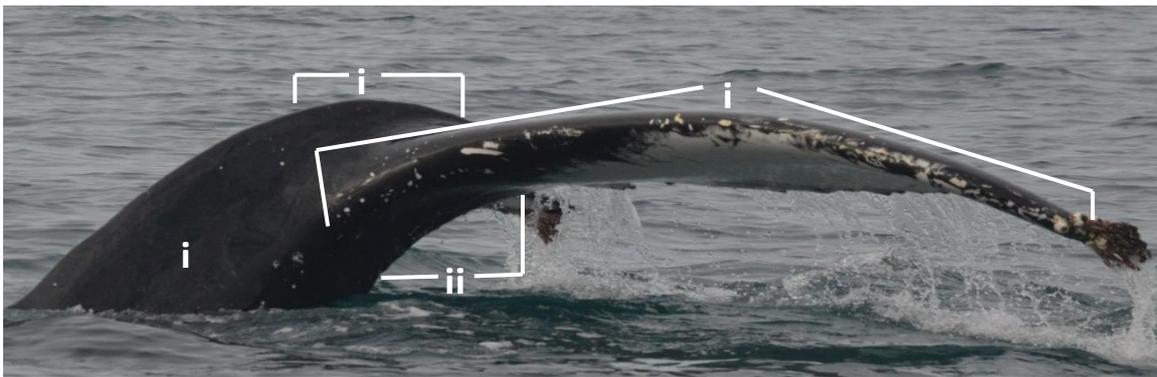


Fig. 2. Photographs showing four of the six coding areas: i) left peduncle flank ii) dorsal peduncle iii) ventral peduncle iv) left insertion point and leading edge of fluke. On the opposite side (not visible here): v) right peduncle flank vi) right insertion point and leading edge of fluke.

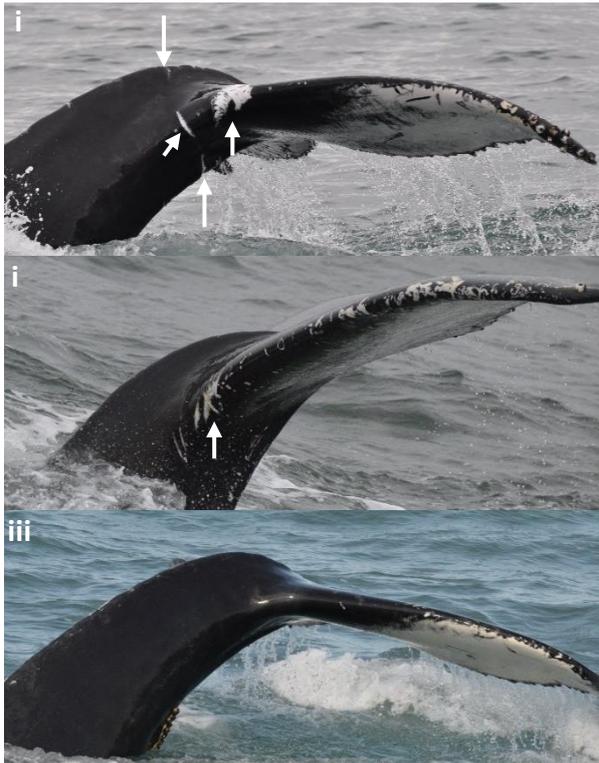


Fig. 3. Examples of prior entanglement history scoring i) high probability of previous entanglement (*HP*) ii) uncertain (*U*) and iii) low probability of previous entanglement (*LP*) when analyzing scarring to estimate the frequency of prior entanglement. Arrows indicate entanglement evidence.

Two metrics were used to estimate the rate at which entanglement injuries were acquired after the baseline scarring pattern was established. Firstly, individuals which had usable photographs in consecutive years, and were given a *HP* score in at least one year, were compared directly across the sightings to determine whether changes in entanglement-related scarring had occurred. For each year an individual was resighted, it was assigned as having increased entanglement-related scarring, equal scarring, or decreased entanglement-related scarring when compared to the previous year (Fig. 4). Images were only compared if they adequately showed the same coding areas. The inter-annual entanglement rate based on scar acquisition (E_s) was then calculated as the percentage of individuals resighted that were assigned increased entanglement-related scarring out of the total examined that year. Due to the sample limitations in the early part of the study, this was only calculated for each year from 2011-2017, and the average percentage over these years was calculated as an estimate of entanglement acquisition rate per year.

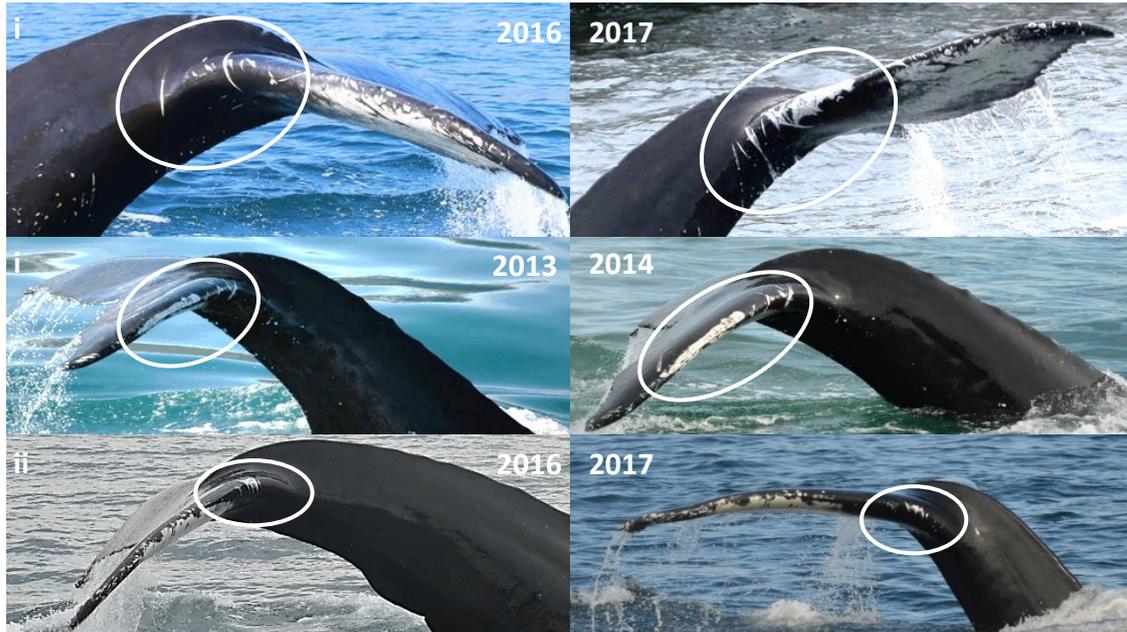


Fig. 4. Examples of changes in entanglement scar patterns from one year to the next: i) increased scarring ii) equal scarring and iii) decreased scarring. Circles indicate where comparisons in scarring can be observed. Cases such as i) were used in the calculation of entanglement rate based on increased scarring (E_s).

Secondly, we evaluated the yearly entanglement rate based on unhealed injuries (E_u) using the percentage of individuals with unhealed entanglement-related injuries in each study year (Fig. 5). These injuries were used as an indicator of a recent entanglement, likely within the past year (Robbins 2011). The percentage of individuals with unhealed injuries was calculated for each study year between 2007 and 2017 and averaged across periods of interest for comparison purposes. Due to small sample sizes in the early years of the study, entanglement acquisition rates were calculated and compared for two periods: 2007-2011 and 2012-2017. Statistical comparisons using Wilcoxon Rank Sum tests were made in JMP software (JMP®, Version 13.2.1. SAS Institute Inc. 2016, Cary, NC).

When an individual was observed still entangled in fishing gear, we used these cases to evaluate the validity of our scar-based assessments and for evaluating the fraction of events that might be missed by focusing only on the caudal peduncle.



Fig. 5. Example of an individual with unhealed entanglement injuries included in the calculation of the E_u rate based on such cases. Arrows indicate unhealed injuries.

RESULTS

Overall, there were 379 individuals included in the scar analysis, from thirteen years of usable photographs (2005-2017). Approximately half ($n = 189$) were assessed as having a low probability of prior entanglement. Of the remaining individuals, 94 were considered to have a high probability of entanglement, while the entanglement status of the remaining 96 was uncertain. Thus, at least 24.8% ($n = 94$ CI: 20.5-29.1%), but potentially as many as 50.1% ($n = 190$ CI: 45.1-55.2%) were estimated to have had a prior entanglement history (Table 1).

Table 1. Percentage of individuals with scar-based evidence of a likely history of prior entanglement. N is the number of individuals in each estimate, % is the estimated percent of the population that has been entangled at least once, CI is the 95% confidence intervals. The total sample size was 379 individuals.

Frequency of prior entanglement	N	%	CI %
Minimum	94	24.8	20.5-29.1
Maximum	190	50.1	45.1-55.1

There were in total 89 individuals that were resighted (23.5%), of which 37 were scored *HP* in at least one year and had photos in consecutive years making them eligible to be considered for *Es* analysis. Of these eligible cases, 33 (8.7% of the total sample) had comparable resightings in consecutive years to be included in the analysis. However, annual re-sightings were primarily limited to the second half of the study. The average *Es* rate from 2011-2017 was 16.3% ($n = 33$ CI: 3.3-29.3%) (Table 2). Three individuals with comparable resightings (0.8%) had entanglement related scarring that healed beyond recognition within one year and three individuals had increased scarring that indicated they had been entangled at least twice. There were 15 individuals (4.0%) that exhibited unhealed entanglement-related injuries, 5 in the first time period and 10 in the second. The *Eu* rate, likely representing entanglements within the prior year, averaged 1.9% (CI: 0.6-3.2%) for approximately the same time period as the *Es* rate (2012-2017) (Table 3). The estimates generated by these two metrics were not significantly different (Wilcoxon Rank Sum test: $p = 0.49$, $z = 0.68$), but the estimate from *Eu* analysis was based on a larger sample size and therefore was more precise. Data on unhealed injuries were also sufficient to estimate the average annual *Eu* rate for the earlier time period (2007-2011) at 7.7% (CI: 1.4%-13.9%) (Table 3). This was not significantly greater than the later time period (Wilcoxon Rank Sum test: $p = 0.39$, $z = 0.86$).

Table 2. Entanglement rate estimate results based on scar acquisition (E_s). N with increased scarring is number of individuals with increased scarring between the years, N resights is the total number of resighted individuals between each year, % is the percentage of individuals with increased scarring per year, Mean is the average percentage of individuals with increased entanglement scarring per year, CI is the 95% confidence intervals.

Year	N with increased scarring	N resights	%
2011-2012	2	6	33.3
2012-2013	1	7	14.3
2013-2014	0	3	0
2014-2015	0	5	0
2015-2016	0	2	0
2016-2017	4	8	50.0
Mean			16.3%
95%CI			3.0-29.3

Table 3. Entanglement rate estimate results based on unhealed injuries (E_u). N with unhealed injuries is the number of individuals per year with unhealed injuries, N total is the total number of individuals in the study each year, % is the percentage of individuals with unhealed injuries each year, Mean is the average percentage of individuals with unhealed injuries per year for the time period indicated, CI is the 95% confidence intervals.

Year	N with unhealed injuries	N total	%	Mean
2007	0	11	0	
2008	3	11	27.2	
2009	1	16	6.3	
2010	0	11	0	
2011	1	21	4.8	
2007-2011				7.7% (CI=1.5-13.9%)
2012	2	51	3.9	
2013	0	46	0	
2014	0	32	0	
2015	1	69	1.5	
2016	7	117	6.0	
2017	0	99	0	
2012-2017				1.9% (CI=0.3-3.2%)

Seven individuals photographed in the study period had fishing gear still attached to the body (Fig. 6). Based on what was visible in the photographs, two had monofilament line (one with hooks attached to the line), two had rope and netting, one had a single rope, and two had just netting. The gear appeared to be attached at the coding areas in five individuals, however, only three of these had adequate photographic coverage for assessment of injuries and inclusion in scar analysis. These three cases confirmed the presence of diagnostic wrapping injuries. In two other cases, there was no documentation of the caudal peduncle or tail to determine the presence of an attachment there or the nature of the injuries. Two individuals picked up entangling gear or acquired new injuries between sightings in the same year. One was photographed gear-free three months earlier in Skjálfandi, and was then resighted entangled in Eyjafjörður. Another individual was photographed in Eyjafjörður with new entanglement injuries that it had acquired within nine days of first being sighted in Skjálfandi. This individual had already shed the entangling gear.

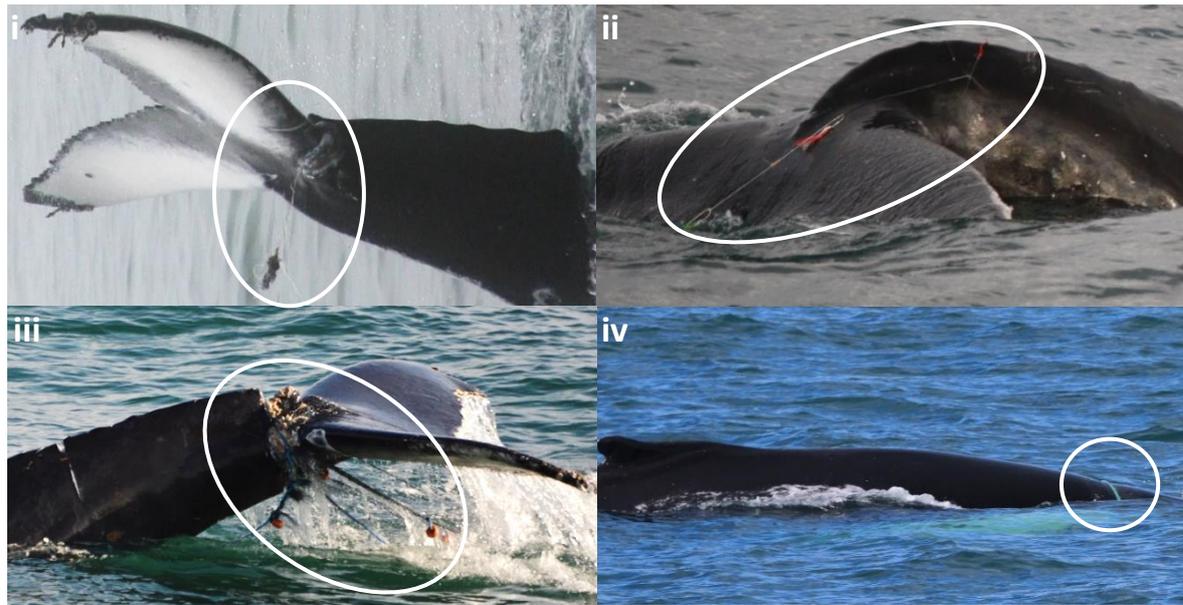


Fig. 6. Examples of individuals with fishing gear (indicated by circles) still attached to the body both within and outside of the coding areas considered in this study. Visible materials included: i) single monofilament line

DISCUSSION

Entanglement is a known source of injury and mortality to large whales, including humpback whales. This is the first effort to quantify humpback whale entanglement rates in Icelandic waters using standard scar-based techniques for comparison to other areas. The results suggest that a minimum of 24.8% and a maximum of 50.1% of individuals in coastal Icelandic waters had a prior history of entanglement at the time they were first sighted. The annual scar-based entanglement rates averaged 1.9% or 16.3% of the sampled population, depending on the method used for calculation. However, none of the comparisons of entanglement rate between time periods or between the two methods of calculation for the same time period were statistically different. The available data therefore suggests that the non-lethal entanglement rate has remained fairly steady over the study period. Of the two results, we have greater confidence in the lower, more precise *Eu* rate of 1.9% per year because it was based on larger sample sizes. Furthermore, three out of thirty-three individuals exhibited evidence of more than one past entanglement.

Although humpback whales are seasonal migrants, there is evidence that at least some of these injuries are occurring locally. Firstly, one individual was photographed with new entanglement injuries it had obtained within nine days of being first photographed with no injuries. Although not based on scar analysis, another individual in this study was observed entangled three months after first being seen without the entangling gear.

The specific types of entangling gear that may have caused the majority of observed injuries was generally not known. In the few cases in which fishing gear was still attached to the body, the gear type was variable including ropes, monofilament netting, and monofilament line. This suggests that the whales are becoming entangled in several different gear types as opposed to a single type. This is consistent with what is known more generally about the gear involved in large whale entanglements (Johnson et al. 2005), and specifically with fisherman reports in Iceland (Basran 2014). The greatest fishing effort in the vicinity of our data collection sites comes from longline, handline, and gillnet

fisheries, which is also consistent with the types of gear observed entangling the whales (Hafrannsóknastofun 2017).

Entanglement estimates obtained in this study are lower than those obtained in other areas using the same assessment methods. In another area of the North Atlantic, the GoM, at least half of individuals had a prior history of entanglement when first observed (Robbins & Mattila 2004, Robbins 2009), acquisition rates were most recently estimated at 16.9% (95% CI: 10.5-23.4%, *Es*) and 13.5% (95%CI: 9.7-17.3%, *Eu*) (Robbins 2012), and there is evidence that some humpback whales have been entangled at least 2-4 times (Robbins 2009). The minimum frequency of prior entanglement off of Alaska (54%, Neilson et al. 2009) was also higher than observed here. The reason for the lower incidence of entanglement in this study is not known, but may relate to differences in fishing gear types, potentially lower fishing effort in Iceland than in larger countries, and the extent of the overlap between the whales and the fishing. Both the GoM and Alaska host pot/trap fisheries that have been directly implicated in whale entanglements (Johnson et al. 2005, Neilson et al. 2009). Iceland does not have any trap/pot fisheries, but rather only gillnet, trawl, hook-and-line, and seine fisheries (Hafrannsóknastofun 2017). This may result in differential risk of entanglement overall in Icelandic waters. There is however, moderate-to-high gillnet effort in all three of our data collection sites, as well as moderate longline and handline effort, suggesting the whales and the fishing in Iceland are overlapping spatially and temporally to some extent (Hafrannsóknastofun 2017). In the GoM, juvenile whales have a higher incidence of entanglement than adults (Robbins 2011) and so demography may explain differences among areas. However, demographic research would be needed to be able to compare entanglement rates from the Icelandic population to other humpback whale populations on the basis of age class.

The minimum frequency of prior entanglement, as calculated by scar-based techniques, is considered to be conservative. Although this is a systematic method, it does not detect entanglements that do not involve the peduncle, injuries that heal over time, and those that result in the death of the whale before it can be studied (Robbins and Mattila 2004). There were a small number of cases in this study where entanglement evidence was opportunistically photographed outside of the peduncle region, suggesting some entanglements of Icelandic whales are occurring on body parts not included in the coding areas. Furthermore, some entanglement scarring can heal beyond recognition (Robbins & Mattila 2004), suggesting that some entanglements can potentially be missed by scar-based studies. Yet, only three individuals in our study with comparable resightings in consecutive years exhibited entanglement scar healing beyond recognition. In addition, our study focused on free-ranging whales, and we did not necessarily encounter entangled whales carrying gear, or injured whales, before they died. There are some reports of humpback whale strandings in Iceland in which entanglement, confirmed by the presence of injuries or entangling gear still attached to the animal, was deemed the likely cause of death (Vikingsson 2004, 2005, 2011). Our results therefore only reflect the non-lethal component of the entanglement rate. Despite this, our study provided evidence that entanglements off of Iceland can be reliably detected based on scarring/injuries in the caudal peduncle areas.

The use of whale watching boats and visiting students was essential to this study by providing a low-cost source of data, however, it did impose some limitations on the research. The whale watching boats were often not in the correct position for properly-angled photographs for analysis, and the researchers had no control over this. In addition, though having individuals other than researchers, such as students, taking photographs greatly increased the effort in the study, it did not always result in usable, high quality data and likely reduced the number of individuals for which comparable coverage was

available. Using whale watching boats as a research platform was useful and mutually beneficial, although having additional dedicated surveys in order to obtain as large of a sample size of usable individuals as possible and to cover larger areas would be valuable. Though the three data collection sites used in this study covered well-known humpback whale sighting areas, humpback whales are also seen in other areas around Iceland, and therefore our sampling may not be representative of the overall population of whales that feed off Iceland. The central North Atlantic humpback whale population around Iceland is estimated to be approximately 12,000 animals (Vikingsson et al. 2015) and some are known to make migrations to different coastal areas around the country, potentially limiting the chances of opportunistically sighting the same individuals in consecutive years when covering only limited areas. Spatial coverage and effort limitations may also explain the low resighting rates and gaps between resightings of more than one year that limited the sample sizes. Though this study included usable photographs spanning thirteen years and covered field sites with predictable humpback whale sightings, usable, comparable resightings were low.

The specific effects of non-lethal entanglements on individuals and populations are not well understood. Several factors, including the severity of the entanglement and resulting injuries, and the length of time that the whale carries gear will influence the severity of the impacts. Nevertheless, entanglement and net encirclement has been found to raise stress-induced hormones, glucocorticoids, in several cetacean species (St.Aubin 2002a, 2002b, Hunt et al. 2006, Rolland et al. 2017) and there may be other, non-lethal impacts on individuals resulting from the stress (Aubin 2002b, van der Hoop et al. 2017). The majority of entanglement injuries in this study were not considered to be outwardly severe, however, we do not know the long-term outcome for these individuals, particularly those with more significant injuries and those with gear that was still attached at last sighting. Further monitoring would help to better understand the long-term effects of entanglement on humpback whales off of Iceland.

Some of the whales that feed off Iceland are known to belong to a small breeding stock occurring around the Cape Verde Islands. The United States recently conducted a global review of humpback whale status (Bettridge et al. 2015) and concluded that the small population of North Atlantic humpback whales that breed off the Cape Verde Islands/Northwest Africa is distinct and Endangered (NOAA Department of Commerce 2016). The breeding stock around the island of Boa Vista is estimated to be 260 individuals (Ryan et al. 2014). Though this estimate is only for the main location of humpback sightings in Cape Verde and not all the islands, it lends to the hypothesis that the breeding stock is not large. These whales mix on the Icelandic feeding grounds with individuals that are part of a larger population that breeds in the West Indies. As these breeding populations cannot be differentiated on the feeding ground, negative impacts of entanglement on even a relatively small number of these humpback whales could have serious implications for the Cape Verde stock. Future, long-term monitoring of humpback whale entanglement in Icelandic coastal waters is recommended to further investigate the frequency of entanglement and changes in entanglement rate over time.

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contributed photographs and/or space onboard their vessels for data collection. Furthermore, we thank the anonymous reviewers who provided valuable input into the manuscript. Photographs for figures are copyright of University of Iceland, Elding Adventures at Sea, and Charlie Frank Lavin (Elding Whale Watching Akureyri).

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Paper IV

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Behavioural Responses of Humpback Whales (*Megaptera novaeangliae*) to Two Acoustic Deterrent Devices in a Northern Feeding Ground off Iceland

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Behavioural Responses of Humpback Whales (*Megaptera novaeangliae*) to Two Acoustic Deterrent Devices in a Northern Feeding Ground off Iceland

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Abstract

Mitigating cetacean entanglement in fishing gear is of global interest and strategies include the use of acoustic deterrent devices to warn whales of fishing gear. For baleen whales, responses to these devices are poorly understood. This behavioural response study compared the behaviour of humpback whales (*Megaptera novaeangliae*) in their feeding grounds off Iceland prior to, during, and after exposure to a whale pinger (Future Oceans, 3 kHz, $n = 9$ exposures) and a seal scarer (Lofitech Ltd., 10-20 kHz, $n = 7$ exposures) using boat-based focal follows. Linear mixed effects models and binary generalized linear mixed effects models were used to analyze the effect of the devices on breathing rate, dive time, swimming speed, swimming directness, and surface feeding. There was a significant increase in swimming speed and a significant decrease in observed surface feeding during whale pinger exposures. There were no significant behavioural changes that were consistent across individuals during seal scarer exposures. In addition to experimental exposure trials, a field trial of whale pingers on a capelin purse seine was conducted. During this trial whales were observed entering the net from the bottom while the whale pingers were attached at the top, but the encircled whales were able to locate an opening free of pingers and escape without damaging the net. All in all, the results suggest pingers can be a useful entanglement mitigation tool in humpback whale feeding grounds given that a reduction in feeding around nets likely reduces the risk of whales swimming through them. Furthermore, the use of pingers may also reduce net damage by guiding encircled whales to a pinger-free opening. However, given the observed behavioural changes that may lead to fitness consequences if exposure to pingers is frequent, whale pingers are most advisable for short-term use in conjunction with other entanglement mitigation measures.

Key words: Humpback whale, *Megaptera novaeangliae*, entanglement, acoustic deterrent device, behavioural response, Iceland

Introduction

There is global concern over marine mammal bycatch and entanglement in fishing gear ie. animals becoming incidentally caught in gear and drowning, or incidentally coming into contact with gear and escaping, sometimes with gear attached to their bodies and/or with injuries. Documented impacts of entanglement on cetaceans include injury (Knowlton & Kraus, 2001; Cassoff et al., 2011; Moore et al., 2013), exhaustion of energy reserves (van der Hoop et al., 2017), emaciation (Moore et al., 2013), and drowning (Cassoff et al., 2011; Moore & van der Hoop 2012). These impacts at the individual level can lead to increased mortality rates at the population level (Volgenau et al., 1995; Robbins et al., 2015). Entanglement is known to occur involving many different types of fishing gear (Johnson et al., 2005) and is likely to affect most cetacean species (Gall & Thompson, 2015). Apart from impacts on cetacean individuals and populations, entanglement also leads to financial losses to the fishing industry because of loss-of-catch, gear damage or loss, and downtime for repairs (Lien, 1979; Lien & Aldrich, 1982). This can be a particularly serious issue in fisheries incurring large whale entanglements, such as those involving humpback whales (*Megaptera novaeangliae*).

Technologies have been developed with the intent to mitigate marine mammal entanglement. One such technology is low-powered acoustic deterrent devices (ADDs) (defined as having source levels ranging from 110 - 179 dB re $\mu\text{Pa}^2 \text{m}^2$) known as “pingers” (Ainslie, 2010). These devices can be attached to fishing gear and emit a sound underwater within the hearing range of target marine mammals (Erbe & McPherson, 2012). The devices warn the animals of the presence of gear or simply serve as an annoying, unnatural sound that the animals want to avoid (Kraus, 1999). Alternatively, since large whales in particular can often escape from or carry away entangling gear, researchers also hypothesize that whales can learn to associate nets and pingers with danger (Jefferson & Curry, 1996). For cetaceans, specific pingers have been developed for porpoises, dolphins, and beaked whales (odontocetes), as well as baleen whales (mysticetes), with varying degrees of success. The high-frequency odontocete pingers have resulted in reductions in bycatch (eg. Kraus et al., 1997; Barlow & Cameron, 2006; Caretta et al., 2008; Mangel et al. 2013), but also no change or even increased bycatch in some studies (eg. Berg Soto et al., 2013; Erbe et al., 2016). Whale pinger and low-frequency sound experiments have been conducted on baleen whales, including North-Atlantic right whales (*Eubalaena glacialis*) (Nowacek et al., 2004), minke whales (*Balaenoptera acutorostrata*) (McGarry et al., 2017), grey whales (*Eschrichtius robustus*) (Lagerquist et al., 2012), and humpback whales (How et al., 2014; Harcourt et al., 2015; Pirotta et al., 2016) with similar varying results. North-Atlantic right whales showed a strong response of swimming to the surface when exposed to 1 kHz alerting sounds (Nowacek et al., 2004), and both minke and humpback whales responded during testing of 4 kHz whale alarm prototypes by making significantly more close approaches and abrupt turns when exposed to active devices (Todd et al., 1992). Humpback whales were also less likely to collide with cod-traps fitted with these 4kHz alarm prototypes in Canada (Lien, 1992) and responded to 2-2.1 kHz “tone stimuli” in Australia by swimming away from the sound source (Dunlop et al., 2013). Conversely, grey whales did not appear to respond to 1-3 kHz sounds though results were inconclusive (Lagerquist et al., 2012) and the majority of recent research conducted on humpback whales in Australia concluded that there is no

clear response from the whales to the modern 3 kHz whale pingers, which are now sold commercially (How et al., 2014; Harcourt et al., 2015; Pirotta et al., 2016). Despite this, anecdotal reports do claim that some industries have had lower incidence of humpback whale entanglement in their feeding grounds with the use of the commercial whale pingers (Fumunda - Alaska Journal of Commerce, 14 June 2012; Laine Welch - Anchorage Daily News, 31 May 2016).

High-powered ADDs (defined as having source levels of 189 dB re $\mu\text{Pa}^2 \text{m}^2$ and above) are often referred to as “seal scarers” (Ainslie, 2010). They produce a high-intensity, high-frequency sound designed to scare seals away from aquaculture operations. (Taylor et al., 1997). Some cetacean species, including harbour porpoises (*Phocoena phocoena*) (Brandt et al., 2013), orcas (*Orcinus orca*) (Morton & Symonds, 2002), and Pacific white-sided dolphins (*Lagenorhynchus obliquidens*) (Morton, 2000), also react to these devices. The only testing of a seal scarer on baleen whales was conducted on minke whales in Iceland, and it was observed that they too were deterred from the area with an active 10-20 kHz device (McGarry et al., 2017).

Humpback whales are one of the most common cetaceans that frequent the waters off Iceland in the North Atlantic, primarily during their feeding season from spring through autumn (Pike et al., 2009), though some sightings are also recorded in the winter months (Magnúsdóttir et al., 2014). The summer-time central North Atlantic humpback whale population is estimated to be approximately 10,000 individuals with the highest concentration found off north/northeast Iceland (Pike et al., 2019). Fish species are estimated to constitute 60% of the humpback whales’ diet in this area (Sigurjónsson & Víkingsson, 1997). Based on modelling of the hearing capabilities of humpback whales, a lower hearing sensitivity threshold of 700 Hz (Houser et al., 2001), or possibly as low as 200 Hz (Tubelli et al., 2018), and an upper threshold of 9-10 kHz (Tubelli et al., 2018; Houser et al., 2001) have been estimated. Their maximum hearing sensitivity is estimated to be between 2-6 kHz (Houser et al., 2001). Humpback whale vocalizations, however, have frequency harmonics that range from approximately 20 Hz up to 24 kHz (Thompson et al., 1986; Au et al., 2006). Hearing is the most important sense for marine mammals to orient themselves in their environment (Tyack, 2008) and large baleen whales, like the humpback, may have trouble detecting the sounds produced by fishing gear in the water depending on factors such as the acoustic signal produced by different gear types and acoustic masking of these signals (Lien et al., 1990).

Commercial fishing is one of the largest industries in Iceland, with 1582 commercial vessels registered in 2019 (Statistics Iceland, n.d.). The fishing methods used in Icelandic waters are long-lines/handlines, gillnets, trawls, and seines (ICES, 2019). In addition, there are also mussel, oyster, and fish farming operations, as well as whelk pot-trap fishing, in coastal Icelandic waters (Young, 2015; Kristján Phillips pers. comm. 2019; Government of Iceland, n.d.; Marine and Freshwater Research Institute, 2019). Estimates indicate that at least one-quarter of the coastal Icelandic humpback whale population has been entangled in fishing gear at least once (Basran et al., 2019), and most Icelandic fisheries have reported issues with humpback whales swimming through, and sometimes becoming entangled in, their gear (Basran, 2014; Young, 2015). These incidences have caused gear damage or loss, as well as injury or death to the whales in some cases (Víkingsson et al., 2004, 2005; Víkingsson, 2011; Basran, 2014; Basran et al., 2019).

Currently there are no mitigation methods or regulations in place for minimizing whale entanglement in fishing gear in Iceland, despite growing concern over this issue in the local fishing industries. This study conducted the first analysis of behavioural responses of free-ranging humpback whales in their northern feeding grounds off the coast of northeast Iceland to exposure to a whale pinger (Future Oceans) and seal scarer (Lofitech AS ltd.). In addition to the experimental exposures of whales to these ADDs, this study conducted the first field trial of whale pingers in the capelin purse seine fishery in Iceland. This study aims to provide a scientific basis for deciding if these ADDs are likely to effectively mitigate humpback whale entanglement, and resulting gear damage, in their feeding grounds and to investigate any potentially adverse effects of the devices on natural humpback whale behaviour.

Methods

Study area

Experimental exposures of humpback whales to a whale pinger took place in two locations in Northeast Iceland: Skjálfandi Bay and Eyjafjörður (Figure 1). Skjálfandi (66°05'N 17° 33'W) is a bay with an area of approximately 1100 km² that is known for predictable humpback whale sightings from spring through autumn during their feeding season. The bay harbours the fishing and whale watching town of Húsavík on the southeast shore (Stefánsson & Guðmundsson, 1978; Stefánsson et al., 1987; Einarsson, 2009; A. Gíslason unpub. data, 2004). Eyjafjörður (65°50'N 18° 07'W) is a narrow fjord, approximately 440 km² in area, located approximately 80 km west of Skjálfandi Bay (S. Jónsson, unpub. Data, 1996). Eyjafjörður is also well known for humpback whale sightings and harbours fishing and whale watching in the city of Akureyri as well as the towns of Dalvík, Hauganes and Hjalteyri. Experimental exposures to a seal scarer took place only in Skjálfandi Bay. The field trial of whale pingers took place in collaboration with a capelin purse seine vessel based in Neskaupstaður in East Iceland. The boat fished for capelin (*Mallotus villosus*) off South Iceland (Figure 1).

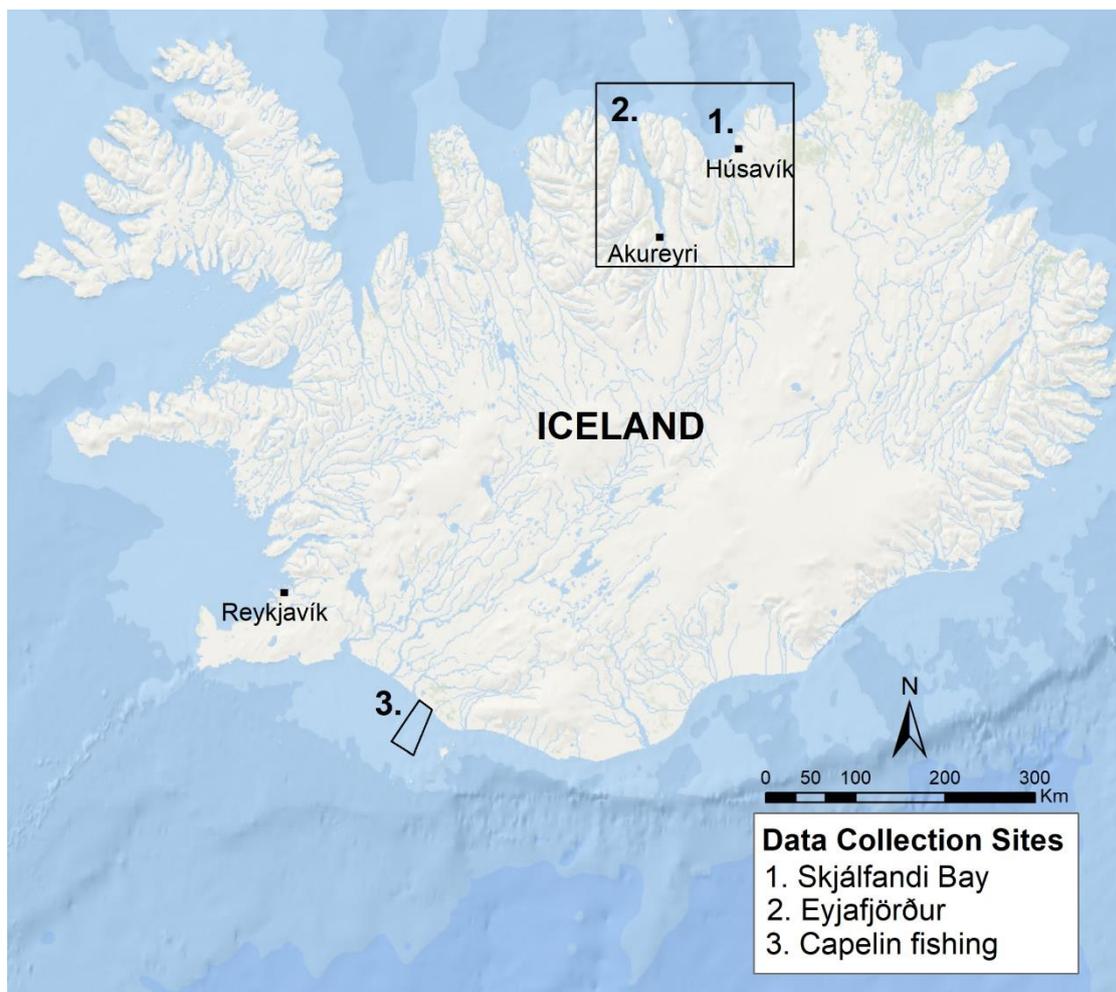


Figure 1. Map showing the locations of humpback whale experimental exposure trials (1. and 2.) using the whale pinger and/or seal scarer, and location where capelin fishing with a purse seine equipped with the whale pingers took place during onboard observation (3.)

Acoustic Deterrent Devices

Two ADDs were used in the present study. The first was the 2016 version of the Future Oceans whale pinger. This whale pinger operates on a single 3.6 V lithium battery and activates automatically when in contact with saltwater. When active, the whale pinger produces a 145 dB re 1 μ Pa at 1 m tone at 3 kHz for 300 ms at 5 s intervals (Future Oceans, n.d.). The second device was the Lofitech AS Ltd. seal scarer composed of a control box with a 25 m long cable with a transducer at the end that produces the sound. This control box is powered by a 12 V marine battery onboard the boat. When active, the device produces a 189 dB re 1 μ Pa at 1 m sound with a fundamental frequency of 14.5 kHz and a frequency range between 10-20 kHz for 500 ms at random intervals of 5-60 s.

A calibration of both ADDs was conducted in the harbour in Húsavík (Skjálfandi Bay) to confirm the manufacturers specifications. Each device was lowered 5 m into the water and recorded by a Reson 4032 hydrophone (also at 5 m depth) connected to an Etec amplifier with the sound signal recording to a Microtrack recorder. The whale pinger was recorded at distances of 1, 5, 10 and 20 m from the hydrophone, while the seal scarer was recorded at 20, 30 and 40 m to avoid the signals being clipped due to the much higher source level

of this device. The recorded signals from the devices were compared with a 153 dB re 1 μ Pa (rms) calibration signal recorded using a calibrator with an adapter for the 4032 Reson hydrophone. The emitted sound from the whale pinger had an actual source level of 137 dB re 1 μ Pa (rms) calculated from the received level recorded at 1 m. The received levels measured at 5, 10, and 20 m were 123, 117, and 116 dB re 1 μ Pa (rms) respectively. Based on previous modelling of the whale pinger sound, humpback whales are expected to detect the sound at a distance of at least 500 m from the source (Harcourt et al., 2014; Pirotta et al., 2016). The emitted sound from the seal scarer had an actual source level of 188 dB re 1 μ Pa (rms) calculated from the received level recorded at 20 m assuming spherical spreading. The received levels measured at 20, 30, and 40 m were 162, 161, and 160 dB re 1 μ Pa (rms) respectively.

Experimental Exposure Trials

Experimental exposures of humpback whales to the ADDs (experimental exposure trials, EETs) were conducted in Skjálfandi Bay in June, July and October 2017, and June and October 2018. In Eyjafjörður, EETs were conducted in May and July 2018. A different, private boat was used in each location. Both boats were 9 m long research vessels from which distance and angle measurements to the whale were conducted from the bow, with the researcher sitting approximately 1 m above the sea surface. Data collected during EETs were recorded with the *Logger 2010* computer program (IFAW) and a hand-held video camera (Sony HDR-CX160E handycam) was used to record the surface behaviours of the whale during each EET. *Logger 2010* recorded time, boat GPS position, boat heading, and any comments that were entered by the data recorder. EETs were attempted when the sea state was considered 3 or less on the Beaufort scale. During an EET, an individual focal humpback whale was chosen based on the criteria that it was swimming alone and that there were no whale watching boats observing the animal. Photo-identification images of the individual were taken of the unique pigment pattern on the ventral fluke and of the dorsal fin shape. This was to ensure each individual whale was not exposed to the same device more than once within the same year, to avoid possible habituation to the sound. When photo-identification was complete, the pre-exposure phase (PrE) began with the boat slowly following the focal whale from a distance of approximately 100 m for 30 min to obtain a baseline of behaviour of the individual, considered the control phase for each EET. The 100 m distance complies with whale watching criteria set forth in many countries globally to minimize disturbance (Carlson, 2008) in order to observe natural behaviour while still being within range to collect all necessary data. This time also allowed for the focal whale to habituate to the presence of the boat, although whales in both study areas encounter boats often so the boat was not a novel stimulus. Each breath the whale took was recorded as “up” and each terminal dive (when the whale arches the back or lifts the fluke to go down for a deep dive) was recorded as “dive” in *Logger 2010*. Other information was also noted, including if the whale dove with or without raising the fluke, if the whale was surface feeding, and if there were other whales in the area. Furthermore, one researcher used an angle-board and rangefinder to obtain the angle to the whale in relation to the boat and the distance to the whale, and this data was also recorded into *Logger 2010*. If the distance could not be obtained from the rangefinder, this researcher estimated the distance to the whale when it took a terminal dive. This was done conservatively, based on the last recorded distance from the rangefinder, and usually only when the whale was at a distance of 400 m or greater. The angle-board, rangefinder, and distance estimation were always done by the same researcher (C.J.B.) for consistency.

Once the PrE phase was complete, the boat was positioned beside where the focal whale was seen taking its last terminal dive and the engine was turned off. To begin the 15 min exposure phase (E), a single whale pinger or seal scarer was placed off the side of the boat into the water at 5 m depth, attached to a weighted rope and buoy. The breaths, dives, angles, and distances of the focal whale were then recorded in *Logger 2010* in the same manner as in PrE phase, with the boat remaining stationary. After the 15 min E phase ended, the ADD was removed from the water, the boat was positioned approximately 100 m from the focal whale, and the same data were collected for an additional 30 min for the post-exposure phase (PoE). If the focal whale disappeared from sight for more than 20 min during an EET, it was considered lost and the EET was ended.

Behavioural Response Variables

Surface Feeding – The number of surface feeding events was determined by watching the video footage of each phase of each EET. For each surfacing of the focal whale, surface feeding behaviour was categorized as yes (Y), no (N), or not able to determine (NA). Feeding behaviour was recognized by observing surface lunging behaviour or expanded throat pleats indicating the whale had a full mouth (Figure 2). A surfacing was also categorized as Y if researchers can be heard in the video commenting that the whale was feeding, even though the surfacing was not visible in the footage.



Figure 2. Photographs of lunge-feeding behaviour and expanded throat pleats used to determine if the focal humpback whale was surface feeding in video analysis.

Breathing Rate and Dive Time – For each phase of each EET, the focal whale's breathing rate was calculated as breaths per min for each surface interval (the time between diving). The time of each dive in seconds in each phase of each EET was also calculated from the time stamps of “dive” and the following “up” recorded in *Logger 2010*.

Directness Index – A directness index (DI) from 0-100, indicating the directness of the focal whale's swimming pattern, was calculated for each phase of each EET, when enough data were available. First, the coordinate position of the whale at each terminal dive was calculated. Then, the DI was calculated as the distance between the two end points of the track divided by the sum of the distances between all the points in the track, and the result multiplied by 100. A DI of 0 corresponds to swimming in a complete circle, while a DI of 100 corresponds to swimming in a straight line (Williams et al., 2002).

Swimming Speed – The focal whale's swimming speed was calculated for each phase of each EET, when enough data were available. Speed was calculated from each terminal

dive to the next terminal dive (and therefore included distance information from when the focal whale was diving and at the sea surface).

Analysis of behavioural response variables

Linear mixed effect models were used to examine the effect of ADD exposure on breathing rate, dive time, swimming speed, and swimming directness. Separate models were set up for each ADD and each of the four response variables. The phase of the EET (PrE, E, PoE) was the only fixed effect predictor variable. To account for the repeated measures within individual whales, exposure trial-ID was included as a random intercept term in all models. Plots of residual versus fitted values revealed that breathing rate and swimming speed needed to be log-transformed to satisfy the modeling assumption of homogeneity of variances (using natural logarithm, ln). Plots of the autocorrelation function of the residuals revealed significant temporal autocorrelation in the models for ln(breathing rate), dive time, and ln(speed). Auto-regressive correlation structures of order 1 were specified in the models for these response variables. Inspection of the autocorrelation function plots verified that this approach successfully accounted for the observed autocorrelation.

Since an individual whale's response to sound can depend on behavioural state (Southall et al., 2019) or vary between individuals (Lien et al., 1990), individual-specific response variation was incorporated into the models by introducing random slopes for the predictor variable, phase. Likelihood ratio tests were used to determine if random intercept and slope models fitted the data significantly better than pure random intercept models. Selection of the random effects structure was done prior to selection of the fixed effects structure (as recommended by Zuur et al., 2009). Selection of the optimal fixed effects structure, i.e. comparison of models with phase as fixed effect to pure intercept models, was also based on likelihood ratio tests. For response variables in which phase had a significant effect, a post hoc pairwise comparison with Bonferroni correction was used to infer between which phases significant changes of the response variable occurred. Additionally, for response variables in which phase had a significant effect and for response variables for which random slope models fitted the data significantly better, separate models and post hoc analyses were calculated for each individual exposure in order to identify the differences that gave rise to the significant effect in the overall analysis. These statistical analyses were performed using the nlme (Pinheiro et al., 2014) and multcomp (Hothorn et al., 2008) libraries in the statistical software *R* (R Foundation for Statistical Computing).

Surface feeding behaviour was recorded as a binary variable and thus could not be modelled by linear mixed effects models. A binary generalized linear mixed effects model was fitted using the function glmer in the lme4-package (Bates et al., 2015). Model specification and selection was analogous to the protocol described for the linear mixed effects models except for the specification of the autocorrelation structure. Since the glmer function does not allow for the specification of temporal correlation structures, the feeding behaviour at the previous surfacing event (lag1_feeding) was included as a fixed effect to account for temporal autocorrelation. Surface feeding behaviour could only be analyzed for whale pinger (WP) EETs, because very little surface feeding was observed in all phases of the seal scarer (SS) EETs.

Field Trial of Whale Pingers on a Commercial Purse Seine

In addition to the individual EETs, the effect of whale pingers was also studied in a field trial. Pingers were fitted on a capelin purse seine used by the vessel Börkur NK122 operating out of Neskaupstaður in east Iceland for the 2018 season (January – March). For the season prior to this trial (January – March 2017), the vessel captain kept a log of humpback whale sightings and any encirclements by the purse seine. For the 2018 capelin fishing season, 10 whale pingers were attached to the float line of the purse seine 30-40 m apart from each other, complying with the manufacturer’s recommendations. The captain kept record of any issues associated with whale pinger use and any incidences of whales inside the purse seine. In addition, one researcher (C.J.B.) joined as an onboard observer for one trip (24-28 February 2018). During onboard observations, the vessel track and whale sightings were recorded in the *SpotterPro* app (Conserve.IO) during all transit and active fishing days. The number of net casts and tonnes of fish caught with each cast were also noted. Any encirclements of whales by the purse seine were video recorded for documentation using a hand-held video camera (Sony HDR-CX160E handycam).

Results

Experimental Exposure Trials

A total of 23 research trips were undertaken in 2017-2018, totalling approximately 83 h of effort (Table 1). Of these, enough data for analysis were collected on 14 trips resulting in 9 whale pinger (WP) and 7 seal scarer (SS) experimental exposure trials (EETs).

Table 1. Data collection trips undertaken in 2017-2018 with the Date (DD.MM.YY), Location (SB = Skjálfandi Bay, EF = Eyjafjörður), number of hours, what experimental exposure trial was completed (Trial Complete: na = not available; no usable trial, SS = seal scarer ID, WP = whale pinger ID), the data that was collected in each experimental exposure trial (B = breathing rate, DI = directness index, D = dive time, S = swimming speed, F = feeding), and the reason the trip did not result in a usable trial (Reason if na).

Date	Location	Hours	Trial Complete	Data	Reason if Trial na
29.04.17	SB	3.5	na		Whale disappeared during WP exposure phase
03.05.17	SB	4.5	SS1	B, DI, D, S	
04.05.17	SB	3	na		No usable whale
04.05.17	SB	3	na		Boat broke down
16.06.17	SB	3.5	WP2	B, DI, D, S, F	
20.06.17	SB	4.5	WP5	B, D, F	
27.06.17	SB	4.5	SS2	B, DI, D, S	
			SS3	B, DI, D, S	
28.06.17	SB	3	WP3	B, DI, D, S, F	
11.07.17	SB	4	na		No usable whale
14.07.17	SB	6.5	WP4	B, DI, D, S	
			SS4	B, D, S	
21.08.17	SB	2.5	na		Rough seas
01.10.17	SB	3.5	WP6	B, D*	
28.04.18	EF	1.5	na		Rough seas
30.04.18	EF	2	na		Rough seas
02.05.18	EF	4	WP7	B, DI, D*, S*	
08.05.18	EF	5	na		Whale disappeared during WP exposure phase
07.06.18	SB	3.5	WP9	B, DI, D, S, F	
12.06.18	SB	3.5	WP10	B, DI, D, S, F	
11.07.18	EF	3	na		Rough seas
09.10.18	SB	3.5	WP11	B, DI, D, S	
15.10.18	SB	3.5	SS5	B, DI, D, S	
14.11.18	SB	3.5	SS6	B, DI, D, S	
21.11.18	SB	4	SS7	B, DI, D, S	

* denotes experimental exposures for which data is only available for the pre-exposure and exposure phases.

Fifteen individual whales were used for the successful behavioural trials which produced usable data (Fig 5). Only one individual whale was used twice, in two separate SS trials, but these trials were conducted 18 months apart. Fourteen of the individuals could be identified in the Húsavík Research Center humpback whale catalogues. One individual in Eyjafjörður was not identifiable beyond confirming that it was only used once in the study.

While all seven attempts to complete a SS EET were successful, two of the eleven attempts to complete a WP EET did not produce enough data to be included in the analysis, since the whales disappeared from sight for more than 20 min and were considered lost.

Whale Pinger – For the WP EETs there was little evidence for individual- or behavioural state-specific variation in responses. For breathing rate, swimming speed, swimming directness, and surface feeding, models that included a random slope for the predictor phase did not fit the data significantly better than models that only accounted for baseline variation between trials by a random intercept term (Table 2). The model for dive time was the only case in which a random slope model fitted the data significantly better than a random intercept model ($p < 0.001$; Table 2) providing evidence for individual- or behavioural state-specific, divergent responses in terms of dive time. There were four individuals for which a significant effect of phase on dive time was observed, three of which showed significant changes in the E phase (Figure 3). For two of these three individuals (WP2, WP11) dive time was significantly lower in the E phase than the PrE and/or PoE phases, while for one individual (WP5) dive time was significantly higher in the E phase than in the PrE and PoE phases.

Humpback whale swimming speed differed significantly between the phases of the trial ($p = 0.006$; Table 2; Figure 3). During the E phase, swimming speed was 1.7 times higher than during the PoE phase ($p = 0.0024$; Table 3) and 1.4 times higher than during the PrE phase, though the latter difference was not significant at the 0.05 significance level ($p = 0.11$; Table 3). No significant difference in humpback whale swimming speed was observed between the PrE and PoE phases ($p = 0.62$; Table 3).

Apart from swimming speed, surface feeding differed significantly between phases of the trial ($p = 0.019$; Table 2; Figure 3). The probability of surface feeding was significantly lower during the E phase than during the PoE phase ($p = 0.026$; Table 4). There was also a reduction in surface feeding from the PrE to the E phase; albeit, this was not significant at the 0.05 significance level ($p = 0.099$; Table 4). Rates of surface feeding amounted to 11% in the PrE phase, dropped to 4% in the E phase, and then rose to 13% in the PoE phase (Figure 4). No significant difference in surface feeding was observed between the PrE and PoE phases ($p = 1.00$; Table 4).

No significant effect of phase of the trial on breathing rate ($p = 0.42$; Table 2), dive time ($p = 0.79$; Table 2), or swimming directness ($p = 0.40$; Table 2) was observed (Figure 3) providing no evidence for a change in these behavioural response variables that was consistent across individuals in WP EETs.

Table 2. Assessment of the random and fixed effects structures of five models explaining the change in a behavioural response variable after exposure to a whale pinger. To test if the effect sizes of the contrasts to the pre-exposure phase differed significantly between individuals, a random intercept and slope model was compared to a pure random intercept model by means of comparison of Akaike Information Criterion (AIC) values and a likelihood ratio test. The fixed effects structure was tested by comparing models with and without the predictor phase. Assessment of random effects was based on models estimated by restricted maximum likelihood, whereas assessment of fixed effects was based on maximum likelihood estimation. Significant p-values are bolded.

Response Variable	Test	AIC (intercept model)	AIC (complex model)	Chi- squared	DF	p-value
Ln(Breathing rate)	Random effect slope	471.0	475.0	0	2	1
	Fixed effect phase	461.1	463.4	1.755	2	0.42
Dive time	Random effect slope	2557.2	2518.2	43	2	<0.001
	Fixed effect phase	2541.6	2545.1	0.479	2	0.79
Directness	Random effect slope	176.7	180.1	0.59	2	0.75
	Fixed effect phase	194.0	196.2	1.833	2	0.40
Ln(Speed)	Random effect slope	411.4	414.7	0.73	2	0.69
	Fixed effect phase	412.4	406.1	10.28	2	0.006
Surface feeding	Random effect slope	483.3	487.3	0.059	2	0.97
	Fixed effect phase	487.3	483.3	7.97	2	0.019

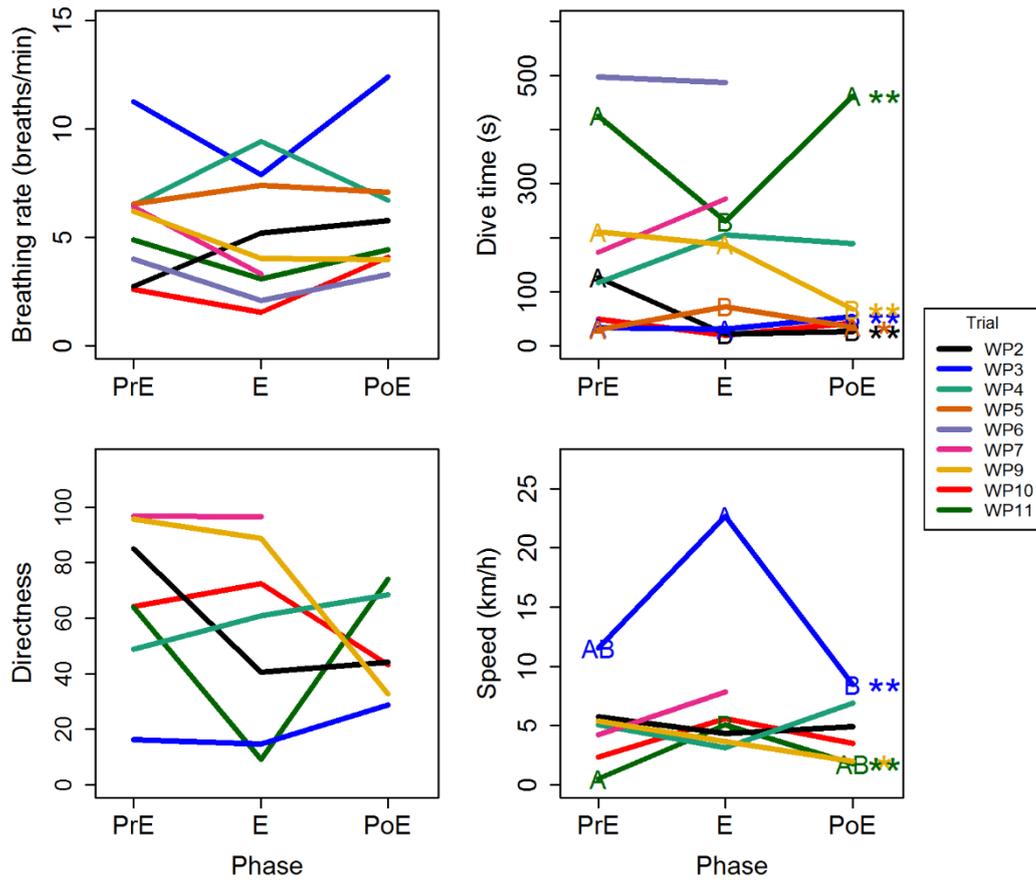


Figure 3. Averages of the behavioural response variables breathing rate, dive time, swimming directness and swimming speed for the pre-exposure (PrE), exposure (E) and post-exposure (PoE) phases of each whale pinger (WP) experimental exposure trial. Stars highlight individual whale pinger exposure trials in which the response variable differed significantly between the phases (* uncorrected $p < 0.05$; ** Bonferroni-corrected $p < 0.05$). Letters indicate between which phases significant differences occurred. Models for individual whale pinger exposure trials were only calculated for response variables for which overall models found a significant effect of phase or random slope (see Table 3).

Table 3. Posthoc comparison for the predictor phase (PrE = pre-exposure, E = exposure, PoE = post-exposure) in the swimming speed model based on the whale pinger data (See Table 2). Since the response variable speed is ln-transformed, effect is the difference in $\ln(\text{speed})$ and e^{Effect} is the ratio between speeds in the two compared phases. Adjusted p-values are Bonferroni-corrected p-values. Significant p-values are bolded.

Posthoc Comparison	Effect on $\ln(\text{speed})$	e^{Effect}	Std. Error	Adjusted p-value
E - PrE	0.35	1.42	0.17	0.11
PoE - PrE	-0.18	0.83	0.14	0.62
PoE - E	-0.53	0.59	0.16	0.0024

Table 4. Posthoc comparison for the predictor phase (PrE = pre-exposure, E = exposure, PoE = post-exposure) in the surface feeding model based on the whale pinger data (See Table 2). Effect and std. error are the effect size on the linear predictor scale and its standard error. Adjusted p-values are Bonferroni-corrected p-values. Significant p-values are bolded.

Posthoc Comparison	Effect on surface feeding	Std. Error	Adjusted p-value
E - PrE	-1.02	0.48	0.099
PoE - PrE	0.21	0.26	1
PoE - E	1.22	0.47	0.026

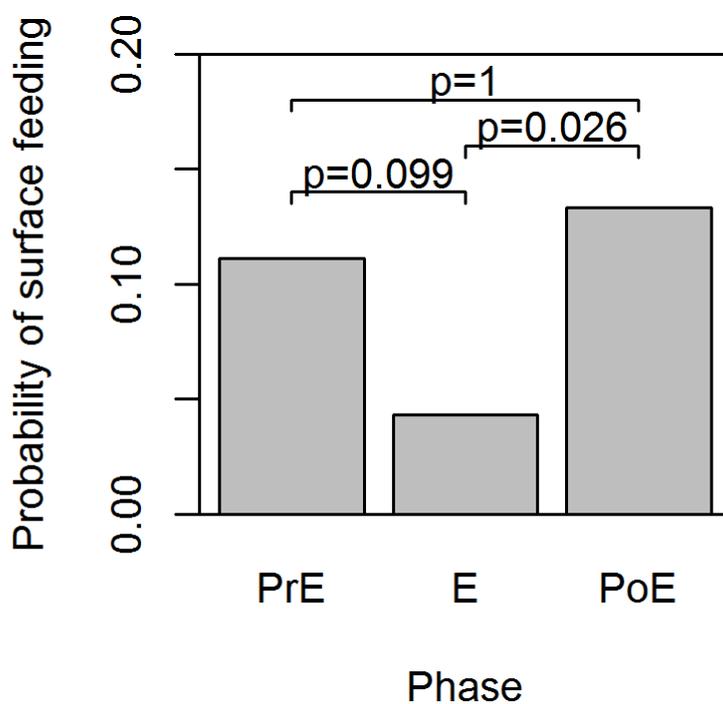


Figure 4. Graph showing the probability of surface feeding during whale pinger experimental exposure trials for each phase (PrE = pre-exposure phase, E = exposure phase, PoE = post-exposure phase). P-values are Bonferroni-corrected p-values obtained in the post hoc comparison (See Table 4).

Seal Scarer – For the SS EETs there was also little evidence for individual- or behavioural state-specific variation in responses. For breathing rate, swimming speed, and swimming directness, models that included a random slope for the predictor phase did not fit the data significantly better than models that only accounted for baseline variation between trials by a random intercept term (Table 5). The model for dive time was the only case in which a random slope model fitted the data significantly better than a random intercept model ($p = 0.002$; Table 5) indicating that individual- or behavioural state-specific responses in terms of dive time may exist. There were three individuals for which a significant effect of phase on dive time was observed; however, post hoc analysis could only resolve between which phases the significant difference existed for one individual (SS4; Figure 5). For this

individual, dive time was significantly lower in the PoE phase when compared to the PrE and E phases.

No consistent response to the seal scarer across individuals was observed for any of the response variables. Phase of the trial did not have a significant effect on breathing rate ($p = 0.55$; Table 5), dive time ($p = 0.10$; Table 5), swimming directness ($p = 0.55$; Table 5), or swimming speed ($p = 0.93$; Table 5).

Table 5. Assessment of the random and fixed effects structures of four models explaining the change in a behavioural response variable after exposure to a seal scarer. To test if the effect sizes of the contrasts to the pre-exposure phase differed significantly between individuals, a random intercept and slope model was compared to a pure random intercept model by means of comparison of Akaike Information Criterion (AIC) values and a likelihood ratio test. The fixed effects structure was tested by comparing models with and without the predictor phase. Assessment of random effects was based on models estimated by restricted maximum likelihood, whereas assessment of fixed effects was based on maximum likelihood estimation. Significant p-values are bolded.

Response Variable	Test	AIC (intercept model)	AIC (complex model)	Chi-squared	DF	p-value
Ln(Breathing rate)	Random effect Slope	271.8	275.8	0	2	1
	Fixed effect Phase	262.2	265.0	1.18	2	0.55
Dive time	Random effect Slope	1427.3	1418.7	12.6	2	0.002
	Fixed effect Phase	1447.1	1446.5	4.594	2	0.1
Directness	Random effect Slope	143.4	147.0	0.4431	2	0.81
	Fixed effect Phase	159.6	162.4	1.2	2	0.55
Ln(Speed)	Random effect Slope	237.4	238.9	2.473	2	0.29
	Fixed effect Phase	226.5	230.4	0.138	2	0.93

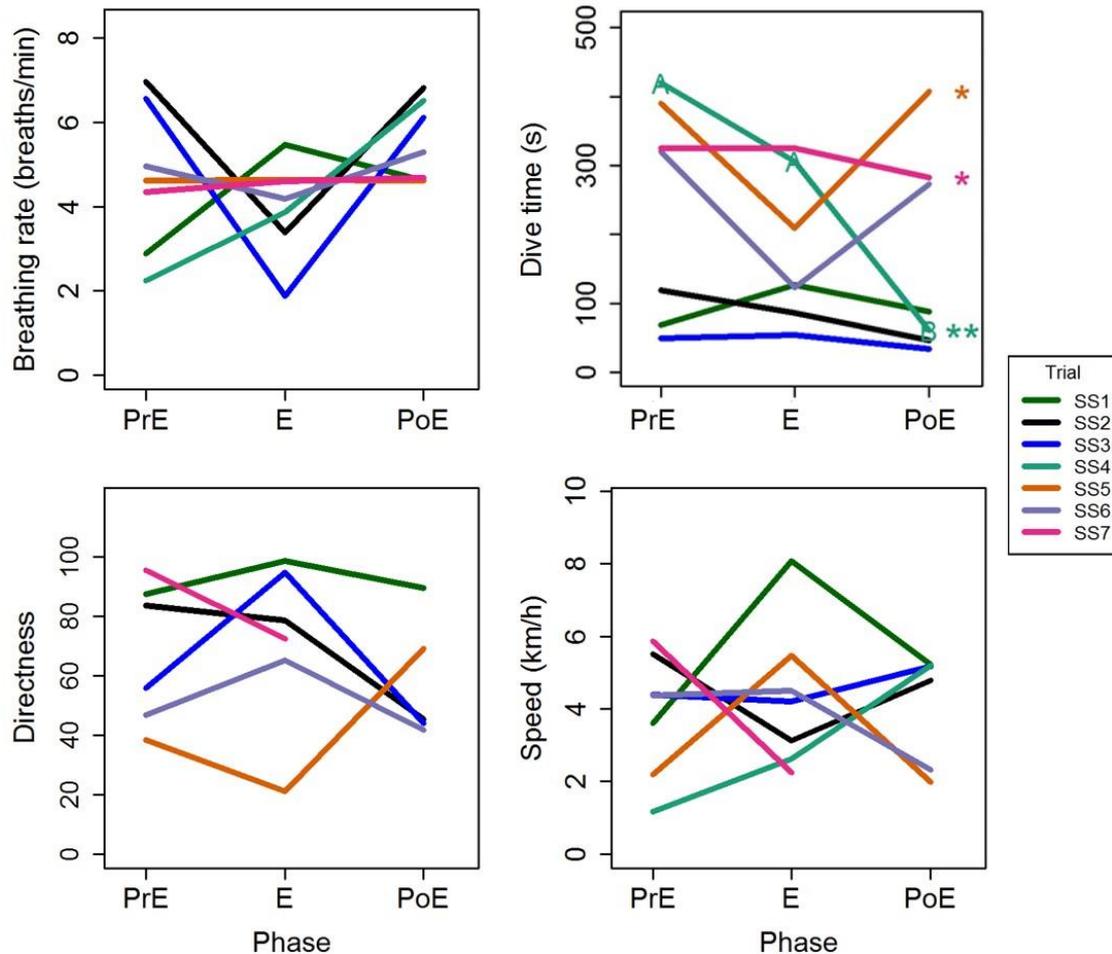


Figure 5. Averages of the behavioural response variables breathing rate, dive time, swimming directness and swimming speed for the pre-exposure (PrE), exposure (E) and post-exposure (PoE) phases of each seal scarer (SS) experimental exposure trial. Stars highlight individual seal scarer exposure trials in which the response variable differed significantly between the phases (* uncorrected $p < 0.05$; ** Bonferroni-corrected $p < 0.05$). Letters indicate between which phases significant differences occurred. Models for individual seal scarer exposure trials were only calculated for response variables for which overall models found a significant effect of phase or random slope (see Table 5).

Purse-seine trial of the whale pingers

The captain of the participating capelin purse seine vessel did not report any issues with humpback whales inside the purse seine in the 2017 season and reported that there were generally lower sightings and incidences than in the previous (2016) season. During the 2018 capelin fishing season, the onboard observer recorded 34 individual humpback whale sightings at seven locations during 16 h of observation (Table 6). A total of 70.6% ($n = 24$) occurred while the boat was on the capelin fishing grounds off the south/southwest coast of Iceland. The purse seine was cast three times during onboard observations and a total of 1510 tonnes of capelin were caught. Whales at the sea surface near the vessel when fishing operations began were noted to swim away from the area, with one whale specifically observed turning 180° to the opposite direction from where the purse seine was being set into the water. There were two incidences where humpback whales were encircled by the purse seine fitted with the whale pingers during the 2018 fishing season, once when the onboard observer was present and once when the observer was not. In both incidences two humpback whales appeared at the sea surface inside the purse seine once the bottom of the

net was being closed, indicating the whales entered from the bottom. When the onboard observer documented the first incident, it was noted the whales were “trumpeting” and showed signs of distress (Weinrich, 1999). In an attempt to release the whales, (in both cases), the extra line attaching the end of the purse seine to the vessel was not brought in towards the boat, while the purse seine was closed at the bottom creating an approximately 100 m wide opening in the side of the net towards the stern where there were no whale pingers, as well as no floats, on the line. During the observer documented encirclement, the two whales spent approximately 5 min inside the purse seine before locating this opening and escaping without causing any damage. According to the captain, the second incident occurred in the exact same manner. The captain and crew reported that in previous seasons, when the whale pingers were not fitted on the rest of the purse seine apart from the line creating the opening left for whales to escape, whales rarely, if ever, found this opening and escaped without further action or damage to the purse seine. Only 270 tonnes of capelin were caught in the cast where the whales were encircled by the purse seine during the observer documented incident (compared to 690 and 550 tonnes in the other two casts).

Table 6. Effort during onboard observation on the capelin purse seine vessel using the whale pingers including date (DD,MM,YY), time, whale sightings (Mn = humpback whale (*Megaptera novaeangliae*), Bp = fin whale (*Balaenoptera physalus*)), location (latitude, longitude), status of the boat, and comments.

Date	Time	Sightings	Boat Location	Status	Comments
24.02.18	2000			leaving port	
25.02.18	0900-1200	1Mn	63.514593N -17.864615W	transit	
25.02.18	1340-1540	NA		transit	
25.02.18	1610-1810	4Mn	63.430734N, -19.595009W 63.437207N, -19.901842W	transit/docking	Two pairs of whales
26.02.18				in port	
27.02.18	0930-1145	9Mn	63.722643N, -20.818695W 63.727772N, -20.836443W 63.736444N, -20.884974W 63.737366N, -20.887947W 63.75826N, -20.912274W 63.764711N, -20.92963W 63.785706N, -20.989416W	traversing grounds	Pair of whales Pair of whales
27.02.18	1330-1600	3Mn	63.766879N, -20.969197W 63.729173N, -20.892273W 63.784402N, -20.985329W	traversing grounds/fishing	
27.02.18	1700-1800	3Mn	63.604162N, -20.773594W 63.596906N, -20.714554W	traversing grounds	Pair of whales
28.02.18	0835-1000	6Mn*	63.499573N, -20.940331W 63.498824N, -20.937591W 63.498249N, -20.945592W 63.500046N, -20.946389W 63.499475N, -20.9425W	fishing	Pair of whales
20.02.18	1645-1800	5Mn 1Bp	63.372122N, -18.879468W 63.36858N, -18.812109W 63.367307N, -18.774776W 63.378524N, -18.599105W 63.382446N, -18.559984W 63.369304N, -18.693336W	transit	

* denotes in which sighting two whales were encircled in the net.

Discussion

Mitigating large whale entanglement in fishing industries is of global interest. This study represents the first *in situ* experiments exposing humpback whales to commercially available ADDs in their North Atlantic feeding grounds off Iceland and is the first study to examine changes in surface feeding as a behavioural response to a pinger. The whale pinger had a significant effect on surface feeding behaviour during whale pinger (WP) experiment exposure trials (EETs). Surface feeding was only 4% during the exposure (E) phase of the WP EETs, when the whale pinger was active in the water, compared to 11% prior to- and 13% after exposure. This indicates that the whales reduced or stopped surface feeding in response to the whale pinger. Previous studies have found that humpback whales ceased feeding in response to sonar sounds (Sivle et al., 2015), decreased side roll feeding in response to ship noise (Blair et al., 2016), and decreased detectable lunge feeding behaviour during approaches of whale watching vessels in one of the study sites for this experiment (Skjálfandi Bay, Ovide, 2017). A reduction or cessation of feeding may therefore be a common response of humpback whales to anthropogenic noise.

Whales reducing or stopping feeding when exposed to the whale pinger sound could lead to lower incidence of humpback whale encirclement and entanglement in Icelandic fisheries, since the whales are likely feeding when these incidents occur. During the feeding season, humpback whales spend the majority of their time foraging (Friedlaender et al., 2013; Ovide, 2017), and entanglement of humpback whales has been observed to coincide with spawning of one of their main prey species, capelin, in Newfoundland Canada (Perkins & Beamish, 1979). Similarly, humpback whales that were evidently feeding on capelin were observed being encircled by a purse seine during the present study. Based on this observation, it can be hypothesized that if the whales stop feeding in the vicinity of fishing gear with active pingers, they may be more likely to take notice of the gear and less likely to become entangled or encircled. This indicates pingers may be a useful mitigation tool. Similarly, Lien et al. (1992) also hypothesized that whales may not notice nets while they are foraging and found that when cod traps, set in humpback whale feeding grounds in Canada, were fitted with 4 kHz alarm prototypes, the number of whale collisions was significantly reduced.

This study documents a reduction in feeding behaviour in response to a pinger for the first time, with only hypothetical explanations offered for why the whales reacted as they did. One possibility is that they were simply distracted by or curious about the sudden introduction of an unnatural, unfamiliar sound in their environment, as suggested by Lien et al. (1990). Since the received sound level from the whale pinger was likely low, it is unlikely that the whales were startled and stopped feeding. There was also no clear indication that they moved away from the sound based on results from the directness index model. However, three of the 11 individuals involved in attempted WP EETs were considered lost (disappeared for more than 20 min) during the E phase. Two out of three individuals (WP1, WP8) were excluded from the analysis due to lack of data. One individual (WP1) dove and disappeared 35 s after the E phase began, the second individual (WP7) started traveling and stopped taking terminal dives lifting the fluke 23 s after the E phase began and was last sighted an estimated 1000 m away before it was considered lost, and the third individual (WP8) was recorded taking a terminal dive before the whale pinger was set in the water and was not seen again within 20 min after the E phase began. Since the boat was stationary during the E phase of the trials, the probability

of losing sight of the focal whale was higher than during the pre-trial (PrE) and post-trial (PoE) phases (when the boat is maneuvered); however, trials were only conducted in good weather with good visibility and, therefore, complete disappearance within 20 min of the E phase beginning was most likely due to a change in behaviour. It is possible that these individuals were disturbed by the whale pinger sound and moved away. Lien et al. (1990) found similar results when testing whale alarm prototypes, reporting that some whales in those experiments moved significantly further away while some moved significantly closer. However, we cannot rule out the possibility that these whales changed behaviour during the E phase of these trials for some reason unrelated to the pingers, particularly in the case of WP8 where the whale was not sighted at all during this phase.

Previous research indicates that the responses of the whales observed in the present study are unlikely due to the whale pinger sound impacting the distribution of the prey they were feeding on at the time. Generally, fish species have the highest sensitivity to sounds below 0.5-1 kHz (Whalberg & Westerberg, 2005) and humpback whale prey species, such as capelin and krill (*Euphausia spp.*), are hypothesized to have low sensitivity to sound and little behavioural reactions to sound exposure (Brierley et al., 2003; Jørgensen et al., 2004). Therefore, it is unlikely that the whale pinger sound (3kHz, 137 dB re 1 μ Pa at 1 m) affected the prey that the whales were feeding on during the EETs and more likely that the whales were responding directly to the whale pinger itself.

The disruption of humpback whale feeding behaviour observed in this study is cause for some concern for potential negative impacts on the individual, and possibly the population, if pinger use becomes widespread in fishing industries. Humpback whales need to consume an estimated 1432 Kcal of food per day during the summer feeding season in order to have a large energy storage for their migration and winter breeding season (Sigurjónsson & Víkingsson, 1997). Insufficient energy stores may lead to decreased ability to migrate or decreased reproductive success, which can impact the recruitment rate of the population (Butterworth et al., 2012). However, it is important to note that exposure to the whale pinger in the present study during the E phase was only for 15 min, so it is unknown if the whales habituate to the sound and continue feeding normally after a longer exposure. No lasting effect of the whale pinger on surface feeding was observed, given that there was no significant difference between the PrE and PoT phases, suggesting that when the whale pinger is removed from the water the whales quickly returned to their pre-exposure behaviour.

The whales in this study that were encircled by the purse seine fitted with the whale pingers were not surface feeding and entered the net from deeper than 120 m while the whale pingers were near the sea surface. This may indicate the whale pingers were not in the correct position to cause the whales to stop feeding and avoid entering the net, suggesting the importance of positioning pingers strategically on gear to obtain the desired result. Further experimentation with pingers at different depths and tagging of whales to gather information about their underwater feeding activity could provide valuable information to further explain how a change in feeding behaviour or increased awareness of the nets could lead to lower incidence of entanglement or encirclement.

Humpback whales significantly increased their swimming speed during exposure to the whale pinger. An increase in humpback whale swimming speed has not been reported in previous studies investigating behavioural responses to pingers; however, Todd et al. (1992) reported that humpback whales exposed to 4 kHz alarm prototypes made

significantly more abrupt turns towards an active alarm, and abrupt turns have been associated with higher swimming speeds (Edel & Winn, 1978). The increase in speed observed in the present study supports that humpback whales responded to the whale pinger sound, though further investigation into the whales' swimming behaviour is required to infer how this response may relate to entanglement mitigation.

There was no significant behavioural response of humpback whales to the whale pinger in terms of breathing rate, dive time, or swimming directness which is consistent with experiments conducted during whale migration in Australia (Harcourt et al., 2014; How et al., 2015; Pirotta et al., 2016). There was also no evidence for individual- or behavioural state-specific responses in terms of breathing rate or swimming directness, thus there is no evidence that individuals reacted to the whale pinger significantly in terms of these variables. The received sound level may have been too low to elicit a detectable behavioural change in terms of these variables, which are variables that can indicate whether the whale was disturbed or startled (Nowacek et al., 2007) rather than attentive or curious. The humpback whales foraging in the study sites are regularly exposed to considerable anthropogenic noise. Both locations host a high number of whale-watching vessels that primarily target humpback whales for their sightings, as well as industrial ports with associated development and maintenance noise and fishing vessels, cruise ships, and cargo ships entering and exiting often. There are also commercial fishing grounds within the area of both study sites. Therefore, humpback whales in these areas may be habituated to anthropogenic noise and may not show behavioural changes that would indicate they are significantly disturbed or stressed, but will still show some behavioural changes when a new, novel sound, such as the whale pinger sound, is introduced.

Response to sound may differ between individuals and may depend on behavioural state (Southall et al., 2019). The results from the dive time models for both the whale pinger and the seal scarer showed no consistent change in dive time across individuals or exposure trials and the random slope models that account for individual-specific responses fit the data best. While dive time during the E phase significantly increased for some individuals, it significantly decreased for others, which suggests support for individual-specific, divergent responses. An alternative explanation is that individuals may have been naturally switching between a behavioural state of long dive times and a state of short dive times, and this change coincided with the phases of some of the EETs. Given that there was evidence for individual-specific response in dive time for both ADDs despite there being no consistent response in dive time to either device, and furthermore no other significant responses to the seal scarer for any variable, a natural change in behavioural state is considered the most likely explanation of these findings

There was no evidence for a consistent significant effect of the seal scarer on humpback whale breathing rate, dive time, swimming speed, or swimming directness. The seal scarer had a source level 51 dB re 1 μ Pa louder than the whale pinger (188 dB re 1 μ Pa (rms) compared to 137 dB re 1 μ Pa (rms) based on calibration measurements) and therefore it was hypothesized humpback whales would have some reaction to the high-powered sound even though the frequency of the device is at the top or slightly above their modelled hearing range (Houser et al., 2001). Results from the present study are consistent with findings of Henderson et al. (2016) in which it was also concluded humpback and blue whales (*Balaenoptera musculus*) did not react to high frequency pingers (though the pinger used in their study was 17-35 kHz higher in frequency than the seal scarer used in this study) and with Lien et al. (1990) in which it was determined that high-frequency alarms

(7-30 kHz higher in frequency than the seal scarer used in this study) did not significantly lower the incidences of humpback whales colliding with gear. It is possible that the frequency of the seal scarer was just too high for humpback whales to hear the device well enough to exhibit a significant response, confirming that ADDs need to target the best-estimated hearing range of the whales.

The use of the whale pingers on the capelin purse seine for one season provided the first insight into the use of the devices in a practical application in Iceland. On two occasions, a pair of whales entered the purse seine fitted with the whale pingers from the bottom before it had been closed. Since the whale pingers were attached along the float line at the top of the net, it is possible that they were not in the correct position to prevent whales from entering the gear through the bottom opening (below 120 m depth). Despite the whale pingers not deterring the whales from entering the purse seine from the bottom, the whales were able to find their way out through an approximately 100 m wide (at the surface) opening where there were no whale pingers in both cases. The whales escaped without causing any damage to the purse seine and without further intervention methods from the captain (such as putting the boat into reverse to sink the float line). The captain and crew reported that whales escaping the net on their own was a very rare occurrence. This led to an overall positive view of the whale pingers and an increased interest in further trials for use in the Icelandic capelin purse seine fishery to prevent net damage. Suggestions for repositioning the whale pingers on the purse seine could be considered in the future including attaching them to the lead line at the bottom or sewing specialized pockets for them into the lower portion of the purse seine itself (Hjörvar Hjálmarsson pers. comm., 2018; Geir F. Zoega pers. comm., 2019). The observations of humpback whales finding an opening in the net free of pingers in the present study provides insight into the currently unknown directional hearing capabilities of humpback whales. Ten whale pingers were spaced approximately every 30-40 m along the float line of the purse seine (which measured 450x120 m in total). When the whales were inside the purse seine there was an approximately 100 m opening left at the surface by a single rope attaching the purse seine end to the vessel, and the first whale pinger was attached approximately 30 m from the “bag” netting (the net that remains in the water to prevent fish from escaping as they are hauled on board). This equals an estimated 150 m space without whale pingers, of which approximately 100 m is the opening for the whales to escape through. If the whale pingers were truly guiding the humpback whales to the opening, as was suggested based on the captain and crew’s several years’ of experience with whales becoming encircled by the purse seine, then possibly the whales were able to acoustically detect this 150 m space. That is, maybe this space with no whale pingers was devoid of detectable sound and discernible by the whales. If further trials can confirm that humpback whales can be guided to a net opening by pingers, this would indicate that humpback whales have good directional hearing capabilities.

In conclusion, humpback whales in their feeding grounds off north Iceland significantly reduced surface feeding in response to whale pinger exposure. In addition, when encircled in a purse seine fitted with the whale pingers, the whales managed to exit the purse seine through a pinger-free opening without causing damage. Since a reduction in feeding around nets likely reduces the risk of whale entanglement or encirclement, these findings suggest that whale pingers may be effective in mitigating humpback whale entanglement and minimizing fishing gear damage. This is consistent with Lien et al.’s (1992) conclusions that low-frequency pingers appeared to be a useful mitigation tool that

significantly reduced the incidences of humpback whales colliding with fishing gear. The whale pinger also had a significant effect on whale swimming speed in the present study; however, the implications of this response in terms of entanglement reduction are unknown. No significant reactions to the high-powered, high-frequency seal scarer in terms of dive time, breathing rate, swimming speed or swimming directness were observed that were consistent across individuals, which indicates these devices are not effective for humpback whales; however, their feeding response to such a device requires further investigation. Results from the present study suggest that pingers may be effective in mitigating humpback whale entanglement and minimizing fishing gear damage in their feeding grounds; however, the devices should be used with caution until further information is gathered on the longer-term consequences of the reduction in feeding. Therefore, pingers may be best suited only for a confined set of short-term applications, where gear is not left in the water for long periods of time, and used in conjunction with other possible entanglement mitigation methods such as seasonal or area restrictions on fishing and modified fishing gear.

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Paper V

Paper V

Details of whale entanglement in fishing gear in Iceland from the fishers' perspective, with focus on humpback whales (*Megaptera novaeangliae*)

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CJB

Fishers and whales in Iceland: Whale interactions with fishing gear from the fishers' perspective, with focus on humpback whales (*Megaptera novaeangliae*)

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ABSTRACT

In Iceland, as in many places globally, the detrimental impacts of whale interactions with fishing gear on both fisheries and whales are not well understood and managed. This study conducted anonymous questionnaires of Icelandic fishers and interviews of capelin purse seine boat captains to gather first-hand knowledge of the issues fishers face due to whale interaction with their fishing gear. Results suggest that the humpback whale is the large whale species that is most often entangled or encircled in fishing gear and causing damage; however, on occasion other large whale species are interacting with gear as well. Interactions between humpback whales and fishing gear appears to be primarily concentrated in the north/northeast and southwest of the country where there is high fishing effort and known humpback whale feeding habitat. Humpback whale interactions with gear occurred most often with capelin purse seines, which are targeting humpback whale prey, and data suggests that bycatch of whales in this fishery may be underreported. Damage and losses due to whale collisions with gear were reported to cost fishers up to a maximum of 55.000.000ISK per incident, suggesting this can be a costly issue for which mitigation measures should be explored. The use of acoustic “pingers” is one mitigation measure that has been previously tested by capelin purse-seiners and is something that captains indicated they would be interested in continuing to try. The creation of a whale entanglement/whale-gear interaction reporting system in Iceland would aid in gathering more data, quantifying these events and determining what the consequences are both to fishers and whales. This study provides new information about the consequences of large whale interactions with Icelandic fisheries and suggests that future collaboration with fishers can provide insight contributing to best management practices for sustainable fishing and whale conservation.

KEYWORDS: INCIDENTAL CATCHES, FISHERIES, HUMPBACK WHALE, PURSE-SEINES, ICELAND SEA

INTRODUCTION

Interactions between commercial fishing and cetaceans are of increasing global concern. Fifty years ago, the global fish capture was 60 million tonnes, increasing to 80 million tonnes 20 years ago and to 90.5 million tonnes in 2016 (FAO, 2018). Some fisheries directly target cetacean prey species, such as capelin (*Mallotus villosus*) and herring (*Clupea harengus*), which is likely to increase interaction between cetaceans and fishing gear. In addition to expanding fisheries and fisheries targeting cetacean prey, many cetacean populations, particularly the humpback whales (*Megaptera novaeangliae*), have been increasing since their protection (Wedekin *et al.*, 2017; Zerbini *et al.*, 2019) which further increases the likelihood of negative fisheries interactions.

The interactions between cetaceans and fishing can be detrimental to both the animals and the fishers. An entanglement in fishing gear can lead to injury or death of the whale which can have consequences at the population level (Mazzuca *et al.*, 1998; Cassoff *et al.*, 2011; Knowlton *et al.*, 2012; Robbins, 2015). The creation of stronger, synthetic net and line material in fisheries has likely increased the risk of cetaceans becoming fatally entangled or seriously injured since this material is more durable and difficult to break (Volgenau *et al.*, 1995). Interactions between whales and gear also causes financial loss to fisheries in terms of gear damage, down-time for repairs and loss of catch (Lien, 1979; Lien and Aldrich, 1982), particularly due to large whale interactions such as the humpback whale. For humpback whales, it is estimated that the studied populations in Iceland, the Gulf of Maine, and Alaska are entangled in fishing gear at a rate of 2%, 14-17% and 8% per year respectively (Basran *et al.*, 2019; Robbins, 2012; Neilson *et al.*, 2009). Likely due to concern over negative consequences that the fishing industry could face, underreporting of bycatch of, or interactions with, marine mammals in general is common (eg. Baker *et al.*, 2006; Robbins, 2011; Reeves *et al.*, 2013). Fishers likely have valuable information about this issue that is seldom quantified in order to effect change by scientists, managers, or policy makers.

In Iceland, export of fishing products is the third highest grossing industry, and 1582 commercial fishing vessels were registered in 2019 (Statistic Iceland a, b). Methods used for catching commercial fish species include gillnets, demersal seines, purse seines, trawls, and hand/long-lines (ICES, 2019), which have been implicated in cetacean entanglements in previous studies around the world (eg. Reeves *et al.*, 2013; Archer *et al.*, 2004; Rossman, 2007; Pusineri and Quillard, 2008). It is mandatory in Iceland that fishers report any catch of cetaceans in their logbooks (Atvinnuvega- og nýsköpunarráðuneyti, 2020) and several cetacean species have been reported, including harbour porpoises (*Phocoena phocoena*), white-beaked dolphins (*Lagenorhynchus albirostris*), minke whales (*Balaenoptera acutorostrata*), humpback whales, and fin whales (*Balaenoptera physalus*) (Marine and Freshwater Research Institute, unpub. data). Fishers in Iceland tend to complain specifically about humpback whales colliding with, being encircled in, or becoming entangled in their gear and causing damage (pers. obs.). The humpback whale population in the central north Atlantic is estimated to be approximately 10,000 individuals and the majority of sightings from surveys occurred in the north and northwest of Iceland (Pike *et al.*, 2019). An estimated 25% of Icelandic humpback whales have scarring indicating they have been entangled in fishing gear at least once and some of these entanglements are known to occur locally in Iceland (Basran *et al.*, 2019).

Interviews and written questionnaires are methods used to gather eye-witness accounts and expert knowledge from resource-users, including fishers. Using these methods to engage

with fishers can improve the relationship between fisheries and research institutes and can lead to increased data and better fisheries management (Johnson and Densen, 2007). This method has been used to study experiences and effects of whale depredation on fisheries in Alaska, USA (Peterson and Carothers, 2013), seal-fisheries interactions in Greece and Cornwall, England (Glain *et al.*, 2001), gear damage caused by whales and sharks in Newfoundland and Labrador, Canada (Lien and Aldrich, 1982), fisher knowledge of marine megafauna bycatch off Mayotte Island, Mozambique (Pusineri and Quillard, 2008), cetacean-fisheries interaction in Galicia, Spain (Goetz *et al.*, 2014) and Bahia, Brazil (Seminara *et al.*, 2019) and marine mammal bycatch in the South China Sea (Liu *et al.*, 2016), Victoria, Australia (Norman, 2000), Northwest Spain (López *et al.*, 2003), artisanal fisheries in African, Asian and Caribbean countries (Moore *et al.*, 2010) and Iceland (Ólafsdóttir, 2010). Surveys of fishers and onboard observation can be useful tools to collect eye-witness accounts of whale-gear interactions and specific details of these incidents that cannot be inferred using conventional methods of studying whale entanglements (Knowlton *et al.*, 2005). Observations of whales interacting with fishing gear are considered to be rare and fishers are the most likely people to be able to provide first-hand insight. This study used questionnaires, with Likert-type scales for frequency, yes/no, multiple-choice and open-ended questions, as well as semi-directed interviews to collect information about whale-gear interactions. Data included entanglements, collisions and encirclements of whales in Icelandic fisheries from the fishers' perspective, primarily focusing on humpback whales. Rarely reported details of the events were collected such as location, fishing gear used, and damage sustained to the gear. Likert-type scale and yes/no question responses were statistically compared using Wilcoxon Rank Sum tests. The information collected in this study aids in creating a clearer understanding of the issues surrounding interactions between whales and Icelandic fisheries, which can in turn be used to improve fisheries management for both mitigating financial losses to fishers and whale conservation.

METHODS

An anonymous questionnaire about cetacean sightings and entanglement in/interaction with fishing gear was designed to gather information from fishers in all types of fishing industries in Iceland. The aim was to gather answers from any fisher, not just those that had whales interact with or become entangled in their gear. Experience of the fishers and job onboard was not considered when inviting participants. The questionnaire was primarily focused on entanglement and gear interactions involving humpback whales. It was created in English and translated into Icelandic prior to distribution. Pilot-project questionnaires were distributed first in 2013, and then finalized questionnaires were used 2015-2018.

A total of 40 registered commercial fishing companies were contacted about the questionnaire through email, phone, and/or post either through contacting the company office or making contact directly with fishers working for the companies. A list of companies with active fishing vessels was compiled using Marine Traffic and Skipaskrá (the Icelandic ship list) and questionnaires were sent to companies in all parts of the country. Contact about the questionnaire was attempted with all companies identified as operating two or more vessels ($n = 25$) and 15 single-boat companies for which contact information could be found. Type of vessel, fishing gear, and species fished was not considered when compiling the list, to minimize potential bias in responses. Ultimately, the

companies covered all gear-type categories used in Iceland (hooks and line, gillnets, trawls and seines). The first effort to contact the companies was conducted through email. Secondly, the largest and most successful effort was through post, for which 158 questionnaires with a pre-paid and pre-addressed envelope were sent to 24 companies. The number of blank surveys sent to a company corresponded with the number of fishing vessels the company had (2 per vessel). The companies to which the questionnaires were mailed included those which did not respond to the initial email contact within one year. Phone contact was attempted with companies which did not answer through email or post, in order to assess if they would be willing to answer the questionnaire if it was sent to them again. Lastly, the largest remaining companies (operating three vessels or more) which had not answered through any method were contacted by email a final time shortly before concluding the study. In addition, in-person and social media contact requesting participation in the questionnaire was made with seasonal fishers and an online link to the survey was available for one month, both of which did not provide information about which companies the participants worked for.

The questionnaire started with a short explanation of the project, stating the goal was to gather information from fishers about cetacean sightings and entanglement in/interaction with fishing gear and the impacts of these incidents. It was made clear that all participants would be kept anonymous. The question methods used were Likert-type scales for frequency (where answers are selected on a scale ie. from never to very often), yes/no, multiple choice and open-ended. Both the pilot survey and the continued survey first asked generally about cetacean sightings while fishing, then about humpback whale sightings specifically. It went on to ask about cetacean entanglement or interactions in general, then about humpback whales specifically. The continued survey, from 2015 on, furthermore inquired if humpback whale entanglement/interaction had occurred in the past 5 years, giving a more reliable time range for these incidents (from 2010-2018). If the participant answered yes to having humpback whales in their gear, they were requested to supply details of the incident including date, gear-type, target fish species, location, and what (if any) action was taken (in both versions of the survey). Next, the continued survey asked if the fisher had experienced gear damage due to whales in the past 5 years. If they answered yes, they were asked to supply details including whale species, location, gear type, type of damage, and estimated costs of the damage and down-time. Lastly, the continued survey inquired about reporting of whale entanglement/interaction incidents and what the reason(s) would be that the participant would not report an incident.

Data from the questionnaires were compiled and visualized for the results. The Likert-type scale question responses regarding frequency of observing animals entangled in/interacting with fishing gear were updated to “never”, “once” and “more than once” to give more exact answers in the finalized survey started in 2015. To compile the data for these questions to include the pilot survey, the categories were “never”, “once + occasionally”, and “more than once + often”. Statistical comparisons between answers to Likert scale and yes/no question responses were conducted using Wilcoxon Rank Sum tests performed in the statistical software program R (R Foundation for Statistical Computing version 3.1.6) and mean ranks for comparison were calculated using SPSS (IBM SPSS version 25.0). Data could only be included in statistical analysis when the respondent answered both the questions of interest.

In addition to the questionnaire, five capelin purse-seine vessel captains, four who were current captains and one who was retired, took part in semi-directed interviews. The interviewer asked both closed questions and open-ended follow-up questions to guide the

interview, allowing the respondent to provide detailed answers of varying length and scope (Adams, 2015). The five captains were chosen based on the criteria that they had prior incidents with humpback whales in their nets and they were willing to be interviewed in-person or over the phone with the conversation being audio recorded. Three interviews were conducted in English and two in Icelandic, and the interviews were later transcribed. These interviews served to gather more in-depth information about issues with humpback whales interacting with capelin purse seines in Iceland, since the capelin fishery is the industry with the most complaints about this.

RESULTS

A total of 60 completed questionnaires were returned, and 59 were used for analysis. Two questionnaires were returned in the same envelope and contained the exact same answers and therefore were counted as one. Fifteen companies (37.5%) of the ones which were known to have been contacted (through email, post or personal contact) returned at least one questionnaire. The majority of questionnaire respondents reported seeing whale species (spp.) “often” or “very often” while fishing in Iceland (57.6%) (Fig. 1). Nearly half (47.5%) also reported seeing specifically humpback whales “often” or “very often”. In addition, 55.9% reported seeing dolphins and/or porpoises “often” or “very often” while fishing and only 8.5% reported seeing pinnipeds “often” or “very often”.

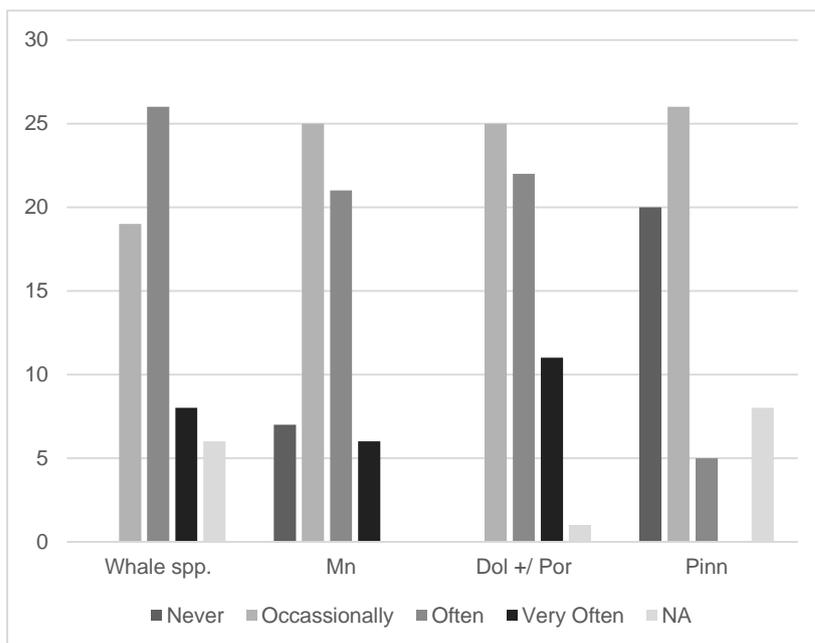


Figure 1. Graphs showing how often questionnaire respondents reported seeing whales of any species (Whale spp.), humpback whales (Mn), dolphins and/or porpoises (Dol +/- Por) and pinnipeds (Pinn) while fishing in Iceland.

Over one-quarter (n = 18, 30.5%) of respondents reported that they had observed whale spp. interact with their fishing gear at least once, and 13.6% (n = 8) reported this happening more than once (Fig. 2). Three of those who answered “Never” to observing whales in their gear provided details of an observed whale-gear interaction in a later question, and therefore it was assumed they misunderstood the initial question and their

answer to whether they had observed whales interacting with their gear was changed to “Once”. Of the eight that reported this happening more than once, one report stated the species were unknown, two reports indicated they had seen different species in their gear (humpback whale and blue whale (*Balaenoptera musculus*) and humpback whale and orca (*Orcinus orca*)) and the remaining five reports indicated they had seen only humpback whales in their gear more than once. In addition, nearly half (47.5%) of respondents reported having dolphins and/or porpoises in their gear at least once, and 18.6% reported this happening more than once. Ten observed whale-gear interactions involved humpback whales (55.6%), two involved orcas, and there was one report each of minke whale, sperm whale (*Physeter macrocephalus*) and blue whale interactions (Fig. 3). There were an additional four reports where the species were not reported and listed as unknown.

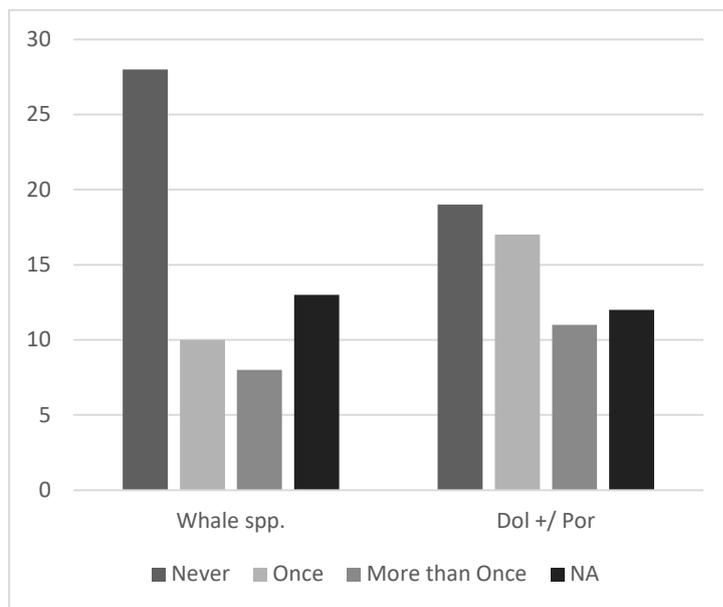


Figure 2. Graph showing how often questionnaire respondents witnessed whales of any species (Whale spp.) and dolphins and/or porpoises (Dol +/- Por) interacting with their fishing gear while fishing in Iceland.

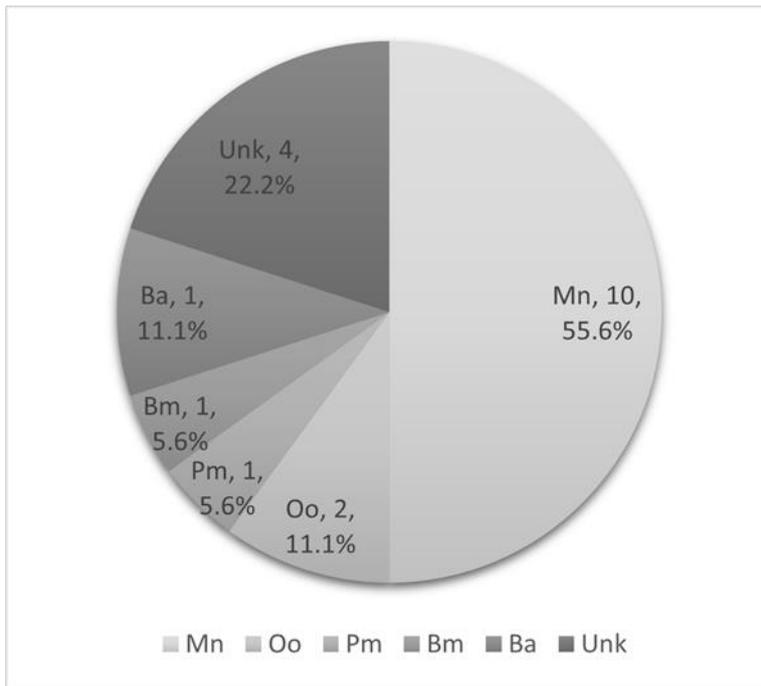


Figure 3. Graph showing the number of each species of whale, and the percent of the total that each species represents, that questionnaire respondents reported witnessing interacting with their fishing gear while fishing in Iceland. Mn = humpback whale, Oo = orca, Pm = sperm whale, Bm = blue whale, Ba = minke whale, Unk = unknown.

Of the ten humpback whale-gear interactions, six (60%) occurred in capelin purse seine nets, one occurred in a cod set net, two occurred in cod/haddock hooks-and-lines, and one report had no details (Table 1). Five respondents who reported having humpback whales in their fishing gear reported that they delayed closing the net, opened the net, or sunk the net in order to try to let the whale(s) out. All five of these respondents had whales in their capelin purse seine net. One respondent, who reported having a humpback whale entangled in their cod set net, reported cutting the whale out to release it. The other five respondents who reported having humpback whales in their gear either reported they took no action or did not provide any details. There was location information reported for eight of the ten observed humpback whale-gear interactions. The majority of incidents occurred in coastal waters in the southwest ($n = 3$) and northeast ($n = 4$). One reported incident occurred in offshore Icelandic waters “southeast of Scoresbysund” (Fig. 4). One respondent simply wrote that they have seen humpback whales in their net in “all areas” of the capelin fishing grounds, while the final respondent did not provide a location.

Table 1. Information provided by questionnaire respondents of humpback whale interactions with their fishing gear in Iceland. NA = no response was provided.

	Report	Date	Target Fish	Gear Type	Action taken in attempt to release whale
Within 5 years of questionnaire (2010-2018)	1	02/2016	Capelin	Purse seine	Delay closing the net to let the whale escape
	2	03/2016	Capelin	Purse seine	Delay closing the net to let the whale escape
	3	03/2015	Cod	Net	Cut out of the net
	4	06/2014-2016	Cod, Haddock	Hooks and line	NA
	5	NA	NA	NA	NA
	6	"every year" (2014-2018)	Capelin	Purse seine	NA
	7	2018	Capelin	Purse seine	Delay closing the net to let the whale escape
	8	06,07/2012-2013	Cod	Hooks and line	NA
Prior to 2010	9	12/1979	Capelin	Purse seine	Sunk the cork line and let the whale swim over
	10	07,08/1995	Capelin	Purse seine	Open the net

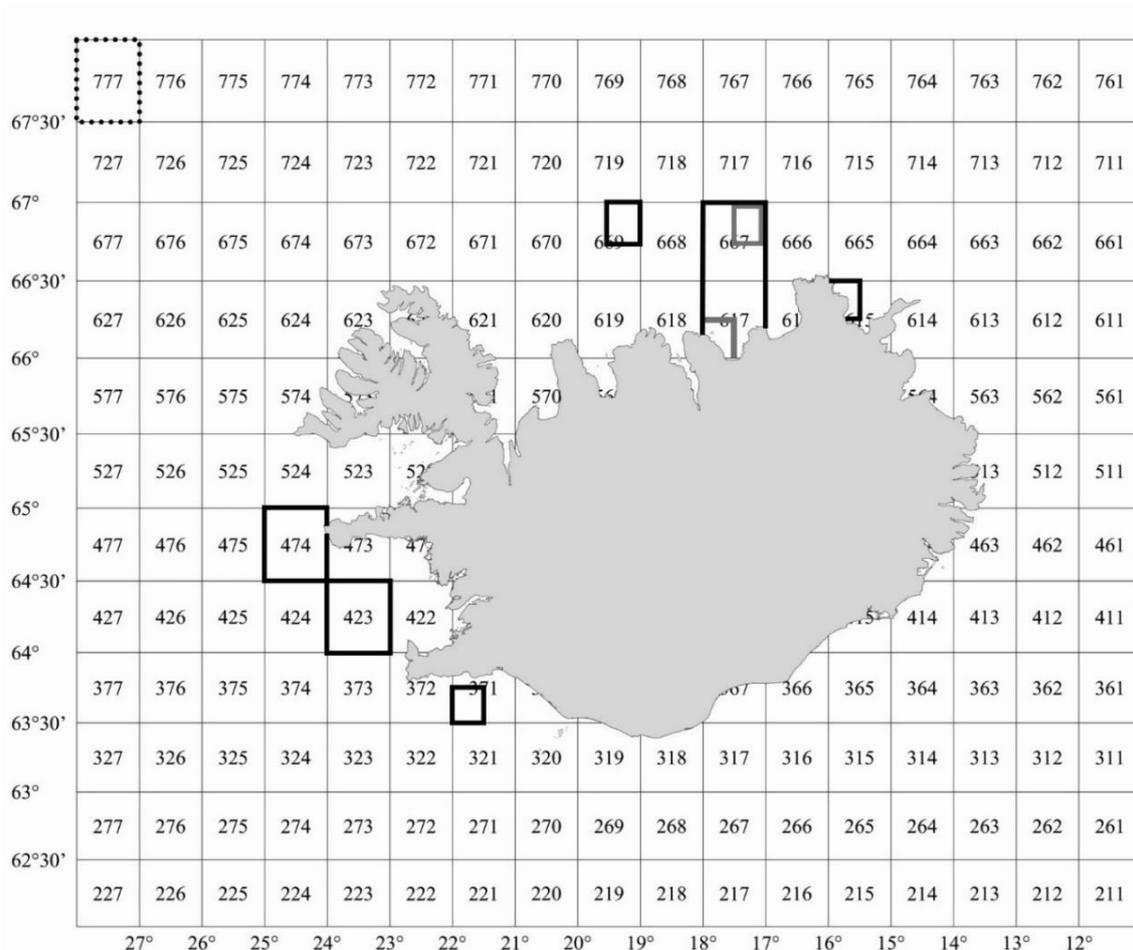


Figure 4. Map showing the eight reported locations in the fishing grounds where respondents observed humpback whales interacting with their fishing gear around Iceland. Solid black boxes indicate reported locations, solid grey boxes indicate two locations given in the same report, however the report was counted as one witnessed event since it was unclear if they were reporting two incidences or estimating where one incident occurred. The dotted box indicates a report of an incident “southeast of Scorebysund” only indicating that this would be in open ocean to the far northwest of Iceland.

There were twelve reports of whale spp. damaging fishing gear between 2010-2018 (Table 2). Of these, seven (58.3%) were humpback whales, two were orcas, one was a minke whale and in one report the species was left blank and considered unknown. The question specifically asked about whales, but one questionnaire response included damage due to a white-beaked dolphin and this was kept in the data as the seventh report. Five reports of damaged gear involved purse seines (four humpback whale and one orca), three involved net (one humpback whale, one white-beaked dolphin and one unknown), three involved hooks-and-lines (two humpback whale and one minke whale) and one involved a trawl (orca). Those that reported monetary loss due to damage in the continued questionnaire (damage occurring between 2010-2018) estimated monetary damage and losses caused by whales ranged from only 10.000 (for broken leader lines) up to 10.000.000 (for torn purse seine nets) Icelandic krona (ISK) (approximately \$80 up to \$80,000 USD (09.2019)).

Table 2. Information provided by questionnaire respondents about damage their fishing gear sustained due to whales in Iceland. La = white-beaked dolphin, Mn = humpback whale, Oo = orcas, Ba = minke whale, NA = no response was provided.

Report	Whale Species	Gear Type	Damage	Issues	Monetary loss estimate (isk)
1	La*	Net	Holes in net	Loss of catch through holes	NA
2	NA	Net	Net torn	NA	NA
3	Mn	Purse Seine	Holes in net	Loss of catch while trying to let whale escape; monetary loss repairing holes	500.000-1.000.000
4	Mn	Purse Seine	Holes in net	Loss of gear, catch, time; high risk of injury to the crew	5-10.000.000
5	Mn	Net	Net torn/destroyed	Net unusable	NA
6	Oo	Trawl	Holes in net	None	NA
7	Oo	Purse Seine	Holes in net	Loss of catch through holes; loss of time for repairs	Minimal, but shortens lifespan of the gear
8	Mn	Hooks and line	Broken lines	NA	NA
9	Ba	Hooks and line	Broken leader lines	Two leaders broken	10.000
10	Mn	Purse Seine	Net torn	Loss of gear, catch	10.000.000
11	Mn	Purse Seine	Net torn	Loss of time and money for repairs	2-3.000.000
12	Mn**	Hooks and line	Broken lines	NA	NA

* The question specifically asked about damage due to whales and did not include dolphins. One respondent still detailed damage due to a white-beaked dolphin (included here).

**This report came from the pilot questionnaire which did not ask about damage by any whale species, but only asked about humpback whales. This report is included here but not in statistical analysis since the questions differed.

Those respondents who had observed whale spp. interacting with their fishing gear (at any time) (n = 16, mean rank (MR) = 22.22) did not significantly differ in their responses to how often they observed whale spp. while fishing compared to those who had not observed an interaction (n = 25, MR = 20.22) (W = 180.5, p = .578). Similarly, those who reported having their gear damaged by whale spp. between 2010-2018 (n= 9, MR = 12.94) did not differ in their responses to how often they observed whale spp. while fishing compared to those who reported no gear damage (n = 17, MR = 13.79) (W = 81.5, p = .793). However, those respondents who had observed humpback whales interacting with their gear (n = 10, MR = 40.5) reported seeing humpback whales significantly more often while fishing than

those who had not observed humpback whale interactions ($n = 46$, $MR = 25.89$) ($W = 110$, $p = .006$). Those respondents who had not observed a humpback whale interaction more often reported they saw humpback whales “never” or only “occasionally” while fishing. There was a trend in the data that suggested that respondents who reported having their gear damaged by whales between 2010-2018 ($n = 10$, $MR = 19.1$) also reported seeing humpback whales more often than those who reported no gear damaged in the past between 2010-2018 ($n = 20$, $MR = 13.7$), however this difference was not significant ($W = 64$, $p = .096$). Those respondents who reported having their gear damaged between 2010-2018 ($n = 9$, $MR = 19.11$) reported observing an interaction (at any time) significantly more often than those who reported no gear damage ($n = 16$, $MR = 9.56$) ($W = 17$, $p = .0004$). Only two (12.5%) of the respondents who reported observing a whale interact with their fishing gear “once” or “more than once” reported that they had no gear damage.

Over one-third of respondents (35.1%) did not answer the question asking about why they would not report catching a whale in their net, and over one-quarter (29.7%) of respondents reported they would always report what they are required to, or they have had nothing to report. Furthermore, 16.2% of respondents answered that they would not report their incident(s) with whales since they believed the animal was released or escaped alive. Additionally, 10.8% answered they would not report their incident(s) with whales for fear of negative consequences to the fishing and 8.1% gave their own explanation in the “other” answer section.

Five capelin purse seiner captains were interviewed about their experiences with humpback whales in their purse seine nets and their responses are summarized in Table 3. Four were current captains and one retired in 2007. All the captains reported that the number of incidents of encircling humpback whales in capelin purse seines has been increasing over the years. One captain stated that 25-30 years ago it was a “special” event to see a humpback whale while fishing but more recently there is always many humpback whales in the fishing area, even in shallow waters. Another captain stated he noticed the number of incidents with humpback whales greatly increased between 1990-2000. All four current captains reported having incidents with humpback whales in their seine nets within the past five years. One captain estimated having “five or six” incidents, one estimated having ten incidents, and two stated they have just had “many” incidents, including nine whales in the net at one time (though this was prior to 2010) and 17 whales in the net in one fishing season (approximately 10 years ago). All five captains discussed the measures they take to try to remove the whales from the seine net. Four of the five specifically noted that, ideally, they would leave the net partially open to let the whale(s) find their way out on their own, though they report this is rare. One captain stated it is a “30:70” percent chance that they would be able to find their way out versus tearing a hole in the net. If the net is already closed around the whale(s) when the crew discovers them, all five captains reported that the main option is to sink the float line of the net so the whale(s) can hopefully escape by going over the top.

Table 3. Summary of capelin purse seine boat captain interview responses. Mn = humpback whale, Issues with Mn = response to “Are issues with humpback whales increasing over time?”, Incidences within 5 years = response to “How many incidences with humpback whales in your net have you experienced over the last 5 years?”, Costs of issues = response to “What are the costs of humpback whale(s) in your fishing net?”. NA = no response.

Interview	Years as captain	Issues with Mn	Incidences within 5 years	Costs of issues	Mn injured or deceased	Marine mammals besides Mn in net	Aware of pingers	Willing to try pingers
1	10	Increasing	10	destroyed net: 10 million isk	No	No	Yes	Yes
2	10	Always occurred in the North, but increasing	Many. 17 whales in one season previously	Loss of catch + destroyed net: 55 million isk	Once (deceased)	No	Yes	Yes
3	31	Increasing problem for 20 years	Many. 9 whales at one time once (10 years ago)	NA	Twice (deceased)	No	Yes	Yes
4	18	Increasing problem. Was rare to see Mn 25-30 years ago	5 or 6	sometimes 10-20 million isk	No	No	Yes	Yes
5	18	Increasing problem. Increased a lot 1990-2000	NA	NA Little thought was given to the cost	Yes (sometimes injuries to the pectoral fins or tail)	No	Yes	NA (retired now but believes they could work, especially in the dark)

Three out of the five captains estimated that gear damage and losses (such as loss of catch, loss of fishing time and damage repairs) due to humpback whale(s) in their purse seine net costed them 10.000.000 to 55.000.000 ISK (approximately \$80,000 to \$450,000 USD). Two out of the five captains reported that a humpback whale had drowned in their net at least once, with one of them reporting that this happened in their net twice. A third captain reported that whales sometimes had injuries to their pectoral fins or tail, likely caused by the fishing gear. All five captains also reported they were aware of acoustic alarm devices known as “pingers” which are advertised as a possible mitigation method for humpback whales entering purse seine nets. The four current captains reported they were willing to try the pingers and they had in fact previously experimented with different pingers.

However, they were not pingers that were designed specifically for humpback whales and the captains did not find the pingers to be useful in reducing the number of humpback whales encircled in and damaging their seine nets. Pingers were not used during the time the retired captain was fishing; however, he reported he believes the pingers could aid in minimizing interaction with humpback whales, particularly in the dark.

DISCUSSION

Questionnaire results showed that cetaceans are seen in Icelandic waters often by fishers, including nearly half of respondents reporting seeing humpback whales specifically. Statistical comparison of the questionnaire responses determined that those respondents who observed humpback whale(s) interact with their gear reported that they saw humpback whales significantly more often than those that did not observe an interaction. Additionally, those who reported having their gear damaged by humpback whales revealed a trend in reporting seeing the humpback whales while fishing more often, though this was not significant. This supports the view that those fishers who are seeing humpback whales frequently, while fishing in the humpback whale feeding habitat, have an increased chance to observe a whale-gear interaction and therefore an increased chance of having their gear damaged. Humpback whales are the third most abundant baleen whale species in Icelandic waters (Pike *et al.*, 2019); however, these results support that humpback whales are the most commonly entangled large whale species in Iceland and are most commonly causing damage and issues for fishers. This is likely due to their preference for coastal habitat which overlaps with commercial fishing, as shown by the reported locations where humpback whales were observed interacting with fishing gear. Though the number of reported locations was low, the majority were concentrated in the north/northeast and southwest of Iceland. These are two areas that are known for humpback whale sightings (Pike *et al.*, 2019; Pike *et al.*, 2009) and are also areas with high fishing effort using nets, hooks-and-lines, trawls and purse seines (Hafrannsóknastofnun, 2017). The reports from the questionnaire reflect areas where it would be predicted humpback whales and commercial fishing are overlapping the most both spatially and temporally. In addition, the estimated summertime subpopulation of humpback whales around Iceland increased by approximately 12% per year between 1987-2001 (Pike *et al.*, 2009) and has remained generally stable since (Víkingsson *et al.*, 2015). This increase in the Icelandic subpopulation is reflected in the interview responses from the capelin purse seiner captains and is likely another large contributing factor to humpback whales being the most reported species observed interacting with fishing gear. Entanglement scar analysis conducted in Iceland also supports that humpback whales from the Icelandic subpopulation are often becoming entangled in fishing gear (Basran *et al.*, 2019), and this is also a known issue in several other areas including eastern Canada (Lien and Aldrich, 1981; Benjamins *et al.*, 2012), eastern USA and Alaska (Robbins, 2012; Neilson *et al.*, 2009), Australia (How *et al.*, 2015), Ecuador (Alava *et al.*, 2012) and Colombia (Capella *et al.*, 2001).

Eight of 14 respondents who reported observing whale(s) interact with their fishing gear (and reported the species of whale) (57.1%) saw humpback whales in their gear within five years of completing the questionnaire (between 2010-2018), or an average of at least one observed humpback whale interaction per year since 2010. In actuality, there are likely more observed interactions between humpback whales and fishing gear within that timeframe, exemplified by one respondent who wrote in his answer that he sees this “every year” but did not provide more specific details on year and month. In addition, one capelin

purse seiner captain stated in his interview that he had observed 17 humpback whales in his net in one season. Since the continued questionnaire (2015-2018) asked about humpback whales interacting with gear within the past 5 years (2010-2018) in order to look at a more accurate time frame, some respondents may have observed humpback whale entanglements prior to 2010 and the survey did not collect that information. The pilot survey did not use a timeframe and collected two reports (14.3%) from prior to 2010, one from 1979 and the other from 1995. Furthermore, one capelin boat captain reported he had nine humpback whales inside his capelin purse seine at one time approximately ten years ago (meaning it could have been shortly before 2010). These reports show that humpback whale-gear interactions were occurring prior to 2010 but this issue likely became more common since the mid-1990s due to the increased humpback whale population.

The capelin purse seine industry has been recognized in Icelandic media as having issues with humpback whales in their gear (pers. obs.). The questionnaire responses reflect this observation, with six out of ten observed reports of humpback whales interacting with gear occurring in the capelin purse seine industry. This could be expected given the capelin purse seine fishery is directly targeting humpback whale prey (Sigurjónsson and Víkingsson, 1997). This has also been observed in the tuna purse seine fishery in the Atlantic Ocean west of Africa, where tuna fishing primarily takes place in areas with high baleen whale prey density, resulting in 122 recorded baleen whale encirclements in purse seines between 1995-2011 (Escalle *et al.* 2015). One Icelandic capelin purse seiner captain reported that he believed there was at least one occasion where the humpback whales purposely targeted the purse seine and entered the net while feeding on the capelin that were inside. Associated feeding with fishing vessels is a known phenomenon involving odontocete species such as orcas and sperm whales (eg. Peterson and Carothers, 2013; Sigler *et al.* 2008; Mul *et al.* 2020) but this has not been clearly identified for baleen whales such as the humpback whale.

Though considered rare, two out of five capelin purse seiner captains said they had observed at least one humpback whale accidentally drown in their purse seine net. Humpback whale incidental mortality in purse seines has also been reported in the Atlantic tuna fishery off Western Africa (Escalle *et al.*, 2015). If a marine mammal is caught as bycatch, it is required by Icelandic law that this information is submitted to the Directorate of Fisheries (Fiskistofa) through a mandatory logbook (Government of Iceland, 2018); however, in the last ten years of reporting there is no record of incidental mortality of a humpback whale in a purse seine (Marine and Freshwater Research Institute, unpub. data). The only record of humpback whale bycatch in a purse seine comes from 2004. In fact, there are only seven records of bycatch of a humpback whale in Iceland in any fishing gear since reporting began in 2002 (Table 4). Humpback whale entanglement reporting is also known to be low in the Gulf of Maine where, despite a developed reporting system, detection and reporting was estimated to be only 5.7% (Robbins, 2011). Given there were three times more reports of humpback whale deaths in purse seines reported in the interviews than shown in the bycatch records for the last 10 years, this suggests bycatch of humpback whales is largely under-reported. Currently there are no quantitative estimates of fatal entanglements of humpback whales in Iceland outside of the official bycatch reports. The fate of the majority of whales which are known to have been entangled in the Icelandic subpopulation is not known (Basran *et al.*, 2019). However, there are incidental records of stranded humpback whales in Iceland for which entanglement in fishing gear was deemed the likely cause of death (Víkingsson and Ólafsdóttir, 2003; Víkingsson *et al.*, 2004; 2005; Víkingsson, 2011), which further suggests this is an under-reported issue.

Although, it is important to note that it is not known if any of the opportunistic records of mortality due to entanglement were actually observed by the fishers when the whales became entangled in gear. It is possible the whales escaped unobserved and then died at a later date and were therefore not reported as bycatch.

Table 4. Summary of officially reported humpback whale bycatch in Icelandic fisheries (Marine and Freshwater Research Institute, unpub. data; Víkingsson *et al.*, 2004, 2005; Víkingsson, 2011). NA = no location information.

Date	Gear-type	# of animals	Location
2003	gillnet	3	NA
2003	bottom trawl	1	NA
01/2004	purse seine	1	NW Iceland
27/09/2010	mussel farm line	1	NW Iceland
03/2016	gillnet	1	NA

Other large whale species reported interacting with fishing gear in the questionnaires included a sperm whale, orcas, minke whales and a blue whale, exemplifying that this is at least occasionally an issue for a wide range of Icelandic whale species. There are reports dating back to 1970 of orcas interacting with halibut longline fisheries in Iceland and depredating fish from the lines (Samarra *et al.* 2018) and reports from the 1950s of orcas destroying seine nets (Anonymous, 1956). However, there is no recent information on orcas interacting with herring seines in Iceland apart from the report collected in this study. The second report of orcas interacting with gear in this study did not provide details on gear type. Similarly, there are reports of sperm whales interacting with longlines in Iceland (Samarra *et al.* 2018), but there are no published reports of interactions with trawls prior to the report collected in this study. However, sperm whales have been documented feeding in association with halibut trawls in the northwest Atlantic (Karpouzli and Leaper, 2004). Documentation of scarring on minke whales in Iceland provided evidence that supports the reports in this study that some individuals are interacting with, and potentially becoming entangled in, fishing gear (Bertulli *et al.*, 2012). In addition, there is one report of minke whale bycatch in a mid-water trawl in Iceland (Marine and Freshwater Research Institute, unpub. data). Globally, there is little documentation of blue whale entanglement or interaction with fishing gear (Basran and Rasmussen, 2020) and there are no published reports of this in Iceland prior to the report collected in this study. The gear-type was not clearly specified for the blue whale interaction, however the same respondent specified having a humpback whale interact with their hook and line gear, so there is a strong possibility the same gear-type was involved in the blue whale interaction. In addition to orcas and larger whale species, almost half of questionnaire respondents reported that they have had porpoises and/or dolphins in their gear. Bycatch of these small cetacean species is

already a well-known issue in Icelandic fisheries (ICES, 2018; Marine and Freshwater Research Institute, 2018; Pálsson, 2015).

Gear damage caused by whales was reported in all the general gear-types used in Iceland. As suspected, those who reported that they had observed a whale interact with their fishing gear also reported that their gear had been damaged by whales significantly more often than those who had not observed whales interact with their gear. This is confirming that when whales interact with fishing gear, they are causing damage the majority of the time; however, the damage can range anywhere from minimal to severe in terms of financial costs. Damage to hooks-and-lines caused little financial loss to the fishers, with the report stating two broken leader lines (broken by a minke whale) costed the fishers ca. 10.000 ISK (ca. \$80 USD). However, a whale entanglement in fishing line can be serious for the animal if the line ends up wrapping tightly around the body, which has been seen in Skjálfandi Bay, Iceland previously (University of Iceland's Húsavík Research Centre unpub. data) (Fig. 5). Damage to a net caused by orcas was also reported as having "minimal" costs but did decrease the integrity of the net and shortened the time it was in working order. Damage to a purse seine net, including loss of catch and downtime, caused by humpback whale(s) was reported to cost up to 10.000.000 ISK (ca. \$80,000 USD) in the questionnaire and up to 55.000.000 ISK (ca. \$450,000 USD) in the interviews of captains. In the majority of cases, humpback whales likely escape from purse seines without serious injury or long-term consequences to the animal, but these events can have serious impacts on the profits of the fishers. In Galicia, Spain, it was also purse seine fisheries that reported being the most affected by gear damage caused by cetaceans, and the majority of incidents caused significant economic loss to fisheries targeting shoaling pelagic fish species (like capelin), though in that study the damage was not caused by large whales (Goetz *et al.*, 2014). The capelin fishing season in Iceland is currently only approximately three months long (from January through March) (Síldarvinnslan hf. n.d.) and purse-seining is weather (sea state) dependent (NOAA, 2003) meaning gear damage due to humpback whales and loss of fishing time to repair this damage can in some cases cost up to an estimated 11% of the revenue of an average fishing season (Geir F. Zoega pers. comm., 20.01.20).



Figure 5. Image showing a humpback whale in Skjálfandi Bay, Iceland with monofilament line (possibly long-line fishing gear) wrapped tightly around the tail stalk causing deep lacerations. (©Húsavík Research Centre).

Only two respondents who said they observed a whale interact with their gear reported that they had no damage. In those two cases one whale was reported to be a sperm whale in a

trawl net and the other was reported as unknown. Two respondents who reported having their fishing gear damaged by whales reported that they did not observe any interactions between whales and their gear, however they saw the animals, which they attributed the damage to, in the vicinity. This is similar to interview results from Galicia, Spain, where cetaceans were observed around the fishing gear 90% of the time that gear damage occurred (Goetz *et al.*, 2014). One of the cases in this study involved orcas and in the other case the species was not reported and listed as unknown. For the case involving orcas, the respondent provided details that they discovered holes in their trawl net while they had orcas around the ship, but they did not observe whales in the net. There are previous reports of orcas associating feeding with fishing operations and becoming incidentally caught in gear (Fertl and Leatherwood, 1997), so it is not unlikely that the orcas were doing something similar in this case. The report exemplifies that some species, such as orcas, may be targeting fishing and damaging gear from the outside but are still not actually observed interacting with the gear or becoming entrapped. The other case also suggest that gear may sustain damage that the fishers attribute to whales even though they did not observe the interaction and therefore the species and other details of the interaction are simply not known.

Of the 40 companies that were contacted, 37.5% provided at least one completed questionnaire; however, the actual total number of questionnaires collected was low. The majority of fishing companies were contacted through more than one method (email, post, phone) and never provided any response. This may be reflecting an unwillingness to provide details about a negative consequence of fishing, potentially due to concerns over the possibility of this leading to fishing restrictions, a view that the issue of whale entanglement is not of high importance or interest, or simply that the companies or fishers could not spare the time to participate. Given that 35% of respondents did not answer the question about what their reason would be to not report whale entanglement and 11% answered that they were concerned about negative consequences to the fishing industry, this further suggests that this is an issue that some fishers are not willing to talk about openly, despite their answers being anonymous. It is also possible that the total number of questionnaire replies was low because each company or each ship that received the questionnaire only filled one out on behalf of all the fishers working there, opposed to having more than one crew member complete a questionnaire individually. The benefit to this is that it is unlikely that the same whale-gear interaction incident was reported more than once in this study. Contacting more fishers directly, opposed to going through the company managers or captains, could result in a higher number of completed questionnaires, though this may result in repeated information. Furthermore, there is the possibility that fishers who had observed whales interacting with their gear or had their gear damaged were more inclined to complete the questionnaire than those who had not; however, second and third contact with companies who did not initially respond was attempted in order to minimize this bias. Further effort to collect follow-up questionnaires could determine if this bias exists in the results reported in this study. Additionally, humpback whales are considered a highly recognizable species (Clapham, 2018) and this could bias the reporting of sightings and gear-interaction observations. However, a recent survey of Icelandic fishers found humpbacks were frequently misidentified from photographs (Stoller, 2020), suggesting there should be minimal bias towards humpback whale reports from fishers solely because they can recognize them.

The results from the questionnaires and interviews reveal that mitigating whale-gear interactions in Iceland would be in the best interest of both fisheries and whale

conservationist, particularly for the humpback whale. One possible mitigation method against humpback whale entanglements and gear damage is the use of acoustic alarms or “pingers”. These devices make a sound which serves to warn the whales of the gear in the water and hopefully prevent them from swimming through it (Erbe and McPherson, 2012). They can be used on set nets, trap lines, and purse seines (Future Oceans, n.d.). Special consideration to whale-gear interaction mitigation should be given to the Icelandic capelin fishery given the high number of incidents they report compared to other fisheries. The five capelin purse seiner captains who were interviewed in this study expressed that they knew about these pingers, and those who are currently working would be willing to try them on their nets to prevent gear damage. Testing of these pingers in the Icelandic capelin purse seine fishery has shown preliminary signs of success in preventing gear damage when whales were incidentally encircled in the seine (Basran *et al.*, 2020). Given that the Icelandic capelin fishing season is short and only operating at a specific time of the year, other management strategies such as area or seasonal closures are not a politically viable option for this fishery, apart from the area closures that can be put in place for protection of the juvenile capelin stock (ICES, 2017). Another possible management strategy to minimize whale-gear interactions could be to switch the fishing method solely to pelagic trawling. Pelagic trawling is a second method of fishing capelin used in Iceland by commercial fisheries, which is currently only permitted in certain areas in the Northeast (ICES, 2017). Trawls are considered one of the gear-types which have the least interactions with large baleen whales, such as the humpback whale (Fertl and Leatherwood, 1997), meaning lower incidents of whales becoming entrapped in the gear and therefore less gear damage. However, it has been hypothesized that there are cons to using the pelagic trawl in terms of there being a higher incidental mortality of juvenile capelin and the possibility of separating or disrupting the migrating capelin schools which could impact the spawning (ICES, 2017). Due to fluctuating capelin stock sizes and low stock estimates in recent years, the Icelandic capelin fishery has received low or no quota to fish capelin (ICES, 2017; Bardarson and Jonsson, 2017, 2018; Bardarson *et al.*, 2019). The capelin fishery continues to be a sensitive and debated topic in Iceland, with some fishers blaming the whale population not only for damage to their gear while fishing, but also contributing to the low capelin stocks that have been recorded (pers. obs.). Continued, open discussions of the issues fisheries in Iceland are facing due to interactions with whales, considering pros and cons of management strategies to address this, should be planned for the future in the best interest of sustainable commercial fishing and whale conservation. This is particularly important for the currently unstable Icelandic capelin fishery.

Overall, the questionnaires and interviews conducted for this study provide detailed insight into the issue of whale entanglement in Icelandic fisheries. The data show that the humpback whale is the large whale species that is most often interacting with fishing gear and causing damage. Interview responses revealed little-known information that encirclement of humpback whales in purse seines in Iceland can be detrimental to the animal, with two captains reporting having seen them incidentally drown and one captain reporting the whales sometimes incurred injuries. Questionnaire and interview responses also revealed that whale-gear interactions can be highly detrimental to the fishers in terms of financial losses due to gear damage and associated costs. Further effort into collecting expert knowledge from fishers on these issues is required in order to advise better management. Creation of an anonymous whale-gear interaction reporting system in Iceland would aid in being able to more clearly quantify how often these events are observed, the financial losses the fishing industry is incurring due to this issue and the extent at which

bycatch of large whales is being underreported. This could be done through additional reporting in the mandatory fishing logbook system, or through an email or messaging group network or smartphone application where reports could be sent to researcher(s) maintaining a database.

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