Estimates of humpback and minke whale entanglements in Scotland

Ellie MacLennan, Russell Leaper, Andrew Brownlow, Susannah Calderan, Dan Jarvis, Lauren Hartny-Mills and Conor Ryan

INTERNATIONAL WHALING COMMISSION

1　**ESTIMATES OF HUMPBACK AND MINKE WHALE ENTANGLEMENTS IN SCOTLAND.**

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14　**ABSTRACT**

15　Entanglement in static fishing gear has been identified as the largest anthropogenic cause of mortality in minke
16　(*Balaenoptera acutorostrata*) and humpback whales (*Megaptera novaeangliae*) in Scottish waters, and is of
17　increasing concern from both a welfare and conservation perspective. However a thorough understanding of the
18　scale and impacts of these incidents is lacking. To address this, data from a number of sources including
19　strandings, live disentanglement reports and interviews with inshore creel fishermen were gathered to provide
20　estimates of entanglements, using a capture-recapture type approach and extrapolation of interview data. The
21　findings suggest that the Scottish creel fishery may be responsible for considerably more whale bycatch than
22　previously thought, with estimates of around five humpback whales and 30 minke whales becoming entangled
23　each year. Entanglements occurring in Scottish waters could potentially impact small populations of humpback
24　whales in the NE Atlantic. For the west coast of Scotland, the estimated fatal entanglement rate of minke whales
25　is 2.2% of the estimated abundance from the SCANSIII survey suggesting a risk of localised depletion. Scottish
26　fishermen have exhibited willingness to engage in mitigation strategies and research, with suggestions such as
27　the introduction of leaded line to the sector. Some have also been participating in informal trials of ropeless
28　technologies. To date these trials have been successful and we recommend that continued support for such
29　mitigations, which could greatly reduce entanglement risk, be considered with urgency.

30　**INTRODUCTION**

31　Entanglement in pot and creel fishing gear has been identified as the largest cause of non-natural mortality in
32　baleen whales stranded around Scotland (Northridge et al., 2010). Data collected by the Scottish Marine Animal
33　Stranding Scheme (SMASS) and through media reports suggest both the incidence and range of affected species
34　is increasing. However, estimates of the total numbers of entanglement events have not been available and
35　previously reported cases are known to represent only a small percentage of total incidents due to under-
36　reporting by fishers, limitations of post-mortem examinations, and the low likelihood of retrieving carcasses.
37　The cetacean species most frequently reported entangled in Scotland are minke (*Balaenoptera acutorostrata*)
38　and humpback (*Megaptera novaeangliae*) whales (MacLennan et al. 2019).

39　In order to generate a better understanding of the entanglement problem, the Scottish Entanglement Alliance
40　(SEA) was established in April 2018. SEA is a two-year European Maritime and Fisheries Fund (EMFF)-funded
41　partnership between six marine research, industry, conservation and welfare bodies. SEA partners aim to
42　provide a co-ordinated, comprehensive monitoring and engagement programme to better understand the scale
43　and impact of marine animal entanglements in Scottish waters. Importantly, this includes economic and human
44　safety implications in addition to conservation and welfare impacts.

45　The aims of SEA include raising awareness of marine animal entanglements amongst fishers and other marine
46　users; improving reporting rates of marine animal entanglements; providing a platform for fishers to suggest
47　solutions to this problem and opportunities for them to become involved in entanglement prevention, research
48　and disentanglement efforts; assessing the risk and impact of entanglements to marine animals at an individual
49　and population level; and improving understanding of the socio-economic impact of marine animal
50　entanglements on the Scottish fishing fleet. More information on the initiative is available here:
51　www.scottishentanglement.org

52　This paper provides estimates of the numbers of minke and humpback whale entanglements in Scotland over the
53　last ten years and reports on information provided by the creel fishing community on the nature of the
54　entanglements and suggestions for ways to reduce entanglement risk. The analysis includes data from Ryan et

55 al. (2016) and MacLennan et al. (2019). We present estimates for total entanglements, including both whales
56 which are released alive and those that die. All situations where whales are entangled present serious welfare
57 concerns, and even whales released alive may give rise to conservation concerns, as their fate post- release is
58 rarely known. Further, live release can present a risk to human safety because of the dangers involved in
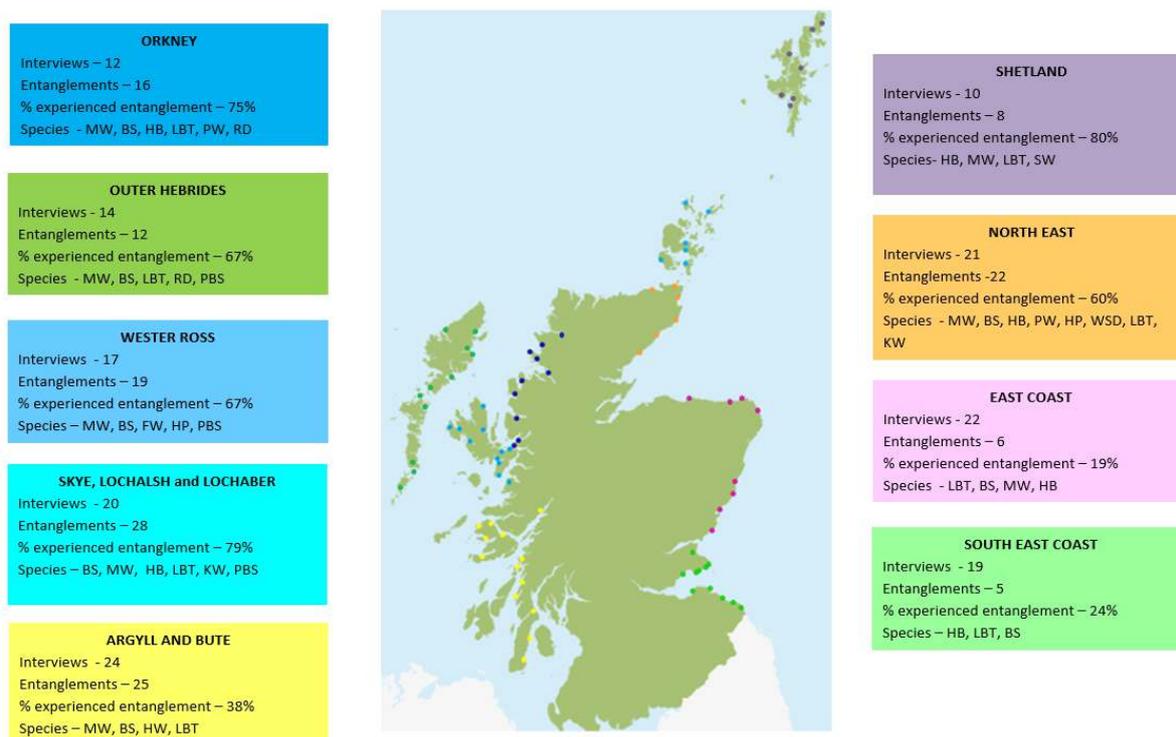59 disentanglement[1].

60 **METHODS**

61 *SEA interviews*
62 Between June 2018 and September 2019, 157 commercial creel fishers from different vessels were interviewed
63 as part of the SEA project. These fishers were operating from 67 different Scottish harbours and represent
64 approximately 11% of the registered inshore fleet.

65
66 Semi-structured interviews based on a standard list of questions were conducted face-to-face, and were all
67 conducted by the same interviewer. The questionnaire comprised 22 questions and included both closed and
68 open-ended questions. Prior to implementation, questions were submitted for ethical review to the University of
69 Aberdeen, adapted accordingly, and piloted. The selection of fishing harbours was made following discussions
70 with Regional Inshore Fisheries Groups (RIFGs) and the Scottish Creel Fishermen's Federation (SCFF), and
71 was based on the distribution and density of creel fishers around the Scottish coastline.

72
73 The majority of interviews were opportunistic, however prior to visiting each harbour, the interviewer made
74 contact with the Harbour Master and/or local fisheries association representatives. This often resulted in advice
75 on the best time of day to visit, names of key fishers who might be willing to participate, and/or a tour of the
76 harbour on arrival and an introduction to fishers. 'Snowball' sampling was used whereby interview participants
77 were asked if they could recommend other fishers who might also be willing to participate.

78

ORKNEY
Interviews – 12
Entanglements – 16
% experienced entanglement – 75%
Species - MW, BS, HB, LBT, PW, RD

OUTER HEBRIDES
Interviews - 14
Entanglements – 12
% experienced entanglement – 67%
Species - MW, BS, LBT, RD, PBS

WESTER ROSS
Interviews - 17
Entanglements – 19
% experienced entanglement – 67%
Species – MW, BS, FW, HP, PBS

SKYE, LOCHALSH and LOCHABER
Interviews - 20
Entanglements – 28
% experienced entanglement – 79%
Species – BS, MW, HB, LBT, KW, PBS

ARGYLL AND BUTE
Interviews - 24
Entanglements – 25
% experienced entanglement – 38%
Species – MW, BS, HW, LBT

SHETLAND
Interviews - 10
Entanglements – 8
% experienced entanglement – 80%
Species- HB, MW, LBT, SW

NORTH EAST
Interviews - 21
Entanglements -22
% experienced entanglement – 60%
Species - MW, BS, HB, PW, HP, WSD, LBT, KW

EAST COAST
Interviews - 22
Entanglements – 6
% experienced entanglement – 19%
Species - LBT, BS, MW, HB

SOUTH EAST COAST
Interviews - 19
Entanglements – 5
% experienced entanglement – 24%
Species – HB, LBT, BS

79
80 Figure 1. Locations and numbers of interviews with fishers (MW: minke whale; BS: basking shark; HB:
81 humpback whale; LBT: leatherback turtle; PW: pilot whale; RD: Risso's dolphin; FW: fin whale; HP: harbour
82 porpoise; PBS: porbeagle shark; KW: killer whale; SW: sei whale; WSD: white-sided dolphin). (MacLennan et
83 al. in preparation)

84

85 Data on entanglements can be derived from a number of sources: stranded animals reported to SMASS, live
86 animal disentanglements by BDMLR, and reports from fishers at the time of incidents (these are referred to here

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[1] https://iwc.int/entanglement

2

87   as *reported incidents*). The combined reports from all these sources provide a minimum estimate of the number
88   of incidents but are negatively biased because there are many incidents that are not reported. The structured
89   interviews with fishers provide another, independent, source of reports for comparison (referred to as
90   *interviews*). If duplicates can be identified between these two data sets then it should be possible to estimate the
91   total number of entanglements using a capture-recapture type approach. One of the simplest estimators that can
92   be applied to survey data is the Chapman modification of the Lincoln–Petersen estimator (Brittain and Böhning,
93   2008).

94   The key challenge in this study is identifying potential and definite duplicates. The reported incidents generally
95   had quite specific locations and dates, whereas the interview responses just had a port of operation and included
96   any incidents over the previous 10 years, although in many cases an approximate year and season were
97   available, or in some cases an actual date.

98   Potential duplicates were examined by looking first at the spatial distribution of direct reports and reports from
99   interviews.

100   The Chapman estimate for total entanglements, *N* is given by:

101
$$\hat{N} = \frac{(n_1 + 1)(n_2 + 1)}{(m_2 + 1)} - 1 \qquad (1)$$

102   With variance

103
$$var(\hat{N}) = \frac{(n_1 + 1)(n_2 + 1)(n_1 - m_2)(n_2 - m_2)}{(m_2 + 1)^2(m_2 + 2)} \qquad (2)$$

104   Where n_1 is the number of from combined reports, n_2 is the number from interviews and m_2 is the number of
105   duplicate incidents common to both data sources.

106   If there are no duplicates then a point estimate may not be valid, but it is possible to estimate a lower bound N_{min}
107   such that there is a 95% probability that $N > N_{min}$

108
$$\left(\frac{N_{min} - n_1}{N_{min}}\right)^{n_2} < 0.05 \qquad (3)$$

109   **Extrapolating interview results based on fishing effort**
110   Entanglement prevalence can alternatively be estimated solely on interview data. Interviews were divided up by
111   regions and districts in order to allow for some stratification, while maintaining sample sizes. The probability
112   that a particular entanglement would be revealed through interviews would depend on a number of factors, but
113   principally the proportion of fishers in that district who were interviewed. This allows for a Horvitz-Thomson
114   type estimator for the total number of entanglements based on stratified interview results. In Scotland, fisheries
115   are divided up into districts[2] and statistics reported annually for each district. The numbers of registered vessels
116   are reported by gear type[3] but this includes vessels that may be inactive. An indication of the number of active
117   vessels may be given by the number of people in full-time employment[4], however these data are not reported by
118   fishery type. To obtain an approximate estimate of the number of active pot and creel vessels based on the
119   employment data, we used the reported mean number of crewmembers for each vessel size category to predict
120   the number of fishers employed in each district. For vessels under 10m, this was 1.5, for shellfish vessels over
121   10m this was 3, and for demersal vessels over 10m this was 4.7 [5]. The predicted employment plotted against
122   reported employment by district is shown in Figure 2. The ratio of actual employment divided by predicted
123   employment was used as an estimate of the proportion of vessels within each district that were active (Table 1).
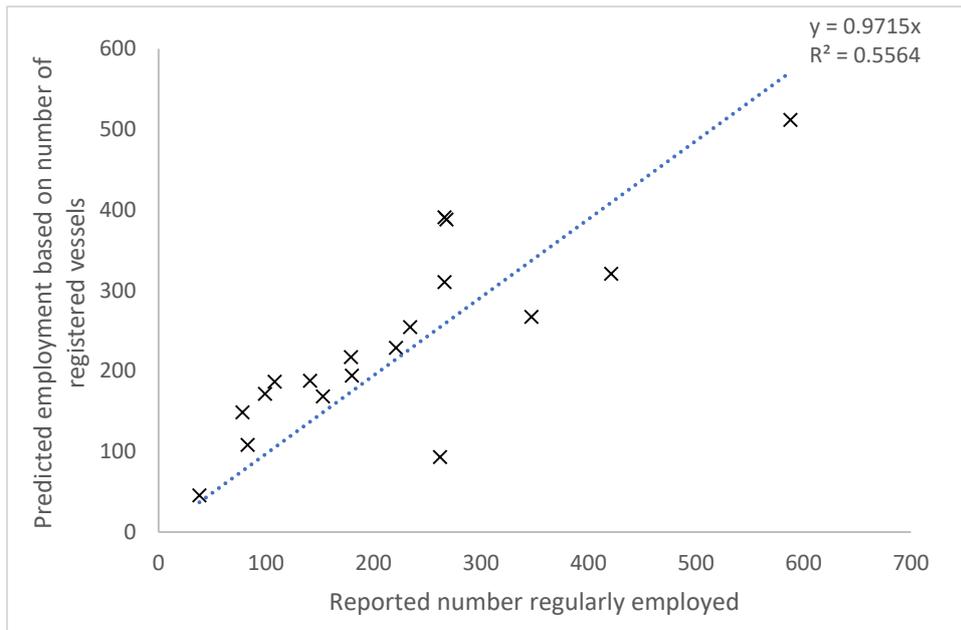
124   This suggests that the median proportion of active vessels by district was around 71%. The estimated total
125   number of active creel vessels for Scotland was 1017 out of a total of 1431 registered vessels. Northridge et al.
126   (2010) estimated that around 300 vessels fished for more than 50 days a year, suggesting that many vessels only
127   go to sea less than once a week. In terms of estimating the proportion of effort included in the interviews the
128   main factor is whether the vessels included in the interviews were representative of the creel fleet in that district
129   rather than the total fishing effort.

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[2] https://marinescotland.atkinsgeospatial.com/nmpi/default.aspx?layers=527
[3] https://www.gov.scot/publications/scottish-sea-fisheries-statistics-2017/pages/49/
[4] https://www.gov.scot/publications/scottish-sea-fisheries-statistics-2017/pages/52/
[5] https://www.gov.scot/publications/scottish-sea-fisheries-employment-2015/pages/10/#Table6

Figure 2. Predicted employment against reported number regularly employed by fisheries district (districts are listed in Table 2).

Table 1. Reported number of vessels in 2017 by fisheries district and estimated numbers of active vessels

District	Region	Under 10m Creel fishing	Over 10m creel fishing	Estimated active proportion	Estimated total active creel vessels
Aberdeen	E	77	5	0.5	43.1
Anstruther	E	82	1	0.6	46.7
Buckie	E	52	1	0.5	28.4
Eyemouth	E	76	2	0.9	70.4
Fraserburgh	E	95	1	1.0	94.8
Peterhead	E	60	2	1.0	62.0
Scrabster	N	84	8	0.9	81.6
Orkney	N	84	26	0.9	99.2
Shetland	N	119	3	0.6	72.4
Stornoway	W	162	13	0.7	118.9
Ayr	W	68	4	1.0	72.0
Campbeltown	W	86	6	0.8	76.6
Kinlochbervie	W	15	0	0.8	11.5
Lochinver	W	10	1	1.0	11.0
Mallaig	W	29	1	0.7	21.0
Oban	W	66	14	1.0	76.0
Portree	W	84	10	0.7	69.6
Ullapool	W	74	10	0.8	66.8

Two forms of stratification were used to generate estimates of the total numbers of entanglements based on the proportions of vessels that were included in the interviews. Interviews were stratified geographically into 18 districts, which were then grouped into three distinct regions. These were defined as 'West' from Cape Wrath to the Clyde including the Outer Isles, 'North' comprising of the north coast between Cape Wrath and Duncansby Head and East coast from Duncansby Hd. To Helmsdale, Orkney and Shetland, and 'East' from

143 Helmsdale to Berwick Upon Tweed. These larger strata gave sufficient samples to allow estimation of variance
144 but also captured some of the geographical variation in entanglement risk.

145 The total number of active vessels V across j strata were calculated by

$$V = \sum_{i=1}^{j} v_i \qquad (4)$$

147

148 Where v_i = number of active vessels in strata i

149 The estimated total number of entanglements $\hat{N}$ is then given by

$$\hat{N} = \sum_{i=1}^{j} \frac{v_i}{k_i} n_i \qquad (5)$$

151

152 Where:

153 k_i = number of interviews by strata i

154 n_i = number of reported entangled whales in strata i

155 With variance

$$var\left(\frac{\hat{N}}{V}\right) = \frac{\sum_{i=1}^{j} v_i^2 \, var\left(\hat{n}_i / v_i\right)}{V^2} \qquad (6)$$

157 If K_i is the total number of interviews in stratum i with k_m being the number in each sub-strata m out of s sub-
158 strata, resulting in n_m reported entanglements. n_i is the total number of entanglement reports in stratum i then the
159 variance can be expressed as (following Buckland et al. 1993):

$$\widehat{var}(n_i) = K_i \sum_{m=1}^{s} k_m \left(\frac{n_m}{k_m} - \frac{n}{K_i}\right)^2 / (s-1) \qquad (7)$$

161 If each interview is treated as a sampling unit (i.e. there are no sub-strata) then k_m=1 giving a standard
162 calculation of $\widehat{var}(n_i)$

163 The log-normal confidence interval (Buckland et al. 1993) can then be given by $\left(\frac{\hat{N}}{C}, \hat{N}.C\right)$

164 Where

$$C = exp\left[z_\alpha \sqrt{\widehat{var}(log_e \hat{N})}\right] \qquad (8)$$

166 and

$$\widehat{var}\left(log_e \hat{N}\right) = log_e\left[1 + \frac{var(\hat{N})}{\hat{N}^2}\right] \qquad (9)$$

168

169

170 *Identifying factors affecting entanglement risk*
171 The total amount of gear multiplied by time in the water is likely to be a good predictor of risk for a whale in the
172 fishing area, but the actual entanglement risk will depend on the distribution of whales in relation to the fishing
173 gear. Data on fishing effort recorded in interviews included total length of all gear when deployed (i.e. fathoms
174 of rope used per fleet), soak time (i.e. number of days between gear being set and hauled), and number of creels,
175 which relate to the risk associated with the gear itself. Other data included information on fishing area such as
176 distance of grounds from shore and depth of water in which gear was typically set. In order to allow for
177 differences between fishers who reported whether they were full and part time, we used an estimate of 'risk' that
178 was proportional to gear length for full time fishers and gear length/2 for part time. All fishers interviewed, both
179 full time and part time, were operating commercially. No recreational ('hobby') fishers were included in

180   interviews but were cited during interviews as being less likely to employ best practice e.g. regular gear
181   maintenance, weighting gear properly or adjusting ends for depth due to a lack of experience and/or concern.

182   Gear length, number of creels, fishing 0-6nm or >6nm from shore and water depth are all correlated to some
183   extent. So choosing the most appropriate model of risk is a challenge. The sample size of 157 interviews was not
184   large enough to allow for stratification and so risk factors were investigated using the full data set.

185

186

RESULTS

The locations of reported entanglements and the ports where entanglements were recorded in interviews are shown in Figure 3 for humpbacks and Figure 4 for minke whales. These show that entanglements occur throughout Scottish waters.
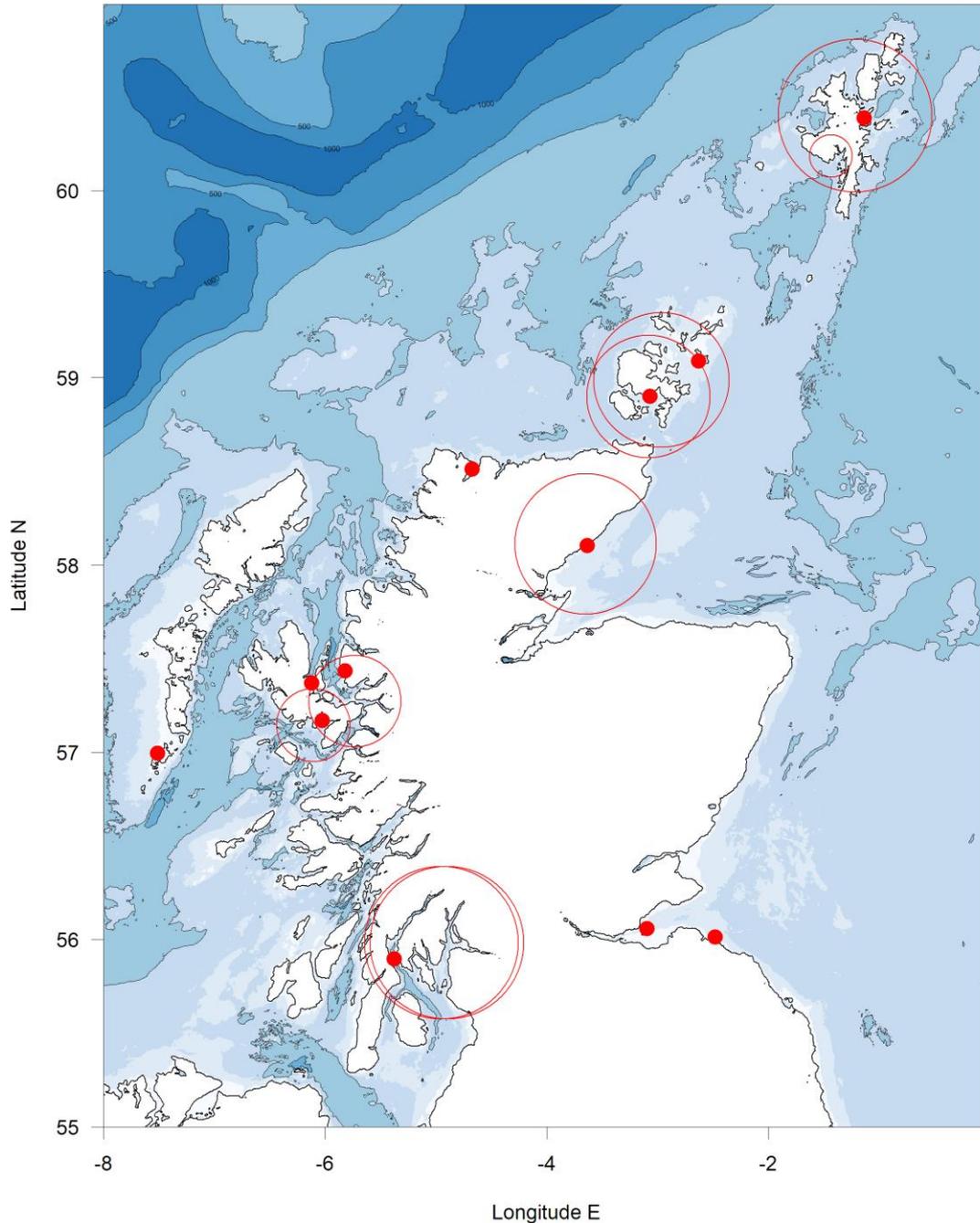
Figure 3. Locations of humpback whales reported to SMASS entangled in rope known or suspected to have been associated with creel fishing (red dots) between 2008 and 2019. Red circles are centred on ports where an entanglement was reported from interviews with creel fishers. Radius of the circle indicates the reported fishing distance from the port.

196

197
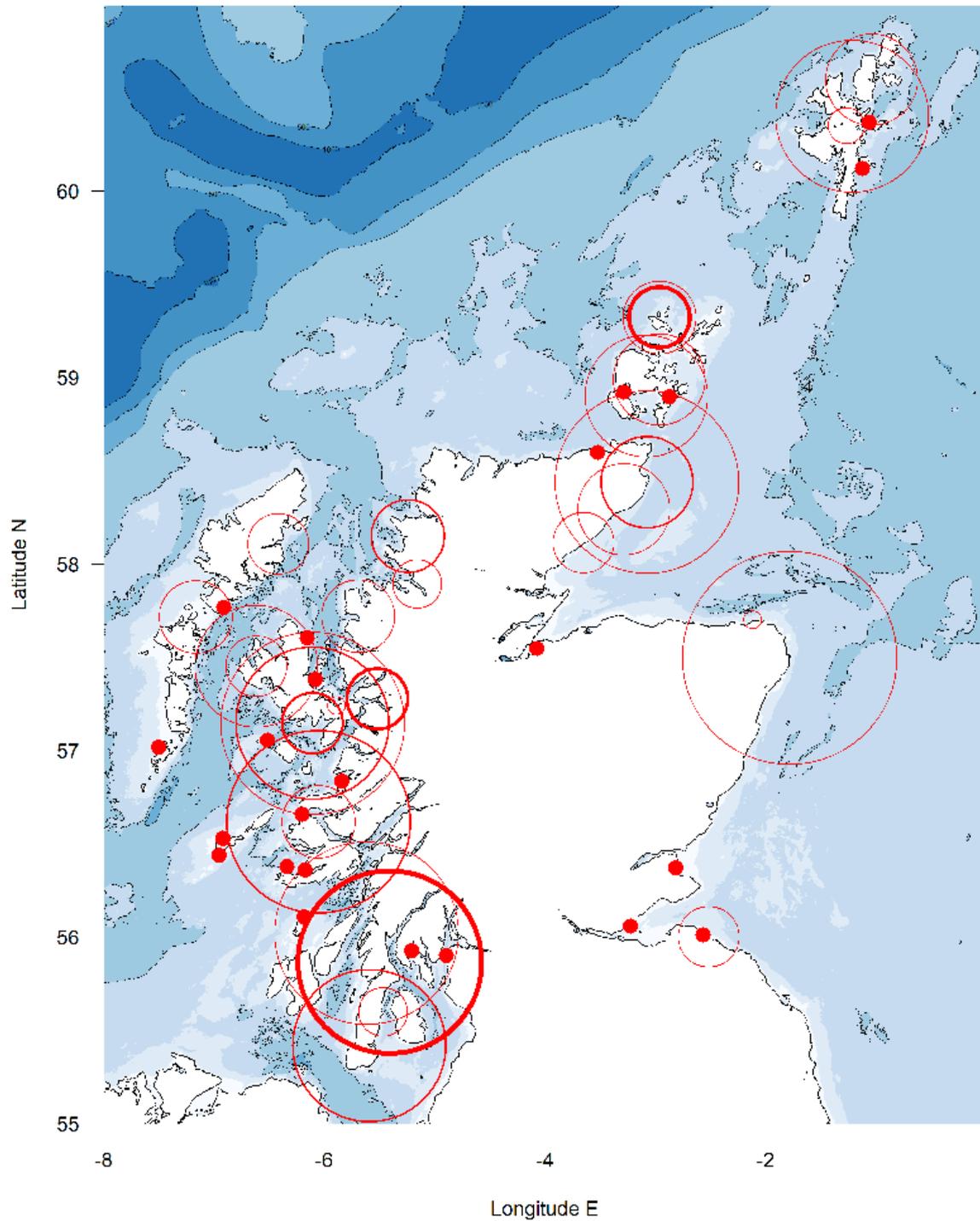
Figure 4. Locations of entangled minke whales from the SMASS database between 2008 and 2019 (red dots). Circles indicate locations of port interviews reporting at least one minke whale entanglement. The radius of the circle indicates the distance from the port where fishing operations occur, and the width of the circle is proportional to the number of entanglements reported (1-6).

203
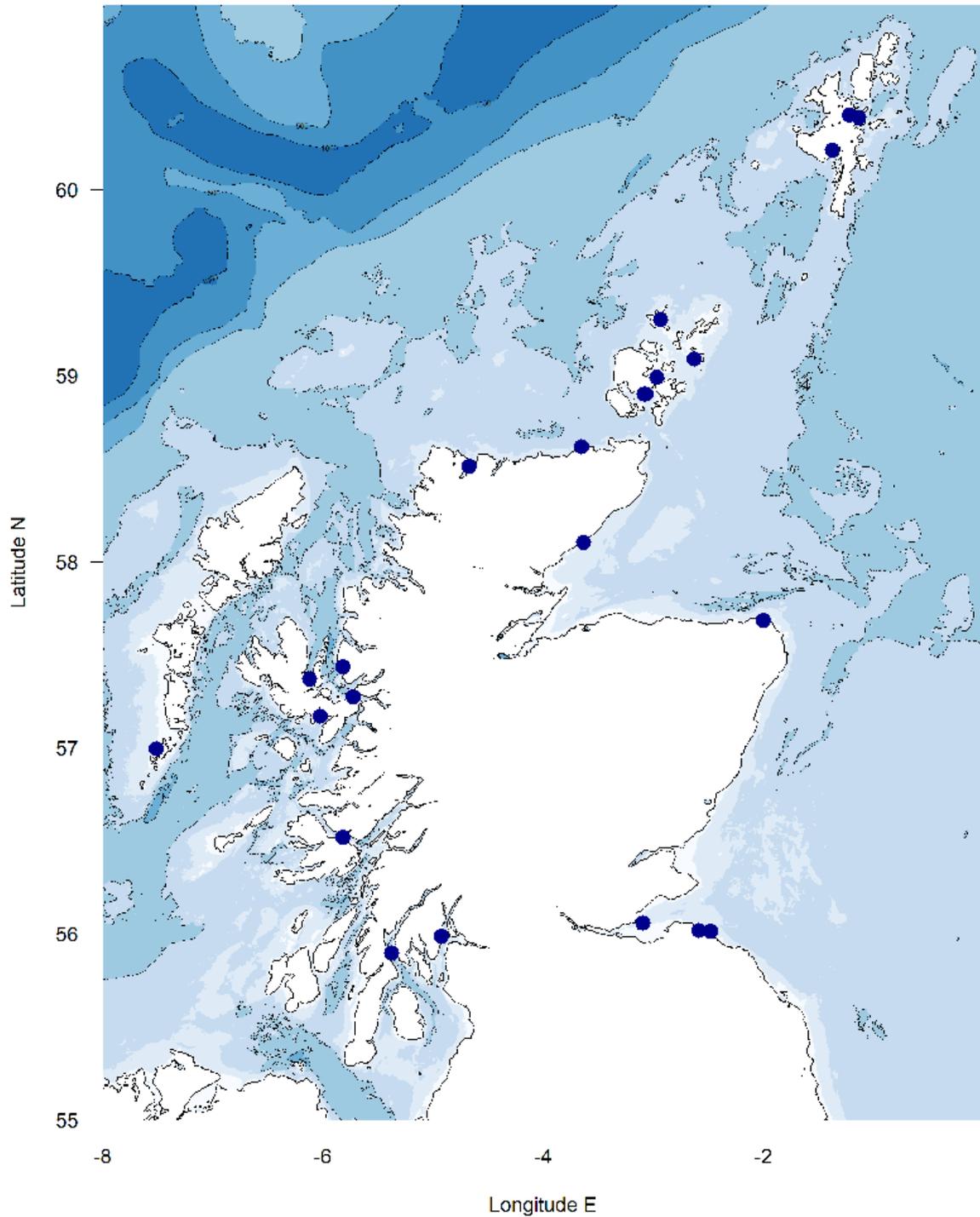
204

205 Figure 5. Indicative locations of all known humpback entanglements. Dots indicate either reported entanglement
206 location, reported stranding location or port where interview reported an entanglement if no additional
207 information was available.

208

209 For humpback whale incidents it was possible to identify two definite duplicates between the reports and the
210 interviews. It was also possible to determine that none of the other seven incidents reported in the interviews
211 could have been duplicate records with the reports.

9

212 It was much harder to determine duplicates for minke whales because of the larger number of reports from
213 interviews (50) and their density and distribution throughout Scottish waters (Figure 3). An approximate date
214 was available for 26 cases of the 50 minke whale incidents identified in the interviews. For all these 26 cases it
215 was possible to eliminate any duplicates with the 24 records from SMASS, BDMLR and other sources within
216 the period of the interview surveys. The lack of identified duplicates effectively precludes calculation of a point
217 estimate but the lower bound based on equation 3 was 220 (i.e. there was a 95% probability that the actual
218 number was greater than this).

219 Results for both species are summarised in Table 2. The distribution of the unique humpback entanglements (or
220 strandings following entanglement) is shown in Figure 5. This indicates entanglements may occur throughout
221 Scottish waters with no obvious concentrations, however the absence of any such patterns could be obscured by
222 the fact that humpbacks are capable of towing gear great distances away from the site of entanglement (Lyman
223 2014).

224 Table 2. Reports of humpback and minke whale entanglements from different sources and estimates of total
225 numbers.

	Humpback	Minke	Minke with approximate date to identify duplicates
Number of records from SMASS, BDMLR and other sources within the period of the interview surveys (2008-2019)	10	24	
Number of records from SMASS, BDMLR and other sources before or after the period of the interview surveys (2008-2019)	6	4	
Other incidents (aquaculture)	1	0	
Number of cases from interviews	9	50	26
Number of duplicates	2	-	0
Minimum total creel estimates (sum of other sources and interviews less possible duplicates)	23	-	-
Chapman estimate for period of interview surveys	35.7 (10.0 – 61.3)	-	-
Estimated total using correction factor from Chapman estimate for those reports outside of period of surveys	57.1 (16.0 - 98.1)	-	-
Estimate of total creels + aquaculture	58	-	-

226

227 The stratified estimates by district are given in Table 4 and by region in Table 5. Sample sizes in some districts
228 were too small to allow variance estimates and so these were only calculated for the three regions.

229

230   Table 4. Stratified estimates by district for the 10 years covered by interviews

District	Region	Number of interviews	Proportion of active vessels included in interviews	Average Depth (m)	Average gear length (km)	Total minke reports	Estimated minke total	Total humpback reports	Estimated humpback total
Aberdeen	E	12	0.28	37	18.5	0	0.0	0	0.0
Anstruther	E	7	0.15	49	8.1	0	0.0	0	0.0
Buckie	E	2	0.07	38	11.7	0	0.0	0	0.0
Campbeltown	W	15	0.20	80	16.7	10	51.1	2	10.2
Eyemouth	E	12	0.17	30	11.3	1	5.9	0	0.0
Fraserburgh	E	6	0.06	42	1.9	1	15.8	0	0.0
Lochinver	W	1	0.09	146	26.5	2	22.0	0	0.0
Oban	W	11	0.14	105	25.7	3	20.7	0	0.0
Orkney	N	12	0.12	56	22.8	8	66.1	2	16.5
Peterhead	E	4	0.06	46	10.9	1	15.5	0	0.0
Portree	W	28	0.40	146	25.8	12	29.8	2	5.0
Scrabster	N	22	0.27	47	20.9	4	14.8	1	3.7
Shetland	N	8	0.11	55	15.9	3	27.1	2	18.1
Stornoway	W	10	0.08	54	12.5	2	23.8	0	0.0
Ullapool	W	7	0.10	145	35.5	3	28.6	0	0.0
Total		**157**				**50**	**321.3**	**9**	**53.5**

231

232   Table 5. Stratified estimates by region for the 10 years covered by interviews

Region	Number of interviews	Estimated number of active vessels	Number of entangled minke whales reported	Estimate of total minke whale entanglements	Variance of entangled minke reports	95% log-normal CI of estimated total entanglements
E	43	345.4	3	24.1	2.8	8.7 - 66.7
N	42	253.1	15	90.4	29.5	45.4 - 179.9
W	72	418.9	32	186.2	58.7	117.2 - 295.7
Total	**157**	**1017.4**	**50**	**300.7**	**541.9**	**258.7 - 350.2**

Region	Number of interviews	Estimated number of active vessels	Number of entangled humpback whales reported	Estimate of total humpback whale entanglements	Variance of entangled humpback reports	95% log-normal CI of estimated total entanglements
E	43	345.4	0	0.0	0.0	0.0 - 0.0
N	42	253.1	5	30.1	4.3	13.8 - 65.9
W	72	418.9	4	23.3	5.7	7.9 - 68.8
Total	**157**	**1017.4**	**9**	**53.4**	**59.4**	**40.4 - 70.9**

233

Factors affecting entanglement risk

234
235   Of 50 minke whales, seven were reported to be entangled in vertical line, 31 in ground or back line, and 12 were
236   unknown, i.e. in the 31 out of 38 (82%) cases where the nature of entanglement was known, entanglement was
237   in the ground or back lines.

238   Of nine humpbacks, two were in vertical line, three in ground line, and four unknown, i.e. three out of five
239   (60%) cases of known cause involved the ground or back lines.

11

240 Because of the correlations between all the risk related variables it was not possible to include more than one co-
241 variate in a modelling approach. Instead, simple linear regression models were used to investigate relationships.
242 For humpback whales, no significant relationships were found between entanglements per interview and any of
243 the factors, but this is most likely due to small sample sizes.

244 For minke whales, the strongest relationship was with the depth in which the gear was set, with entanglement
245 rates increasing with greater depth (Figure 6), but there was also a significant increase in entanglement rates
246 with 'risk' (gear length adjusted for full or part time).

247 Table 5. Linear regressions of entanglement rates, with depth, gear length and 'risk'.

Regression	r-squared	p value
Minke entanglements ~ AverageDepth	0.40	**0.01**
Minke entanglements ~ AverageGearLength	0.21	0.08
Minke entanglements ~ AverageRisk	0.34	**0.02**
Humpback entanglements ~ AverageDepth	0.00	0.91
Humpback entanglements~ AverageGearLength	0.01	0.70
Humpback entanglements ~ AverageRisk	0.00	0.81

248
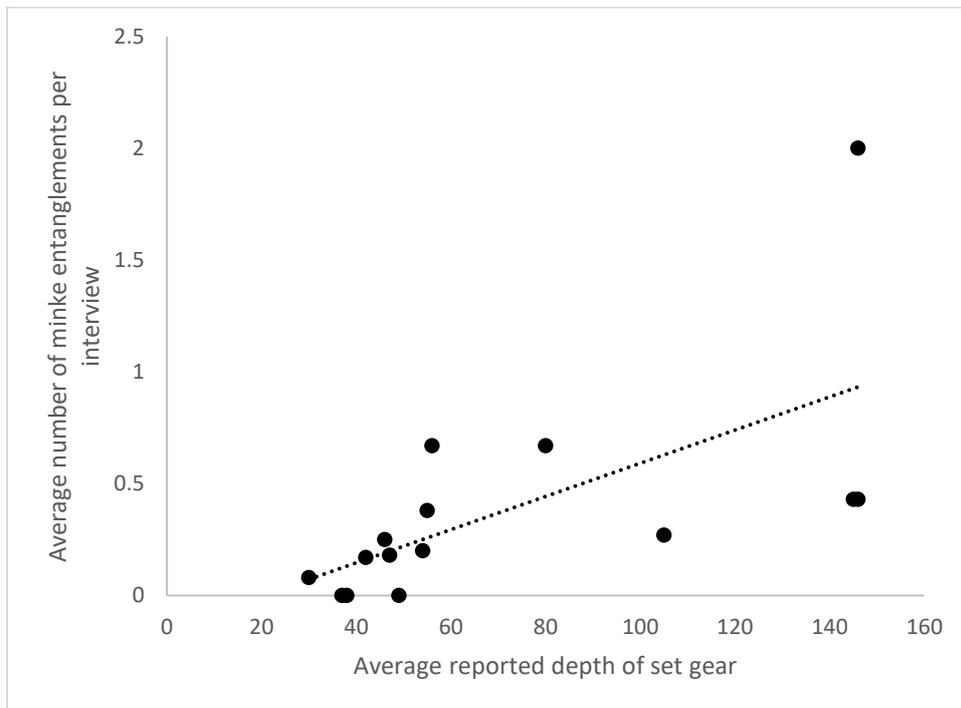
250 Figure 6. Mean number of minke entanglements per interview by fisheries district against average reported gear
251 depth.

252 Of the 50 entangled minke whales from the interviews, 41 (82%) were found dead, compared with humpback
253 whales where three out of nine (33%) were found dead.

DISCUSSION

255 The estimates and numbers of reports presented here are considerably higher than have been previously
256 reported, including to IWC in National Progress reports. They demonstrate a significant degree of historic
257 underreporting and suggest that the Scottish creel fishery may be having a much greater impact on whale
258 welfare and conservation than has previously been recognised. Previous analysis of entanglement rates for
259 humpback whales led by Ryan et al. (2016) concluded that 'Scottish inshore waters could not support a
260 population of humpback whales and these waters currently act as a high mortality sink for the species in the NE
261 Atlantic'. The results here double the number of reported entanglements of humpbacks in Scotland from the 12
262 identified by Ryan et al. (2016) to 24, all but three of which have occurred since 2010. We estimate a total over

263 the last ten years of 53 humpback whale entanglements, but there is also evidence of an increasing entanglement
264 rate in recent years with 2019 having the greatest number of incidents (four) for any year in the SMASS
265 database, which probably provides the most consistent reporting rate over time. Observed densities for minke
266 whales are much higher than for humpbacks (Ryan et al. 2016, Hammond et al. 2017); estimates of numbers of
267 entangled whales are also higher. Minke whale entanglements were also much more likely to be fatal; 82% of
268 the entangled minke whales found by fishers were already dead suggesting minke whale entanglement locations
269 are more informative in terms of understanding the geography of the entanglement issue. The total estimate of
270 300 (95% CI 259-350) from extrapolated interview surveys was not very sensitive to the stratification chosen.

271 There are a number of potential biases that could occur for both the capture-recapture approach to estimates and
272 extrapolation of the interview results to the whole fleet but the sources of bias for the two approaches will
273 generally be different. However, both methods will be subject to negative bias associated with either whales
274 breaking free from the gear or swimming away with entangled gear, such that the fisher may just see that the
275 gear has been lost and not attribute this to a whale entanglement, but rather the effects of weather or other
276 vessels towing gear for example. The latter situation is much more likely to occur with humpback whales, which
277 are known to be powerful swimmers sometimes carrying gear for great distances (Knowlton et al. 2016) and
278 therefore the true entanglement rate, both in terms of mortality and morbidity for humpback whales will be
279 higher. The capture-recapture approach will be most sensitive to any heterogeneity in the probability that an
280 incident will be reported. For example, some entangled whales and disentanglement efforts attract considerable
281 media attention whereas others are only witnessed by the fisher involved. This may lead to a negative bias if
282 highly publicised incidents were more likely to be reported by both methods. The extrapolation from the
283 interviews assumes that those interviewed were representative of the fleet as a whole for either the district or the
284 region. A positive bias would result if fishers who had experienced entanglements were more likely to be
285 interviewed, or a negative bias if an entanglement experience had left them less willing to talk.

286 The consistency of the results of the two approaches does give some confidence in the numbers. For humpback
287 whales the two estimation methods for the period of the interview surveys did not give significantly different
288 results (36 from the capture-recapture approach and 53 from the extrapolation from the interviews). Although
289 the capture-recapture approach could not provide a point estimate for minke whale entanglements because there
290 were no identified duplicates, it can give an indication of a lower bound. This lower bound of 220 (i.e. there was
291 a 95% probability that there were more entanglements than this) was consistent with the lower 95% confidence
292 interval of 259 from extrapolation of the interview surveys.

293 Some of the interview questions related to how entanglements might be addressed and showed a willingness on
294 the part of the fishers interviewed to address the problem. Of those who provided suggestions, 20% thought that
295 the situation could be improved through setting gear with less line, 5% identified self-shooting gear (i.e. where
296 creels are deployed automatically off the deck rather than by hand) as a way to keep greater tension on the
297 ground lines and reduce floating loops, 32% suggested the use of weights or sinking line, and 28% thought that
298 there should be less gear in the water overall.

299 Our estimates suggest that around five humpback whales and 30 minke whales are entangled in Scottish waters
300 each year. These numbers are a concern from both a welfare and conservation perspective and could pose a risk
301 of localised depletion for minke whales. The abundance estimate for the blocks of the SCANS III survey
302 covering the west coast of Scotland inside of the Outer Hebrides, equivalent to the W region in this study was
303 695 minke whales (Hammond et al. 2017). We estimate 15.3 fatal entanglements per year in this region (based
304 on a ten year estimate of 186 and 82% of entanglement proving fatal) which is 2.2% of the abundance estimate.

305 Two known breeding populations of humpback whales in the North Atlantic occur in Cape Verde and West
306 Indies, with some interbreeding (Palsbøll et al., 2017). Wenzel et al. (2020) recently reported that the Cape
307 Verde population remains precariously small (272, 10 SE). There are photo-ID matches to the Cape Verde
308 Islands and to the southeast Caribbean portion of the West Indies (Jones et al 2017) from Scottish waters (n=22
309 individuals compared to the NAHWC), although this is based on a small sample size and research is still
310 ongoing (North Atlantic Humpback Whale Catalog at Allied Whale, unpublished data).Therefore any
311 entanglements occurring in Scottish waters could potentially impact these small populations in the NE Atlantic.

312 Given that 82% of minke and 60% of humpback entanglements were reported to have occurred in the ground
313 lines between creels, the suggestions from fishers of using leaded line could greatly reduce entanglement risk.
314 This was identified by fishers as more practical in areas of soft, muddy bottom because sinking lines would be
315 more vulnerable to snagging and abrasion on rocky ground. Sinking ground line has been used in fisheries off
316 the east coast of the US where all fixed-gear fisheries are required to use sinking or neutrally buoyant ropes for
317 their groundlines (ALWTRP, 2007). Therefore a first step in Scotland could be to examine creel effort by
318 bottom type and investigate typical heights of loops of line between creels to compare to other areas (e.g.
319 Brilliant et al. 2010). This would help inform areas where sinking line could be implemented most effectively.

320 In addition, informal trials of on-call or 'ropeless' gear types in Scotland have gone well to date, and the
321 technologies have been embraced by those fishers employing them. Formalising and expanding these trials,
322 particularly in areas identified as high risk could also reduce entanglement risk in vertical end lines and should
323 be considered with urgency, particularly given the willingness exhibited by fishers to engage in mitigation
324 strategies and research.

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