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Original Article

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Successful collaborative trials of simple gear modifications to reduce entanglement of whales and other megafauna in Scotland's static pot (creel) fisheries

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Abstract

Entanglement in ropes associated with static fishing gear (pots/traps/creels) is a welfare and conservation concern for minke whales (*Balaenoptera acutorostrata*), humpback whales (*Megaptera novaeangliae*), basking sharks (*Cetorhinus maximus*), and other megafauna in Scottish waters. The Scottish Entanglement Alliance estimated that six humpback whales and 30 minke whales become entangled annually. Where entanglement type was known, 83% of minke whales, 50% of humpback whales, and 76% of basking sharks were caught in floating groundlines between pots. We collaborated with fishers on Scotland's west coast to trial sinking groundline (which lies on the seabed) to assess its practicality. A total of 15 *Nephrops* (langoustine) and crab fishers re-roped 61 sets of creel gear and fished the gear for ∼15 months, reporting on each haul. Over 1500 hauls were reported; the fishers encountered few problems, in some cases preferring the modified gear. We also deployed depth sensors/accelerometers and filmed a range of sinking and floating rope configurations with a Remotely Operated Vehicle (ROV) to collect data on performance underwater. This project is encouraging, both because of its results—that there may be a simple option to greatly reduce entanglement risk—and because of the successful, bottom-up, partnership approach with Scottish creel fishers.

Keywords: pots; static gear; entanglement; incidental capture; whale

Introduction

Entanglement in static fishing gear [pots (Food and Agriculture Organization of the United Nations (FAO) gear code FPO), or creels as they are known in Scottish fisheries] is a welfare and conservation concern for megafauna species globally (Hamilton and Baker 2019, Dodge et al. 2022), and for minke whales (*Balaenoptera acutorostrata*), humpback whales (*Megaptera novaeangliae*), basking sharks (*Cetorhinus maximus*), and leatherback turtles (*Dermochelys coriacea*) in particular in Scottish waters (Northridge et al. 2010, MacLennan et al. 2021). The Scottish Entanglement Alliance [SEA (https://scottishentanglement.org/)], a partnership of seven marine research, fishing, conservation and welfare bodies, was formed in 2018 to better understand the scale and impact of marine animal entanglements in Scottish waters. There is very limited use of gill nets in Scottish waters, and creel fisheries are thought to be the main source of entanglement risk in fishing gear. Vessels of 10 m and less in length comprise 76% of the Scottish fishing fleet, and of these 73% are creel vessels (Scottish Government 2023). Based on reported entanglements over a 10-year period (2009–2019), extrapolated to all active creel vessels, it was estimated that an average of 6.4 (95% CI 3.7–13.4) humpback whales and 30.2 (95% CI 22.7–46.9) minke whales become entangled in creel gear annually. Where the gear component (either endlines to surface marker buoys or groundline between creels) involved in the entanglement was known, 33 out of 40 cases (83%) of minke and 4 out of 8 cases (50%) of humpback whales were caught in groundlines between creels (MacLennan et al. 2021, Leaper et al. 2022). The numbers of reported entangled basking sharks were similar to that of minke whales, and where the gear component involved in the entanglement was known, 31 out of 41 (76%) of these were in the groundline (MacLennan et al. 2021). The floating polypropylene rope generally used in Scottish creel fishing forms arches or loops in the water between creel pots, which can be several metres high (Fig. 1). These loops can entangle sharks and whales, generally by the mouth, tail, or flipper (Johnson et al. 2005). The SEA project provided suggestions from Scottish creel fishers about entanglement mitigation options, such as replacing floating rope with negatively buoyant (sinking) groundline, which lies on the seabed rather than floating.

An example of a successful implementation of sinking groundline is the recently established octopus (*Octopus vulgaris*) fishery in South Africa. In this fishery, of seven Bryde's

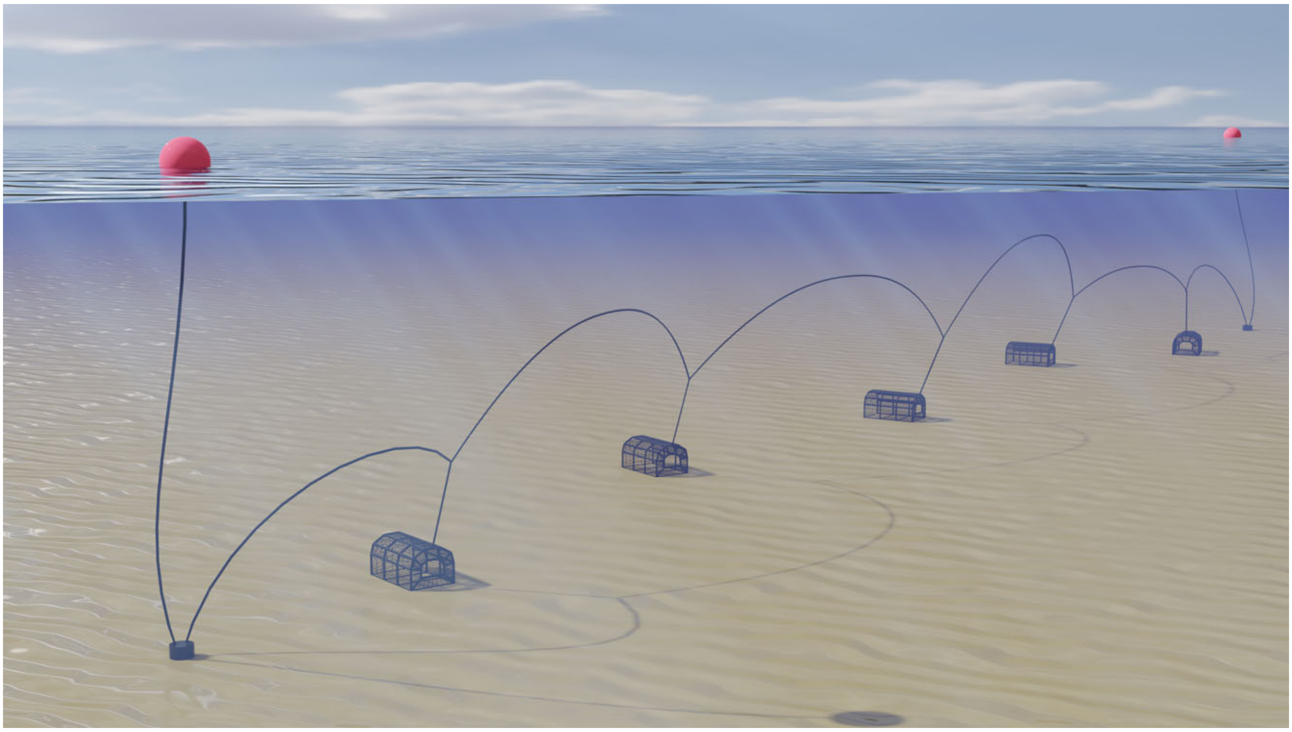

Figure 1. Typical configuration of creels in Scotland comprising a buoy at each end; a vertical line to weights either in the water column or on the seabed; and a main groundline with stoppers attaching the creels to the groundline, both of which float. The number of creels joined together in this way varies, but around 50–60 would be typical (Leaper et al. 2022).

whale (*Balaenoptera edeni brydei*) entanglements where the position in the gear was known, four were in groundline (Segre et al. 2021). The implementation of sinking groundline (amongst other measures) went well, and we are not aware of any further entanglements of Bryde's whales (M. Meyer, personal communication). Sinking groundline has also been implemented extensively on the east coast of the USA in lobster fisheries to reduce entanglement risk to large whales, in particular the North Atlantic right whale (*Eubalaena glacialis*). Some problems with sinking rope were reported by lobster fishers in Maine, including chafing, poor handling, snagging, and noise in the hauler. In response to these complaints, several studies were carried out with a view to improving the performance and operational life of sinking groundline (Ludwig et al. 2016). However, it was not clear whether the implementation of sinking groundline in the USA had reduced serious injuries and mortality of right whales to sustainable levels (Brillant and Trippel 2010, Knowlton et al. 2012, Van der Hoop et al. 2012, Werner and McLellan-Press 2016, Moore 2019). Part of the problem with assessing how effective the measure was is that, whilst floating groundlines were known to entangle some right whales (Johnson et al. 2005), and buoy lines were indicated in other incidents (Knowlton et al. 2016), in the majority of cases it was not clear in which part of the gear the entanglement occurred, and so the extent to which groundlines were the cause of entanglement both before and after the implementation was not well understood, and the risk reduction could not be quantified (Werner and McLellan-Press 2016, Laist 2017).

In 2022, a project was initiated to investigate the viability of using sinking groundline in Scottish creel fisheries. The challenges of monitoring causes of North Atlantic right whale mortality in both US and Canadian waters have meant that it has not been possible to clearly link the use of sinking groundline in US fisheries to a reduced rate of entanglement for North Atlantic right whales. However, there are key differences between the situation in the USA and in Scotland, which suggested the possibility of greater risk reduction from the use of sinking line in Scottish creel fisheries. Primarily, there is clearer information in Scotland as to where in the gear entanglements are taking place and the frequency of groundline entanglements, with the evidence particularly strong for minke whales and basking sharks, as (unlike right whales) they are generally not strong enough to escape from or swim off with gear and instead die *in situ*, making the mechanism of entanglement clear.

On the west coast of Scotland, a large proportion of creel vessels target *Nephrops norvegicus* (known variously as Norway lobster, Dublin Bay prawn, langoustine, or scampi, but referred to here as *Nephrops*). Details of the gear used in this fishery are summarized by Calderan (2022) and Leaper et al. (2022). In 2022, 1415 tonnes of *Nephrops* were landed by Scottish creel vessels with a value of £16 million compared to 18 000 tonnes of *Nephrops,* worth £67 million, that were landed from trawl fisheries. *Nephrops* caught in creels represent a smaller tonnage of landings than trawls but attract an average price per tonne four times that of trawled *Nephrops* (Scottish Government 2023). The *Nephrops* creel fishery accounts for a large proportion of entanglements—27 out of 51 minke whales (53%) and 5 out of 11 (45%) humpback whales reported during the SEA project from creel fisheries throughout Scottish waters (MacLennan et al. 2021). It was decided therefore that this trial would start with vessels targeting *Nephrops*, due to their high entanglement risk. Furthermore, *Nephrops* inhabit seabeds with soft substrates, which, given the experiences in the USA with both soft and rocky substrates, was expected to be a less problematic starting point for the trial. Crab gear fished on harder ground was introduced later on in the project once the rope had been trialled on softer ground.

The objective of the project was to take a collaborative, bottom-up approach, working closely with fishers and the Scottish Creel Fishermen's Federation (SCFF), which is also a member of SEA, to assess whether sinking rope was practical to fish with in Scottish inshore waters. This comprised the next stage following the original SEA project—evaluating the potential use of sinking rope to reduce entanglement risk throughout Scottish creel fisheries. Central to the project was drawing on the expertise of fishers, and ensuring that they were engaged and consulted from the beginning. The aim of the project was not to assess any reduction in entanglement rate during the rope trial, however. This was in part due to the small temporal and spatial scale of the trial. It was also because, as the SEA interview data clearly indicated that loops of groundline in the water column entangle megafauna, it is reasonable to assume that removing those loops would reduce entanglement risk.

Methods

This trial comprised 15 *Nephrops* and crab vessels in the Inner Sound area to the east of the island of Skye on the west coast of Scotland re-roping creel gear with sinking line and then fishing it as normal. Eleven of these vessels trialled only *Nephrops* gear, one only crab, and three both *Nephrops* and crab. Each time a string of creels (known as a fleet) was hauled, the fishers reported this to the project manager (SC) with the location, date, depth and bottom type of the fleet hauled, and any comments on the ease of handling of the rope, snagging (referred to as 'fasteners' in Scotland), signs of abrasion, adherence of mud, or other issues. Throughout the trial, the project manager was in close and regular contact with the participating fishers. The means by which haul data were communicated and the regularity of communication was up to each individual fisher in terms of what best suited them. The participating fishers worked in a variety of bottom types, depths, tidal flows, and exposures. The selected area included the harbour areas in Scotland (Broadford and Kyle) with the greatest *Nephrops* landings from vessels 10 m and under in length, and the harbour area (Portree) with the third highest landings for vessels over 10 m (Scottish Government 2023). It was too onerous for fishers in the trial to report on both hauls of fleets with floating line and sinking line. Instead, fishers were asked to compare their experiences gathered over many years of using floating line over a wide range of conditions, with the quantitative data collected on sinking line. This provided an evaluation of any differences in rates of issues between the two types of line, even though it was not a direct quantitative comparison.

The vessels in the rope trial ranged from 6.5 to 12 m in length with a median length of 9.4 m and just 1 out of 16 vessels (6%) in the over 10 m length category. This is comparable to the Scottish creel fleet as a whole with 10% of active vessels >10 m in length (Scottish Government 2023). Gear was deployed by both hand shooting (where the crewman picks up each creel individually and throws it into the water at similar intervals as the boat moves forward) and self-shooting (where the creels are lined up on the deck of the vessel, and as it moves forward, the first deployed creel pulls the next creel into the water, and each subsequent creel is deployed as the line comes tight), with a variety of hauler types. Most of the fleets in the trial were targeting *Nephrops* ($n = 46$) and ranged from 40 to 60 creels per fleet. Fleets generally comprised 12 mm groundline with 10 mm stoppers (the short rope that attaches each creel to the groundline) or, for the smaller vessels, 10 mm groundline with 8 mm stoppers. Crab fleets ($n = 15$) were shorter (20–30 creels per fleet) and often fished shallower. Typical *Nephrops* creel dimensions were 0.56 m × 0.41 m × 0.32 m with a weight of around 12 kg. The Marking of Creels (Scotland) Order 2020 (https://www.legislation.gov.uk/ssi/2020/168/made/data.pdf) requires any fleet of more than 10 creels to have at least one marker buoy fixed to each end of the fleet. More *Nephrops* than crab fleets were trialled (and the trial commenced with just *Nephrops* fleets), as the *Nephrops* fishery accounts for a large proportion of entanglements and *Nephrops* generally inhabit seabeds with softer substrate than crab ground, which was expected to be less problematic in terms of snagging and abrasion.

The rope used was Polysteel (a blend of polypropylene and polyethylene, which is stronger and more abrasion resistant than polypropylene on its own) and variants thereof. Each fisher was provided with both standard leaded Polysteel rope and Seasteel rope (proprietary to Gael Force Marine—more expensive than Polysteel, but expected to be longer-lasting). Two crab fleets were re-roped with SeaKing XL (also proprietary to Gael Force Marine), an oversized rope known to be particularly hard-wearing. The Polysteel and Seasteel ropes have one thread of beaded lead through the weave, whilst the SeaKing XL has two. Densities of rope varied between 1.2 and 1.6 $g\,cm^{-3}$ compared to 1.025 $g\,cm^{-3}$ for seawater and between 0.90 and 0.96 $g\,cm^{-3}$ for different polymers of polypropylene and polyethylene. Fishers involved in the trial received the rope for free, with a small amount of financial compensation for each fleet that they re-rigged to cover their time on both re-rigging and reporting to the project manager.

Video images from a Remotely Operated Vehicle (ROV) [Fifish V6 (https://www.fifish.co.uk/fifish-v6-expert/)] were used to provide qualitative data on how fleets of creels looked on the seabed with sinking and floating line and in different tidal conditions. ROV deployments comprised a descent down one endline of a fleet; the ROV then followed the ropes and creels at or near the seabed along the length of the fleet or as far as the ROV tether allowed. All video shot was edited and analysed to enable rope and creel characteristics on the seabed to be observed and compared. These observations were also used to assess if there were any impacts on the seabed from sinking rope. Tilt and accelerometer sensors (Star Oddi DST tilt sensors) were also deployed at various points on the ropes and creels of both *Nephrops* and crab fleets, both hand-shot and self-shot. They were also deployed on both sinking and floating ropes to record the height of loops, and the depth and movement of lines. Two sets of calibration trials were conducted with all the sensors recording together over the range of depths of actual deployments in the trials to correct for any offset differences between the sensors and assess the accuracy of relative depth measurements between sensors.

Results

Rope trials

All 15 fishers in the trial contributed to and participated actively in the project over its whole duration, trialling between 2 and 12 fleets each. None withdrew from the trial, and all took the opportunity to re-rope additional fleets of sinking rope when it was offered at other times later on in the trial.

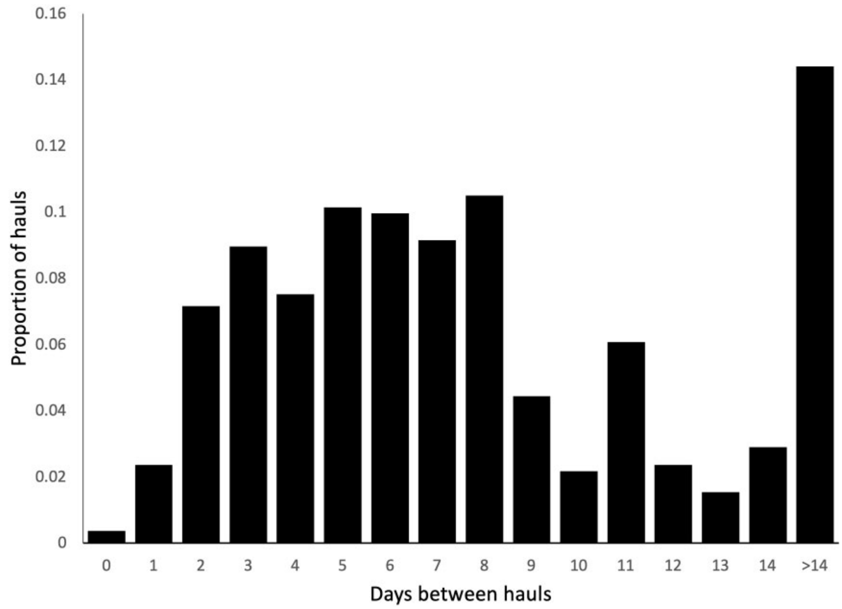

Figure 2. Distribution of reported haul intervals (days between deployment and recovery of a fleet) during the trial for fleets with sinking line. The column at the far right-hand side of the plot includes all hauls with an interval >14 days.

The first re-rigged fleet was deployed in December 2022, and all trial fleets were still being actively fished at the end of the trial (March 2024).

A total of 61 fleets of creels were re-rigged with sinking line and deployed from 16 vessels (15 fishers—one participant changed vessel partway through the project) over the course of the project. This resulted in over 18 000 fishing days for the fleets in total, and 1545 hauls where comprehensive data were reported. The number of days the sinking line fleets were in the water for the purposes of the trial varied between 105 and 426 days (mean 294 days), depending on what stage in the trial the fleet had been re-rigged. The median haul interval was 7 days. The distribution of haul intervals is shown in Fig. 2. Some fleets were not hauled for a period of 2 weeks or more due to weather or other factors.

Of the 61 fleets, 46 were targeting *Nephrops* (80% of fishing days), and 15 fleets were targeting crab (20% of fishing days). The relatively lower proportion of fishing days for fleets targeting crab was due to these trials starting later in the project, with the main focus being *Nephrops* fleets. Fleets targeting *Nephrops* comprised either 40, 50, or 60 creels (mean = 55, median = 50). The fishing depth ranged from 30 to 200 m (mean = 89 m). Fleets targeting crabs comprised either 20 or 30 creels with fishing depths ranging from 6 to 46 m (mean = 20 m). This shows a clear distinction between *Nephrops* and crab fleets. The depths of gear in the trial were broadly representative of the depths of gear set in Scottish creel fisheries where minke whales had been reported entangled in the SEA project (Fig. 3). The mean depth of 20 m for fleets targeting crab was rather shallower than in other areas (mean for Scotland of 53 m) (Leaper et al. 2022).

There were few reported problems with sinking rope, with most fishers reporting that it hauled and handled easily, lay well on deck, and was very similar to standard floating rope. Out of 1545 haul reports, there were 23 reports of an issue, 18 in *Nephrops* fleets, 4 in crab fleets, and 1 in a lobster fleet (one of the crab fleets was shot for lobster at one point in the trial in shallow bouldery ground, where it snagged and came fast). Of these issues, 11 were fasteners, seven were light snags, three were cases of abrasion, one of the rope breaking (at an unknown time, not during hauling), and one case of the rope coming out the hauler when hauling in poor weather and then paying out quickly. Out of these issues, five resulted in some damage to the fleet (rope or creels). The 23 cases out of 1545 where issues were reported related to a range of different circumstances, all of which also occur at times with floating line. This small number precluded any systematic analysis of the factors that might cause these issues to arise. The fishers involved all viewed the occurrence of issues as acceptable and not noticeably different from what they would have expected from floating line in similar circumstances.

In addition to the haul data provided, a large number of qualitative comments were received from the participating fishers. The main points made by fishers are summarized here:

Ease of handling

- No difficulties were reported with working and splicing the sinking rope during re-rigging, apart from the two fleets of SeaKing XL, which were considered tough to work due to the hard lay of the rope.
- The sinking rope was considered to lie better on deck than floating rope when new, and not add excessive weight to the boat, although one fisher reported that his crew disliked it as it was slippery when he stood on it.
- There was no reported difference in the ease of handling the sinking rope between self-shooting and hand shooting vessels.
- Those in the trial who had tried sinking rope before (e.g. 20 years ago) were initially more sceptical about this trial. However, they were all more satisfied with the rope used in this trial—it was considered to be lighter, with

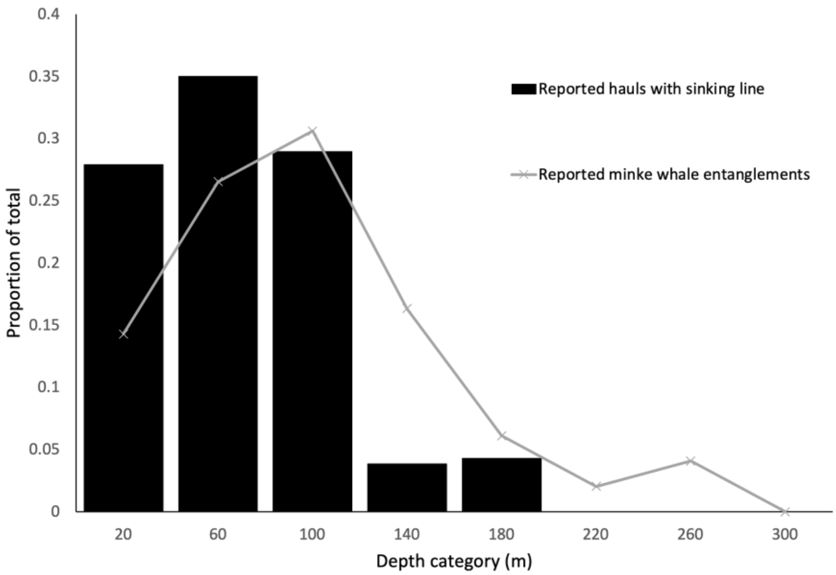

Figure 3. The proportion of reported hauls using sinking line (filled bars) during the trial and the proportion of reported minke whale entanglements from the SEA project interviews (grey crosses), by depth category.

fewer problems snagging on the ground or picking up mud (see below).

Differences between sinking rope types

- There were no differences reported between the handling or wear of the Polysteel vs. the Seasteel. However, the Seaking XL was considered to be too wiry—not coiling well on deck and jumping out the hauler (probably due to it being oversized). This did not improve as the rope wore in through the course of the trial.

Performance in hauler

- Generally, the rope gripped well in the hauler and was quiet. However, when parts of the hauler (plates/knife) became worn, it appeared to become an issue sooner with the sinking rope than with floating rope, although it is not clear why, and there was no indication that the wear was being caused by the sinking rope itself. There was no reported difference in handling between the types of haulers used.

Frequency of coming fast on seabed

- Although the sinking rope did sometimes snag on the seabed, the rate of snagging was not considered by trial participants to be unusual compared with floating rope.

Accumulation of mud/sediment on the sinking rope

- There were some reports of sinking rope on the *Nephrops* ground coming up slightly muddier than floating rope, but this was mentioned only rarely, and generally it was reported that the rope came up clean.

Abrasion

- There were a small number of reports of abrasion to the rope, especially around the end creels where they interacted with the endline/riser, but not considered to be either frequent or serious on either crab or *Nephrops* ground.

Tangling

- Fleets rigged with sinking rope had less tendency to tangle than floating line, especially during big tides and swell.

Loss of endlines

- There are issues in the study area with other vessels, such as military or aquaculture vessels, accidentally cutting one or both endlines. If both ends are lost, a common practice with a fleet roped with floating line is to catch the lost fleet by shooting another over the top of it and hauling them together. Another way is to grapple for the fleet. Both these methods are more difficult with sinking rope, although the one fleet in the trial where both ends were lost was successfully grappled and retrieved.

General safety issues

- In general, no safety issues were reported, apart from that in poor conditions, with strong wind, the sinking rope can pay out quickly if it comes out of the hauler due to the motion of the vessel and the weight of the rope.

Effect on fishing and seabed

- There were some reports of creel fleets rigged with sinking rope fishing better, which was thought to be because they move around less on the seabed. This was especially the case with newer-design creels, which are lighter-weight and are thought to move around when on the seabed. No data were available to validate these reports.
- It is likely that creels rigged with sinking line cause less damage to the seabed, also due to less movement. This observation is particularly interesting, given a concern that sinking line might negatively impact the seabed/sensitive seabed features by lying on it. In fact, the reverse might be the case.

Table 1. Measurements of loop heights of fleets with floating line.

Area description	Average stopper length (m)	Average creel to creel groundline (m)	Mean depth of creels (m)	Maximum heights of loops (m) over deployment. Mean values over time in parentheses			
				Loop 1 (creel 2–3)	Loop 2 (creel 3–4)	Loop 3 (creel 4–5)	Loop 4 (creel 5–6)
1. Hand-shot *Nephrops* fleet, strong tidal stream.	1.43	12.7	110	7.2 (5.7)	6.9 (6.0)	4.2 (3.3)	2.1 (0.8)
2. Hand-shot *Nephrops* fleet, no tide	1.45	11.9	16	4.8 (4.7)	4.3 (4.2)	4.7 (4.5)	4.1 (3.9)
3. Self-shot *Nephrops* fleet, moderate tide	0.83	13.4	20	2.6 (2.1)	2.9 (2.3)	3.6 (3.0)	3.6 (2.9)
4. Self-shot crab fleet, strong tide	1.64	14.4	13	2.1 (1.1)	3.2 (2.7)	3.5 (1.5)	2.6 (1.6)
5. Self-shot *Nephrops*, fleet, no tide	1.18	11.4	196	3.7 (3.2)	5.6 (5.1)	4.8 (4.3)	4.8 (4.2)
6. Hand-shot *Nephrops* fleet, no tide	1.11	10.9	117	0.5 (0.2)	0.6 (0.4)	2.9 (2.8)	2.9 (2.7)

Although the trial was not long enough to test the life expectancy of the sinking line (which may last around 10 years of normal use), a number of tests were conducted by a rope testing facility on samples of line in order to measure the load that they would take before breaking. Two-metre sample lengths of sinking line were placed into a tensile test machine, and the load increased until the breaking load had been achieved. All samples were of 12 mm sinking rope (Seasteel or Polysteel) supplied by Gael Force Marine. The samples that had been used had been on actively fished fleets for over one year. A sample of new Seasteel had a breaking load of 15.0 kN. The rope that appeared to have light wear at the end of the trial had 93% of its original strength, rope with moderate wear had maintained over 90% of its original strength. A sample that appeared heavily abraded still had 88% of its original strength.

Sensor and ROV data

Measurements using Star Oddi DST tilt sensors were from different depths of water for both hand-shot and self-shot fleets and in different tidal conditions. In each case, measurements were obtained from sensors inside creels 3 and 5 and on groundline between creels 2–3, 3–4, 4–5, and 5–6, referred to in subsequent tables and figures as Loops 1, 2, 3, and 4, respectively (see Fig. 4). The length of groundline between each creel was measured [length between the stoppers and the length of the stoppers themselves (Table 1)]. Floating loops follow a catenary curve from the joint with each stopper (Fig. 4), with the maximum height of the loop less the height of the stoppers (h–s in Fig. 4) used in an approximate equation for the catenary giving an estimate of the actual spacing between the creels on the seabed (c), based on the measured length of groundline between the creels (L).

Six experiments were carried out to measure the heights of the arches of floating rope in both crab and *Nephrops* fleets, both hand-shot and self-shot. The measurements obtained are given in Table 1. In areas with strong tide, the height of the loops was often quite variable. To allow for this, both the mean and maximum heights are reported. The mean and maximum heights are similar when not affected by tidal currents.

There was no significant difference (ANOVA, $df = 23$, $F = 0.07$, $P = .79$) in the mean maximum height over the deployment of the loops for self-shot or hand-shot gear (both 3.7 m) although the maximum height of any loop was lower for self-shot (5.6 m) than hand-shot (7.2 m). The mean ratio of creel separation to groundline length was 0.91 for self-shot and 0.89 for hand-shot. The first two loops on the gear in Experiment 6 were surprisingly low given that there was very little current in that location. It is possible that the rope got caught on the seabed and so did not form loops. When these were excluded as outliers, there was still no significant difference between the loops of hand-shot and self-shot gear (ANOVA, $df = 21$, $F = 2.06$, $P = .17$).

The variation in measured loop heights is illustrated in Fig. 5, which shows the changes over several tidal cycles for Experiment 4 in Table 1. The gear was set in an area of fast tidal streams but also close to islands with complex bathymetry, so it is likely that flow rates could be different for each loop. In the main channel, peak flow is between 1 and 2 h after high water, and this is evident with a dip in loop heights for all loops. It is also an area where wind conditions can affect tidal heights and currents, and this is evident after the second high tide on 15 June 2023. This has the most rapid change in tidal height, which also corresponded to the largest change in loop height assumed to be associated with a greater than usual tidal flow.

These results show that fishers generally achieve a spacing between the creels, which is ~90% of the available length of line regardless of the method of shooting. With self-shooting, the line is very taught when it leaves the vessel, but that tension on the lines is not maintained by the time the creels reach the seabed.

Six ROV surveys to obtain video images of creel gear on the seabed in a range of conditions were carried out over the course of the project. In summary, these surveys showed that floating rope forms loops in the water column with both hand-shot and self-shot gear (Fig. 6), that sinking rope has enough weight to prevent it from floating but sits quite lightly on the seabed (Fig. 7), and that a fleet in a tidal area with a soft seabed that had been left for 10 days before being surveyed showed no evidence of the rope having moved, sunk into the substrate, or any scouring marks on the seabed.

Conclusion

This project has demonstrated a viable route to substantially reducing whale and other megafauna entanglement in static fishing gear in Scottish waters—through the implementation

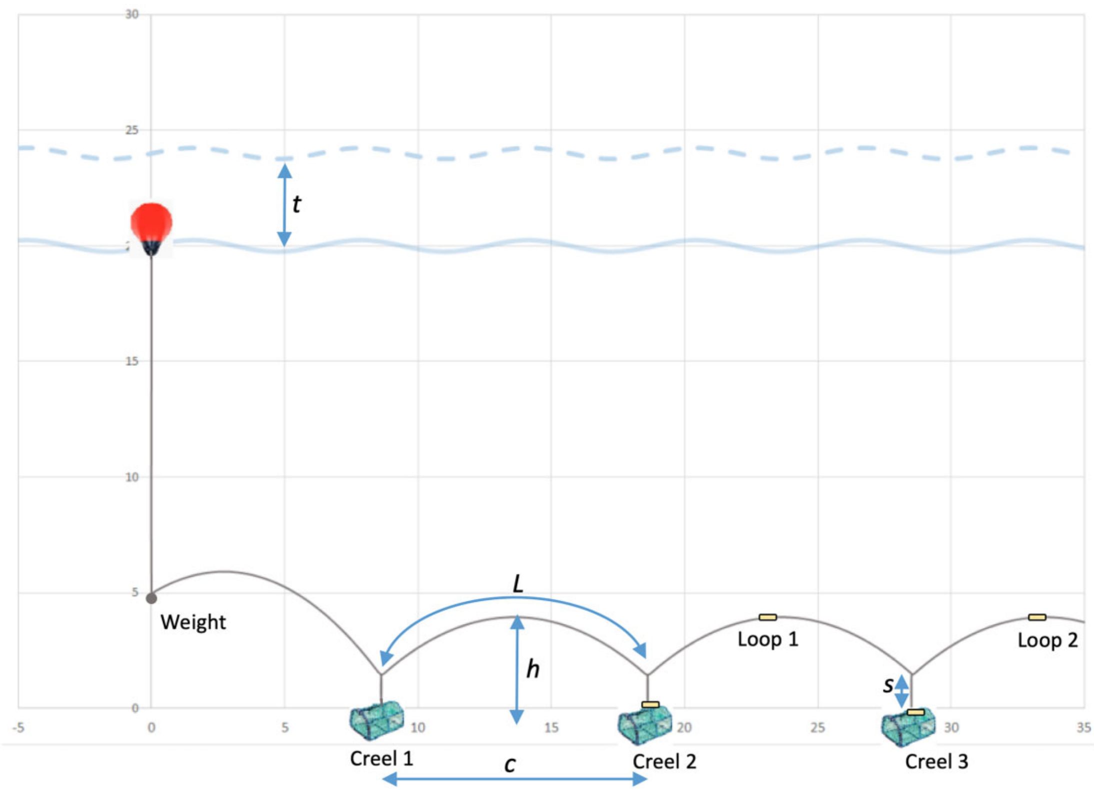

Figure 4. Measurements of typical creel set up in 20 m of water (low tide), *x* and *y* axes in *m*. *h* = height of loop above seabed, *L* = length of groundline between stoppers, *c* = distance between creels on the seabed, *s* = stopper length, *t* = tidal height. Yellow lozenges = sensors on groundline and inside creels. The weight below the buoy is often in the water column to avoid loops of line floating at the surface at times when the line is not otherwise under tension.

of sinking groundline. It has only been possible because of the positive collaborations between the project partners, in particular with fishers. It provides an example of how coordination between research, fishing, conservation, and regulatory bodies in testing potential solutions can provide a rare cause for optimism in tackling bycatch and entanglement, an issue of national and global importance from both a conservation and welfare perspective. The key outcomes from this trial are that there is an available means of reducing bycatch in static pot gear and that the means to do this is through bottom-up, collaborative working, with fishers involved at all stages.

The results have also further demonstrated previously identified risks from floating groundline due to the height of the floating loops above the seabed. The magnitude of the loops can explain the observed position of entanglements in gear reported by fishers in interviews for the SEA project (MacLennan et al. 2021, Leaper et al. 2022). In other static pot fisheries where the heights of loops have been measured, the results are similar to those obtained in this study. In South Africa, Daniel, unpublished work (2021) measured a mean loop height of 5.5 m (range 2.0–8.8 m) for traps in the octopus fishery that were spaced 20 m apart along the groundline. Brillant and Trippel (2010) measured the height of floating groundlines in the Bay of Fundy lobster fishery traps. They describe traps attached to the groundline at intervals of 22–37 m by gangions (equivalent to stoppers in the Scottish creel fishery) connected to the bridles on the ends of the traps. Gangions are typically 1.2–1.5 m long. The average maximum height of loops was 3.8 m and for most deployments the ratio of trap separation to groundline length was between 0.92 and 1 with a minimum of 0.72 and a median of 0.94.

The experience gained in the Scottish fishery together with previous work in the USA and South Africa can help inform mitigation measures globally, both with existing pot or trap fisheries in areas with large whale presence, but also where there are initiatives to replace trawling and gillnet use with pots or traps, whether through environmental concerns or because areas have become unsuitable for mobile gear due to offshore development such as wind farms. Whilst replacing floating line in established pot/trap fisheries will take time and requires dedicated collaborative efforts, ensuring that floating line is not used in any new fisheries should be more straightforward. A first step for established pot and trap fisheries would be to ascertain the extent to which floating line is used to link pots on the seabed. The next step would be to develop collaborations with fishers to trial/implement sinking line and establish whether this is practicable in that fishery and to create support for change. Subsequent work could allow a move towards replacing endlines with ropeless/'on demand' systems, which combined with sinking groundline, could potentially eliminate entanglement risk altogether. However, there are still a number of technical and economic challenges to implementing ropeless systems (Gahm et al. 2023), and for many fisheries endlines are a small proportion (10%–20%) of the total rope that presents an entanglement risk.

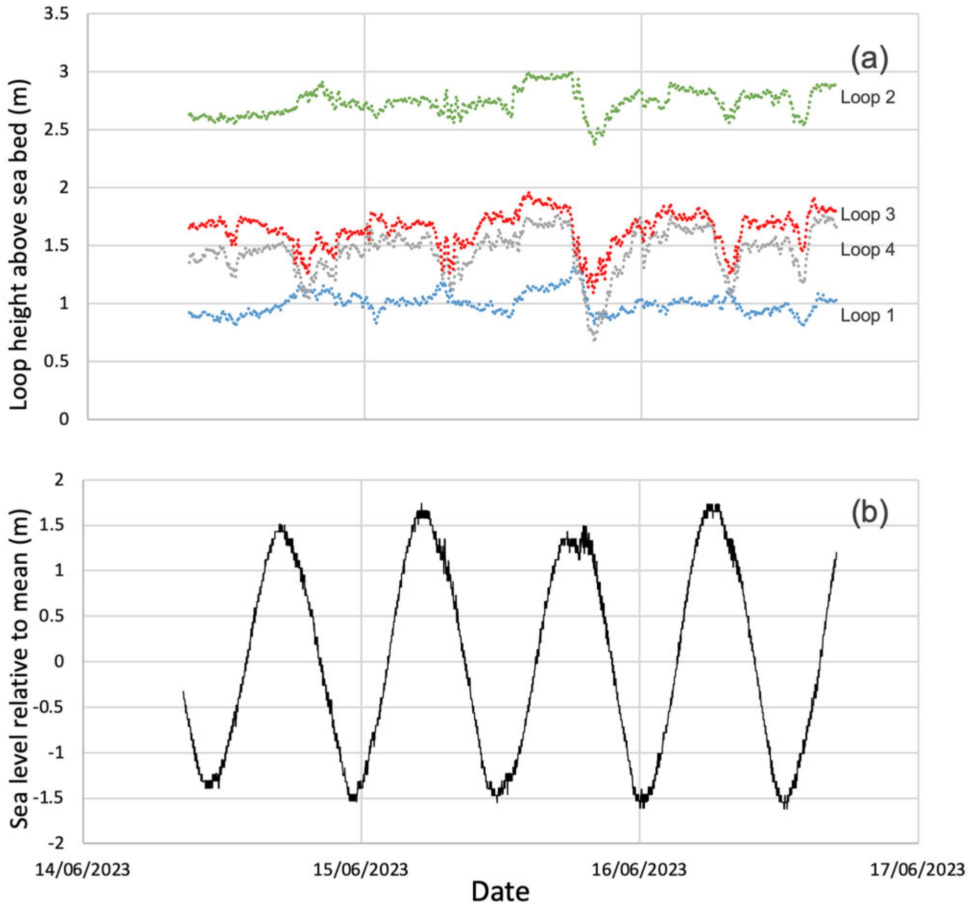

Figure 5. Measurements of the height of the tide and the heights of the loops of floating rope above the seabed over 3 days in an area of fast tidal streams with complex eddies. (a) shows the heights of loops 1–4 above the seabed. (b) shows the sea level height relative to the mean during the deployment. These data comprise a portion of Experiment 4 (see Table 1).

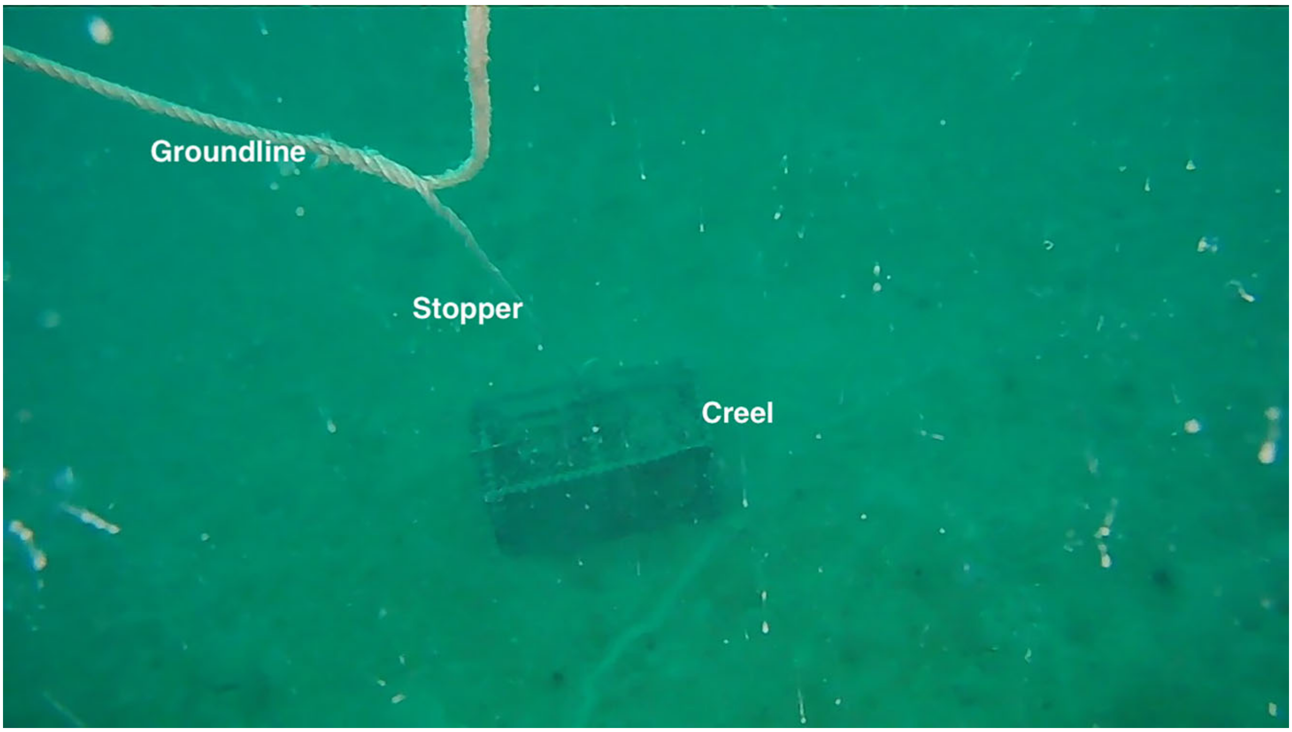

Figure 6. A still from ROV footage showing floating groundline, floating stopper, and a creel. The groundline is rising away from the stopper to form loops.

Figure 7. A still from ROV footage showing a creel, sinking stopper, and sinking groundline on seabed.

Where endlines are considerably longer than the depth of water, there may be scope to reduce entanglement risk by reducing the length to depth ratio. Modifications to reduce the amount of endline have been found to be effective in an Australian rock lobster fishery (How et al. 2021). Another option to reduce entanglement risk in endlines that has been implemented in some pot fisheries on the east coast of the USA (NOAA 2021) is the use of weak ropes in the upper section (33%–75% of the length depending on the fishery). In these fisheries, the average strength of rope should be <7.6 kN. Similar use of weak ropes would be unlikely to achieve a substantial risk reduction in Scottish fisheries because the species most often entangled are minke whales, which are much less powerful swimmers than North Atlantic right or humpback whales and have been found entangled in rope of lower breaking load than 7.6 kN (Knowlton et al. 2016). The strength of rope required to allow minke whales to break free would be problematic for fishers who do experience occasional line failures even with line with a measured breaking strain of around 15 kN.

The reporting from the 15 fishers involved in the project, both from quantitative haul data and qualitative feedback, was that sinking rope is not very different to use compared to floating rope. In some ways, it is preferable, in that rope can lie better on deck and on the seabed, does not move around so much (possibly resulting in higher catches and impacting less on the seabed), and there are fewer tangles, especially in big tides or rough weather. With respect to sinking rope's potential seabed impact, ROV surveys showed that, whilst floating rope formed arches in the water several metres high, sinking rope lay lightly on the seabed and did not cause scouring or damage. This is consistent with the sinking rope rarely snagging, abrading, or picking up mud in either the *Nephrops* or crab fleets. This contrasts with the substantial seabed impacts of bottom trawl fisheries (Sala et al. 2021). Whilst there may be some very rough seabed areas where sinking rope is inadvisable, from our study of 15 fishermen and over 1500 hauls, it was remarkable how few problems there were, in particular when targeting crabs on hard ground, which had been expected to be more difficult to work.

In order to progress implementation, there are some areas that require further work resulting from the limited temporal and spatial scale of this project. The trial area was fairly restricted (although topographically varied and including harbours with the highest *Nephrops* landings), and the timescale of this project was quite short. Work on implementing sinking groundline now needs to take place at a national level within Scotland to reach a wide geographical range. There should be a programme of familiarizing fishers with the results of this trial, working with them collaboratively to develop a fisher-led strategy for broadscale implementation, continuing the bottom-up approach, but facilitated and supported by the Government. The main issues raised by the fishers involved in the trial were establishing the longevity of the rope, and its additional expense compared to floating line. The cost of sinking rope is currently around double that of floating rope, varying according to the global price of lead. The price of the rope and how any transition to sinking rope might be addressed through a socio-economic analysis, developed in consultation with stakeholders.

The Scottish creel fishing fleet comprised around 900 active vessels in 2022 (Scottish Government 2023), and as a major employer, it is a key part of the economic and community structure of Scottish rural coastal communities. The fishery largely has a low environmental and seabed impact. The entanglement rate of marine megafauna is, however, an issue that the fishery can and should address as part of wider inshore fisheries reforms and in response to market-driven demand for more environmentally accountable fishing practices. Through the SEA project and this trial, it has been clear that Scottish inshore creel fishers have both the expertise and willingness to be part of the solution. There is now a need at a national level to engage with megafauna entanglement and with the mitigation options available, in particular sinking groundline. This will address the pressing welfare and conservation challenges to whales in Scottish waters and enable the Scottish creel fishery to develop in an environmentally sustainable way. The work of SEA is consistent with the Scottish Government's priorities and legal obligations, including achieving Good Environmental Status as part of the UK Marine Strategy. Scotland's Future Fisheries Management Strategy (2020–2030) commits to monitoring and reducing incidental bycatch (including cetaceans), and the UK Fisheries Act (2020) establishes an Ecosystem Objective, including to 'minimise and where possible eliminate sensitive species bycatch'. The next steps based on this successful trial—assessing the viability of Scotland-wide implementation of sinking groundline—will play a key role in achieving these objectives.

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Author contributions

S.C.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, writing—original draft, writing—review & editing. B.C.: funding acquisition, project administration, writing—original draft, writing—review & editing. M.D.N.: project administration, writing—original draft, writing—review & editing. R.L.: conceptualization, formal analysis, funding acquisition, investigation, methodology, writing—original draft, writing—review & editing. E.M.: conceptualization, investigation, methodology, writing—original draft, writing—review & editing. B.P.: conceptualization, investigation, methodology, writing—original draft, writing—review & editing.

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Data availability

The data underlying this article cannot be shared publicly due to the privacy of the fishers who participated in the project. The data will be shared on reasonable request to the corresponding author.

References

Brillant S, Trippel E. Elevations of lobster fishery groundlines in relation to their potential to entangle endangered North Atlantic right whales in the Bay of Fundy, Canada. *ICES J Mar Sci* 2010;**67**:355–64. https://doi.org/10.1093/icesjms/fsp231

Calderan S. Investigating the use of sinking groundline in Scottish Creel Fisheries to reduce entanglement risks to marine megafauna. *Report prepared for WDC*, 2022. https://uk.whales.org/wp-content/uploads/sites/6/2024/03/scottish-creel-fisheries-entanglement-report.pdf (11 November 2024, date last accessed).

Daniel MT. Whale entanglements in South African Trap fisheries and their potential mitigation through ropeless fishing techniques. *University of Cape Town thesis*. 2021.

Dodge KL, Landry S, Lynch B *et al.* Disentanglement network data to characterize leatherback sea turtle *Dermochelys coriacea* bycatch in fixed-gear fisheries. *Endang Species Res* 2022;**47**:155–70. https://doi.org/10.3354/esr01173

Gahm M, Coogan C, Galvez B *et al.* US Efforts to develop on-demand fishing gear technology 2022-2023 Updates. *Paper SC/69a/HIM/03 Presented to the International Whaling Commission Scientific Committee, Bled*. 2023.

Hamilton S, Baker GB. Technical mitigation to reduce marine mammal bycatch and entanglement in commercial fishing gear: lessons learnt and future directions. *Rev Fish Biol Fish* 2019;**29**:223–47. https://doi.org/10.1007/s11160-019-09550-6

How JR, de la Mare WK, Coughran DK *et al.* Gear modifications reduced humpback whale entanglements in a commercial rock lobster fishery. *Mar Mammal Sci* 2021;**37**:782–806. https://doi.org/10.1111/mms.12774

Johnson A, Salvador G, Kenney J *et al.* Fishing gear involved in entanglements of right and humpback whales. *Mar Mammal Sci* 2005;**21**:635–45. https://doi.org/10.1111/j.1748-7692.2005.tb01256.x

Knowlton A, Hamilton P, Marx M *et al.* Monitoring North Atlantic right whale *Eubalaena glacialis* entanglement rates: a 30 yr retrospective. *Mar Ecol Prog Ser* 2012;**466**:293–302. http://www.jstor.org/stable/24876125

Knowlton AR, Robbins J, Landry S *et al.* Effects of fishing rope strength on the severity of large whale entanglements. *Conserv Biol* 2016;**30**:318–28. https://doi.org/10.1111/cobi.12590

Laist DW. *North Atlantic Right Whale: From Hunted Leviathan to Conservation Icon*. Baltimore: John Hopkins University Press, 2017.

Leaper R, MacLennan E, Brownlow A *et al.* Estimates of humpback and minke whale entanglements in the Scottish static pot/creel fishery. *Endang Species Res* 2022;**49**:217–32. https://doi.org/10.3354/esr01214

Ludwig L, McCarron P, McClellan K *et al.* Review of sinking groundline performance in the Maine lobster fishery, with recommendations for improving its fishability. *In: Final Report to the Consortium for Wildlife Bycatch Reduction under Award # NA10NMF4520343 to the New England Aquarium*, Boston, MA USA, 44, 2016.

MacLennan E, Hartny-Mills L, Read FL *et al.* Scottish Entanglement Alliance (SEA)—understanding the scale and impacts of marine animal entanglement in the Scottish creel fishery. *NatureScot Research Report 1268*, 2021.

Moore MJ. How we can all stop killing whales: a proposal to avoid whale entanglement in fishing gear. *ICES J Mar Sci* 2019;**76**:781–6. https://doi.org/10.1093/icesjms/fsy194

NOAA. Weak Insert and Weak Line Requirements for Northeast Lobster/Jonah Crab Trap/Pot Fisheries. 2021. https://www.fisheries.noaa.gov/new-england-mid-atlantic/marine-mammal-protection/weak-insert-and-weak-line-requirements-northeast-lobster-jonah-crab-trap-pot-fisheries (11 November 2024, date last accessed).

Northridge S, Cargill A, Coram A *et al.* Entanglement of minke whales in Scottish waters: an investigation into occurrence, causes and mitigation. *Contract Report. Final Report to Scottish Government CR/2007/49*, 57, 2010.

Sala E, Mayorga J, Bradley D *et al.* Protecting the global ocean for biodiversity, food and climate. *Nature* 2021;**592**:397–402. https://doi.org/10.1038/s41586-021-03371-z

Scottish Government. Scottish Sea Fisheries Statistics 2022. 2023. https://www.gov.scot/binaries/content/documents/govscot/publications/statistics/2023/09/scottish-sea-fisheries-statistics-2022/documents/scottish-sea-fisheries-statistics-2022/scottish-sea-fisheries-statistics-2022/govscot%3Adocument/scottish-sea-fisheries-statistics-2022.pdf (11 November 2024, date last accessed).

Segre PS, di Clemente J, Kahane-Rapport SR *et al.* High-speed chases along the seafloor put Bryde's whales at risk of entanglement. *Conserv Sci Pract* 2022;**4**:e12646. https://doi.org/10.1111/csp2.12646

Van der Hoop J, Moore MJ, Barco SG *et al.* Assessment of management to mitigate anthropogenic effects on large whales. *Conserv Biol* 2013;**27**:121–33. https://doi.org/10.1111/j.1523-1739.2012.01934.x

Werner T, McLellan-Press K. 2016. Global assessment of large whale entanglement and bycatch reduction in fixed fishing gear. *Final Report NOAA Award Number: NA15NMF4630357*. https://bycatch.freelock.com/sites/default/files/2022-08/Werner%20and%20Press_2017_Whale%20workshop%20report.pdf (11 November 2024, date last accessed).

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