

# Evaluation of low breaking-strength and acoustic on-demand fishing gear to mitigate entanglements of North Atlantic right whales in the southern Gulf of St. Lawrence snow crab fishery

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## ABSTRACT

Finding methods to mitigate the risk and severity of North Atlantic right whale entanglements in fishing gear is increasingly urgent as these endangered whales use the southern Gulf of St. Lawrence (sGSL) as a summer feeding ground. In collaboration with snow crab fishers in the sGSL, we measured the tension of buoy lines while hauling traps, field tested the hauling of low breaking-strength gear, and explored the use of on-demand gear to avoid deploying vertical buoy lines. With conventional buoy lines, 40% of the hauling events reached maximum tensions of 7.56 kN (kiloNewtons; 1,700 lbf) or more during regular fishing operations. When evaluating methods to reduce the tension of buoy lines while lifting single traps, we found that the use of a hydraulic tension limiter to maintain low tension was effective and relatively easy to retro-fit to existing vessels. Four types of weak gear configurations were tested in sea trials using a hydraulic load tension limiter: (1) buoy lines consisting of weak rope throughout; (2) buoy lines consisting of regular rope with inserts of either weak rope, (3) breakaway sleeves or (4) links, with the only gear modification parting being sleeves. The tension needed to break weak rope reduced after being used to lift a trap six times. During the 2022 fishing season, 300 trawls (strings of multiple traps) were hauled by 19 fishers using on-demand gear in areas closed to conventional buoyed line fishing gear, with a total catch of > 203 tonnes, representing the first commercial application of this technology in Canadian waters. While 94% of the deployed sets were retrieved without grappling, only 65% of them were recovered after sending a single trigger signal from a mobile application. For this technology to be widely implemented, the trigger success rate must be improved. We measured elevation profiles of model groundlines with different proportions of sinking and positively buoyant rope and proportions of excess length at different current speeds. Our results support the use of sinking groundline to achieve low arc heights above the seafloor for on-demand fishing using trawls. We believe that the collaborative framework applied in this study was effective in engaging fishers to apply innovative practices to reduce the risk and severity of right whale entanglements with snow crab fishing gear in the sGSL. The feedback provided by fishers helped define our methods

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and ensure their practical application. Moreover, this initiative strengthened international synergies, fostering collaboration between scientists, industry stakeholders and regulatory bodies to accelerate the adoption of whale-safe fishing practices on a broader scale.

**KEYWORDS:** CONSERVATION; NORTH ATLANTIC RIGHT WHALE; FISHERIES; FISHING GEAR; FISHERIES MANAGEMENT; NORTHWEST ATLANTIC; ENTANGLEMENT

## INTRODUCTION

### 1.1 Right whales and entanglements in the Northwest Atlantic

Testing methods to mitigate the severity of fishing gear entanglement of marine mammals in the Northwest Atlantic has become a pressing issue in recent decades (Knowlton & Kraus, 2001; Johnson *et al.*, 2005; Brilliant *et al.*, 2017; Hamilton & Baker, 2019; Martins *et al.*, 2019; Reed *et al.*, 2024). Along with vessel strikes, entanglement is recognised as one of the leading causes of injury and mortality of large whales in the region (Van der Hoop *et al.*, 2013; Garron *et al.*, 2022; Knowlton *et al.*, 2022). This is especially true for North Atlantic right whales (*Eubalena glacialis*; hereafter right whale), listed as Endangered (Canada: Species At Risk Act of 2003; U.S.: Marine Mammal Protection Act of 1972 and Endangered Species Act of 1973), and whose survival is mostly affected by human activities (Cassoff *et al.*, 2011; Knowlton *et al.*, 2012; Baumgartner *et al.*, 2017). Recent estimates of population size indicate that right whale abundance increased by 2.8% from 1990 to 2010, reaching 483 individuals, before declining after 2010 (Pace *et al.*, 2017). In 2024, the population size was estimated at 372 (+11/−12) individuals (Linden, 2024). When examining identifiable parts of fishing gear involved in entanglements with large cetaceans in the western North Atlantic (31 right whales and 30 humpback whales [*Megaptera novaeangliae*]), it was determined that 81% of cases ( $n = 21$ ) involved buoy and groundlines (Johnson *et al.*, 2005), commonly used with trap and pot fishing gear to catch lobster (*Homarus americanus*) and snow crab (*Chionoecetes opilio*).

### 1.2 Snow crab fishery in the southern Gulf of St. Lawrence

The Gulf of St. Lawrence is among the largest and most productive marine ecosystems in Canada (Morissette *et al.*, 2009; Fig. 1a), supporting numerous commercial groundfish, pelagic and shellfish fisheries (Dufour &

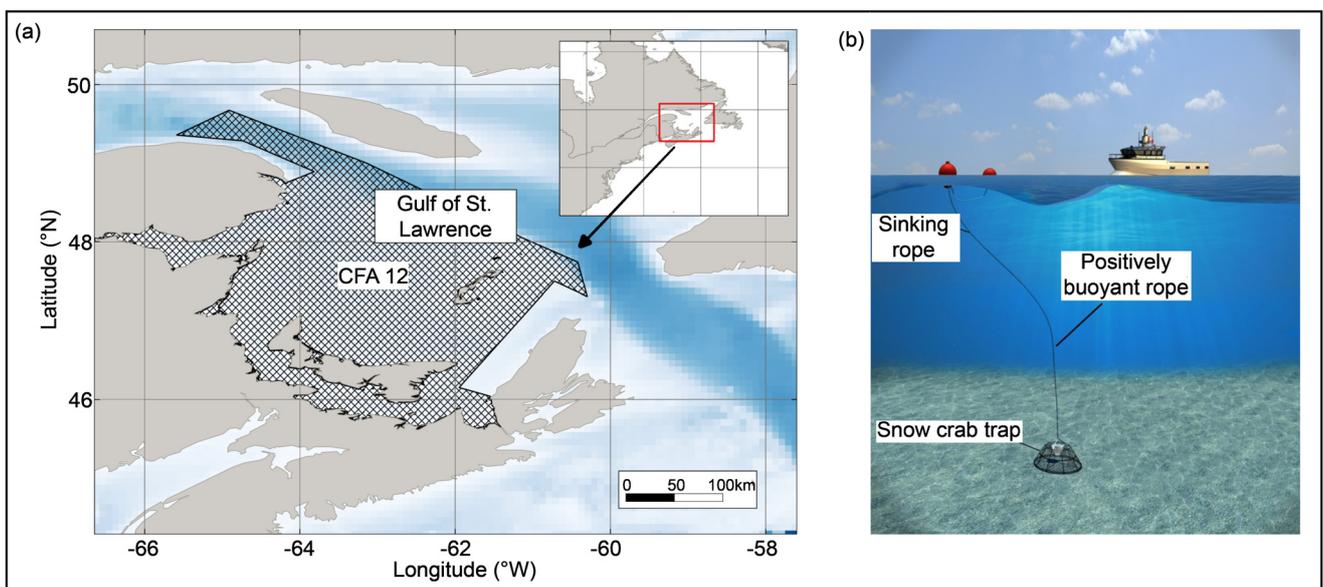


Figure 1. (A) Map of the Gulf of St. Lawrence showing the snow crab fishing area (CFA) 12; (B) unscaled representation of conventional snow crab fishing gear, showing the trap on the seabed and sections of the buoy line composed of positively buoyant and sinking rope, connected to buoys on the surface.

Ouellet, 2007). In particular, the snow crab fishery in the Northwest Atlantic represents the second most lucrative fishery in eastern Canada with landings of 101,000 tonnes in 2023, with a value of \$500 million CAD (DFO, 2023a, b). Snow crabs are caught in the southern Gulf of St. Lawrence (sGSL) using non-tended fixed gear (Fig. 1b) during spring and summer, setting single, baited conical traps for up to 72 hours at a time on muddy or sand-mud bottoms, usually at depths of 73 to 140 m (Moriyasu, 2009). Traps are connected to a surface buoy by rope. These buoy lines, consisting of both positively buoyant and sinking sections (Fig. 1b), are the primary source of entanglement (Johnson *et al.*, 2005; DFO, 2023c, d). Once traps are hauled, they are immediately re-deployed either in the same location or a new one, meaning the effective duration of deployment spans several weeks, until the assigned quota is filled or the fishing season ends, when all traps are retrieved and stored on land. A snow crab fisher's seasonal license in the sGSL generally permits 150 traps for the mid-shore fleet, using vessels from 19.8 to 30.5 m in length.

### 1.3 Right whale entanglements with snow crab fishing gear in the sGSL

The distribution of right whales along the Canada/U.S. eastern seaboard changes seasonally as the population migrates from its southerly winter calving areas to northerly summer feeding grounds (Kraus & Rolland, 2009; Brillant *et al.*, 2015). In recent years, a northward shift in their distribution led to their increased presence in the sGSL (Meyer-Gutbrod *et al.*, 2021). Greater use of the sGSL by right whales after 2015 was driven by a decline in prey availability in their historically high-use summer foraging habitats in the Bay of Fundy, Gulf of Maine and Scotian Shelf (Meyer-Gutbrod *et al.*, 2023). In the summer of 2017, 12 right whales died, in addition to five live entanglements reported in the sGSL (Daoust *et al.*, 2017; Davies & Brillant, 2019). From the right whales that were necropsied, two were entangled in fishing gear while four of the live entanglements were associated with snow crab gear (Daoust *et al.*, 2017).

The spatial and temporal overlap of right whales and fishing gear in the sGSL has since become key to fisheries management plans in eastern Canada. In 2018, Fisheries and Oceans Canada (DFO) introduced management measures aimed at reducing entanglement occurrences. These preventive measures included static and dynamic fixed-gear fishery area closures linked to right whale detection. For example, when a right whale is detected by visual or acoustic methods in the GSL, an area of ~2,000 km<sup>2</sup> is closed for 15 days. If a right whale is detected again in the same area during Days 9–15 of the closure, a season-long closure will be applied (DFO, 2022; Cole & Brillant, 2025). Furthermore, in snow crab fishing area (CFA) 12, an earlier start to the fishing season was allowed, just after sea ice melts when catch rates are highest. This adjustment allows harvesting to begin before right whales move into the sGSL, minimising whale-fishery interactions in this quota-based fishery (Davies & Brillant, 2019; Morissette, 2022; DFO, 2022, 2024). With increased right whale presence in the sGSL, detections in closed areas mainly occurred in CFA 12 (DFO, 2022; Fig. 1a), which has the largest snow crab fleet, with 461 active vessels fishing in 2023 (Landry *et al.*, 2024), contributing most to Canada's total annual snow crab landings (DFO, 2023a). However, it was observed that closures in 2018 shifted crab fishing effort to the southeastern section of the sGSL, where a heightened density of gear increased the risk of right whale entanglement (Cole *et al.*, 2021). Therefore, implementing new fishing technologies to mitigate the risk and severity of entanglement in areas where fisheries remain open to buoyed gear is crucial for protecting right whales.

### 1.4 Fishing gear modifications to reduce the risk and severity of entanglements

DFO and the U.S. National Oceanic and Atmospheric Administration (NOAA) have identified two categories of gear technology to prevent and/or reduce the incidence and severity of large whale entanglements in buoy lines.

Firstly, the use of low breaking-strength rope and weak links or devices inserted in buoy lines with a tensile breaking strength < 7.56 kN (1,700 lbf) could alleviate the severity of entanglements: the large diameter of buoy lines commonly used in the snow crab industry have breaking strengths > 44 kN and are less likely to part when a whale becomes entangled, leading to prolonged and potentially fatal interactions (Knowlton *et al.*, 2012; Knowlton *et al.*, 2016; Lebon & Kelly, 2019). Weak rope and weak link requirements for U.S. Northeast lobster and Jonah crab (*Cancer borealis*) trap/pot fisheries are supported by NOAA (NOAA, 2023a) and were tested as

part of the DFO Whalesafe Gear Adoption Fund (DFO, 2021, 2023e). Strong rope similar to that deployed in snow crab gear has been traditionally used as buoy line in the northeast U.S. offshore lobster trawl fishery. Since May 2022, NOAA has implemented low breaking-strength gear regulations in one of two buoy lines in this fishery and in each buoy line for its other trap fisheries (NOAA, 2023a). In Canada, for shallow water fisheries (< 36 m) subject to closure, once a right whale is detected, fishers can continue to fish but only if they remove one of the two buoy lines of each trawl with the remaining one requiring a weak link (DFO, 2025).

Secondly, in addition to weakened buoy line configurations, on-demand (ropeless) fishing systems are designed to prevent entanglements (Myers *et al.*, 2019; DFO, 2020, 2021; Cooper & Shester, 2021; Daniel, 2022; Hutchings, 2022; Matzen *et al.*, 2025). These systems have been supported by DFO and NOAA under experimental fishing licences as a method to remove buoy lines of trap gear from the water column yet retain fishing capacity. Unlike traditional gear, where buoy lines remain suspended in the water throughout the fishing season, these systems store the buoy line and flotation mechanism on the seafloor and release them only when needed, either via an acoustic signal or a timed-release mechanism. When deploying on-demand gear in a trawl configuration (bottom traps connected by a series of groundlines), the elevation of positively buoyant groundlines between traps acts as a source of entanglement risk which also needs to be addressed (Brillant & Trippel, 2010; Knowlton *et al.*, 2012; Segre *et al.*, 2022; Calderan *et al.*, 2024). The use of trawls in conjunction with on-demand gear rather than the traditional 'one pot, one line' configuration is due to the significant financial cost associated with the underwater portion of an on-demand gear system.

Not all mitigation measures are suitable for broad application across fisheries in eastern Canada. Detailed characterisation of fisheries involved in whale entanglements is needed to inform effective management decisions. For example, in the U.S. Northeast lobster fishery, implementation of weak ropes with a breaking strength of < 7.56 kN is projected to reduce life-threatening entanglements of large whales by at least 72% while maintaining functionality in fishing operations (Knowlton *et al.*, 2016). Regarding on-demand fishing systems, sea trials in various fisheries have demonstrated varying degrees of success. Early trials in the U.S. lobster fishery indicated that fishers found these systems operationally feasible but raised concerns about costs and retrieval efficiency (Myers *et al.*, 2019; NOAA, 2023b). In the snow crab fishery, experimental trials of on-demand gear have shown they can be a viable alternative in closed areas, allowing fishers to continue fishing while reducing entanglement risk (DFO, 2024). However, logistical challenges remain, such as ensuring reliable acoustic signal transmission, cost barriers, enforcement of regulations, and fishery-wide coordination to avoid gear conflicts (CLF, 2023; NOAA, 2023b, 2024; Matzen *et al.*, 2025).

The present study required the collaboration of industry engineers, researchers and fishers belonging to both the Association des Crabiers Acadiens (ACA) and the Association des Pêcheurs Professionnels Crabiers Acadiens (APPCA) to explore fishery practices that could mitigate the severity of large whale entanglements or prevent their occurrence in gear set by the sGSL snow crab fishery. In the first phase, we met with fishers from the ACA and APPCA who gave us access to vessels and voluntarily answered a questionnaire to characterise practices of conventional snow crab fishing with single traps.

Based on these survey results, we investigated practical ways to fish using low breaking-strength buoy lines that are more likely to enable a whale to break free in the event of an entanglement. This was done by first measuring buoy line tensions during experimental and commercial hauling of snow crab gear. Subsequently, we evaluated methods to reduce hauling tensions to < 7.56 kN using hydraulic tension limiters. A variety of weakened buoy line configurations were tested in sea trials with the tensile strength of ropes evaluated after being used to lift traps. To eliminate the presence of the buoy line from the water column and thereby reduce the risk of entanglement, we evaluated the functionality of on-demand fishing methods when hauling trawls of snow crab traps during the commercial season. When fishing trawls, the ropes connecting traps at the bottom of the ocean can present an entanglement risk as floating arcs are created when fitted with positively buoyant rope. We assessed arc heights of model groundlines composed of different proportions of positively and negatively buoyant rope, and different proportions of excess length at different current speeds. Finally, we considered how this information can be incorporated in fishing gear and practices that allow for the coexistence of snow crab harvesting and right whales in the sGSL.

## MATERIALS & METHODS

### 2.1 Snow crab fishing operation and tension of buoy lines

#### 2.1.1 Collecting fishers' knowledge to characterise the snow crab fishing operation

A questionnaire was developed in collaboration with two mid-shore snow crab associations from New Brunswick, the ACA and APPCA. This questionnaire was designed to obtain qualitative data on existing fishers' practices in crab fishing area (CFA) 12 and identify potential constraints for using new technologies. The questionnaire was divided into four sections: (1) buoy line characteristics; (2) buoy line usage; (3) fishing equipment; and (4) fishing operation. Surveys were carried out by ACA and APPCA staff and conducted by five prominent fishers. These (non-random) surveys took place in May 2018 and included 25 voluntary respondents from the ACA ( $n = 20$ ) and APPCA ( $n = 5$ ), representing around one-third of the current members of these two associations and 5% of the active sGSL vessels fishing in 2018. We used this information to design experiments to measure tensions in buoy lines when hauling gear and select which weak rope/link configurations and on-demand fishing gear would be most suited to explore in sea trials.

#### 2.1.2 Tension profiles of buoy lines while hauling actual snow crab filled traps and a simulated trap

In order to establish whether the current fishing operation was generating rope tensions higher than the 7.56 kN threshold, hauling tests were performed using various vessels under various conditions. A test pot of constant weight, referred to as the simulated loaded trap (SLT), was designed to mimic a heavily loaded trap. To evaluate how well the hydrodynamic drag of the SLT represented a near-full crab trap, tension profiles of buoy lines were first examined on 26 June 2019 while hauling a 79 kg conical trap (diameter 2.1 m) filled with 200 kg of snow crab and the SLT of similar total weight. The weight of the test trap was within the range of near-full traps. To prepare the crab-loaded test trap, 12 other traps were fished on 24 June 2019. On 26 June (the trial date), we combined the catches of snow crab above legal size ( $> 95$  mm carapace width) into the test trap, until reaching 279 kg, close to the average maximum catch reported by fishers in our survey (272 kg), which includes the weight of snow crab and trap. The trap top opening was covered with mesh to avoid losses (Fig. 2a).

To obtain tension profiles, we used 137 m buoy lines (46 m of sinking and 91 m of positively buoyant 19 mm diameter rope) at a fishing depth of 73 m. Once all the slack rope had been hauled into the boat and the trap lifted off the seabed, we measured three tension profiles with the crab loaded trap at full hauler speed (60 s/haul or 1.2 m/s), which is commonly used during fishing operations. We also measured three tension profiles with the SLT. The SLT (Fig. 2b) consisted of a crab trap steel frame without mesh and equipped with a 19 mm thick plywood bottom (to simulate the drag of a loaded trap during hauling), a 25 kg concrete block as fixed weight (to simulate the difference of specific weight between crabs and water) and six bottles each containing 18 L of water (to simulate the inertia created by crabs filling the pot). To measure tension, we equipped the chartered fishing vessel with a Dillon EDXtreme dynamometer (Weigh-Tronix, Fairmont, MN, U.S.) inserted between the davit and the hanging block redirect pulley (48 kg weight) using shackles (Fig. 2c). The dynamometer continually

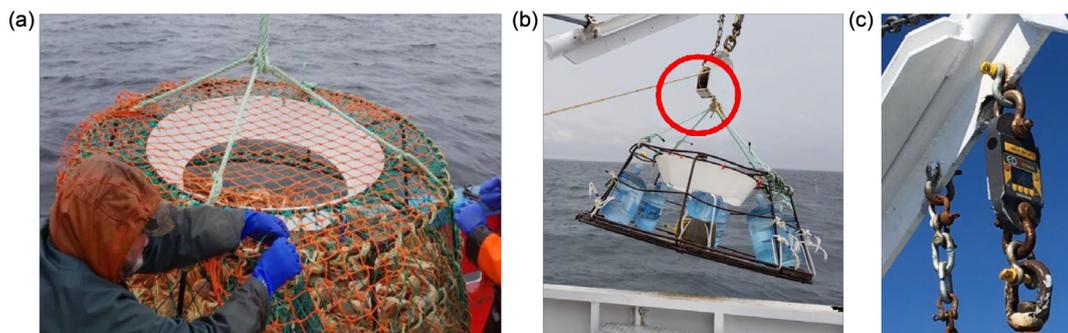


Figure 2. Equipment used to register the tension profiles of buoy lines while hauling: (A) a test trap filled with snow crab; (B) a simulated loaded trap (SLT) showing where the rope forms an angle with a red circle; (C) a Dillon load cell above the hauler.

recorded the weight of the pulley, plus the force exerted by the buoy line at a predefined frequency. From this, we derived the tension in the rope by considering the subtended angle between two rope segments – see details in Supplementary Material (SM) 1. Tension readings obtained from the trap filled with snow crab and the SLT were compared using Student's t-tests on the maximum, median and mean tension values for each hauling event using the function '*t.test*' implemented in R (v4.1.2; R Core Team, 2021).

### ***2.1.3 Effects of hauler speed on hauling time and maximum tension of buoy lines***

We performed a sea trial on 18 June 2019 to obtain tension profiles of buoy lines while hauling the SLT with the hauler wheel set across a range of speeds. We used the same configuration as for the tension profiles at a fishing depth of 77 m with a muddy seabed to set and haul the SLT. The hauler sheave (inside diameter 19 cm; outside diameter 38 cm) speed was set to generate four hauling velocities: 0.42, 0.71, 0.96 and 1 m/s, and for each speed, the SLT was lifted three times. A tachometer (TATUM TKS02441, Japan) was used to measure the rotational speed (revolutions per minute or RPM) of the hauler. The digital tachometer used a fixed point on the wheel, in this case a piece of reflector tape fastened to the face of the hauler, as a reference point. Using the wheel diameter, the rotational speed was then converted into linear speed. Differences in hauling time and maximum tension at different hauling speeds were determined using linear models using the '*lm*' function implemented in R (R Core Team, 2021).

### ***2.1.4 Tension of hauled buoy lines in the 2022 snow crab season***

We documented directional forces and tension profiles of conventional buoy lines where the top section comprised sinking rope and the lower section positively buoyant rope (1:2 ratio) during approximately 150 hauling events of single snow crab traps in areas open to buoyed line fishing during the 2022 season. A shackle-dynamometer prototype developed by CORBO Engineering was used to measure the rope tension on fishing vessels. This dynamometer recorded force measurements with a timestamp. All files produced by the data loggers were compiled using R (R Core Team, 2021). Readings from the dynamometer above the bidirectional redirect pulley were converted to kN. Rope tension was calculated using a subtended angle of 97°, maintaining consistency with previous angular vector force results. From the compiled tension readings, we extracted the hauling events and excluded the tension data recorded once the trap was out of the water. Details are provided in SM1 and SM2.

## **2.2 Efficacy of low breaking-strength gear and hydraulic tension limiter**

### ***2.2.1 Effect of hydraulic pressure regulator on maintaining low tension during hauling***

We performed three sea trials to test an automatic pressure regulator that acts as a tension limiter while hauling the SLT on 13 and 15 July 2019 and 12 August 2019. The Hydraulic Pressure Regulation System (HPR; Solutions Plus APDG Ltd., Shippagan, NB, Canada) is custom-made equipment that modulates the speed at which the traps are hauled to the surface, thereby controlling the tension on the buoy line during hauling (Fig. 3). The HPR pressure relief valve was manually adjusted to limit pressure when there is a rope tension of 5.78, 6.67 or 7.56 kN (1,300, 1,500 and 1,700 lbf, respectively). When the tension of the buoy line is exceeded, the HPR's pressure relief valve starts bypassing the hydraulic oil to the return. The higher the pressure, the more the pressure relief valve will open to send the oil back, which means less oil will go to the hauler, slowing it down. If the hydraulic pressure rises enough, the pressure relief valve will open completely so that the hauler stops turning. During the adjustment of the pressure relief valve, the buoy line was securely attached to the gunwale of the vessel. The pressure relief valve was then carefully adjusted to the desired tension setpoint by monitoring the inline dynamometer reading. During the operation, we used the same SLT and rope configuration described in Section 2.1.2 to deploy and retrieve the SLT at a fishing depth of 73 m with a muddy seabed. The tension profiles were recorded using the Dillon dynamometer.

### ***2.2.3 Evaluation of low breaking-strength gear***

We performed sea trials to test low breaking-strength sinking rope, made of polyethylene with a specific gravity (SG) of 1.3 (the SG of seawater is 1.03) provided by beaded lead in its core (Tufropes Pvt Ltd., India). The low breaking-strength rope used was 16 mm in diameter with a breaking strength between 8.23–9.56 kN (1,850–

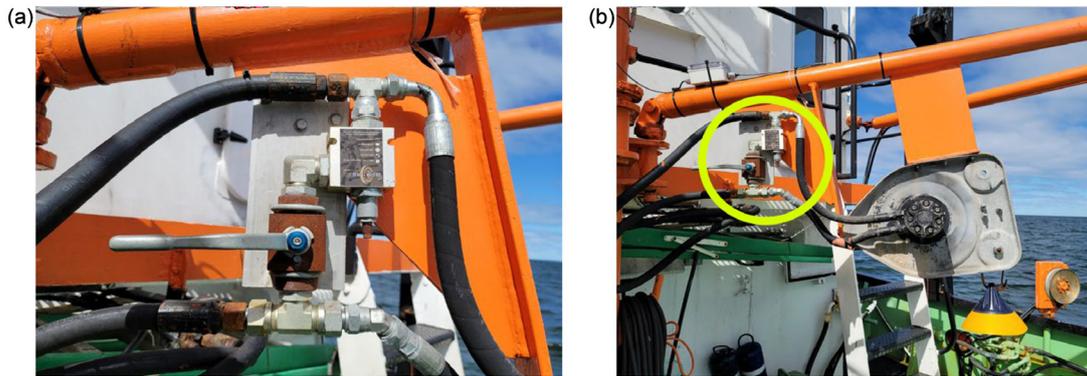


Figure 3. (A) Hydraulic pressure regulator; (B) the hydraulic pressure regulator connected to the hauler wheel on the vessel.

2,150 lbf) prior to use (R. Martin, NOAA, Woods Hole, MA, pers. comm.). Tufropes was unable to achieve a lower breaking strength product prior to the test period, though it is almost five times lower than conventional 16 mm snow crab buoy lines (> 44 kN; 9,890 lbf). The decision to use low breaking-strength ropes of large diameter was influenced by operational considerations. Fishing vessels are equipped with hydraulic hauling systems calibrated for specific rope diameters and using ropes with smaller diameters could result in slippage between the hauler plates, compromising efficiency and safety. Besides weak rope, another method to reduce the breaking strength of buoy line configurations is the use of breakaway (weak) links, such as the Novabraid sleeve (SSL 2.0, Novatec Braids Ltd., NS, Canada) that can be fitted in a regular buoy line and has a breaking strength of < 7.56 kN. We also evaluated the CoastLine Cordage Break-Away Release Link (CoastLine Cordage Group, NS, Canada), consisting of a 1.8 m braided rope (11 mm diameter) that includes a stitched eye splice at each end (3.8 cm eyelet diameter) that tears apart under tensions > 7.56 kN.

During the snow crab fishing season of 2022, four different configurations of weakened buoy lines were used to test the functioning of low breaking-strength rope and links while hauling traps (Fig. 4):

1. Tufropes 16 mm low breaking-strength rope only, comprised of 46 m of sinking rope and 91 m of positively buoyant rope. The sinking rope section was attached to the main buoy and the floating section connected to the bridle of the trap (Fig. 4a).
2. A buoy line where we spliced 46 m of low breaking-strength Tufropes sinking rope (16 mm) attached to the main buoy with 91 m of positively buoyant rope (Polysteel 16 mm; SG = 0.91–0.94) for the bottom portion (ratio 1:2).
3. A neutrally buoyant buoy line (137 m HydroPro-Polysteel 16 mm; SG = 1.04–1.05; neutrally buoyant refers to the addition of polyester as opposed to the addition of beaded lead filaments in sinking rope)

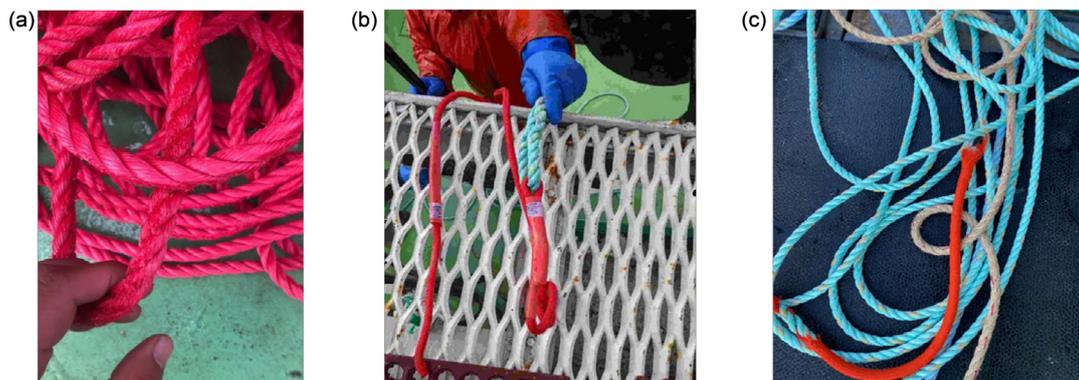


Figure 4. Buoy line configurations tested: (A) full-length and top 1/3 of buoy line consisting of Tufropes weak rope; (B) conventional buoy line with three CoastLine Cordage Break-Away Link inserts; (C) conventional buoy line with three Novabraid sleeves.

with three inserts of 1.8 m of CoastLine Cordage BreakAway Release links, placed at 33%, 50% and 75% from the surface buoy (Fig. 4b).

4. A neutrally buoyant buoy line (137 m HydroPro-Polysteel) with three inserts of Novabraid sleeves (16 mm) placed at 33, 50 and 75% from the surface buoy and secured with safety loops to prevent gear loss (Fig. 4c).

In all trials, the traps were secured with a safety buoy line in case of failures during the hauling stage. The safety buoy line was fastened at the main buoy and at the bridle of the trap. The traps lifted using these gear configurations were conventional 2.1 m diameter single traps, weighing around 146 kg (79 kg trap frame containing an average catch of 67 kg). The tension of the buoy line was kept under 7.56 kN using the HPR.

To assess the impact of wear and tear on the breaking strength of buoy lines, samples of positively buoyant and sinking weak ropes were collected throughout the fishing season. Rope samples were removed at the intersection of the positively buoyant/sinking ropes where the Tufropes section of the buoy line experienced most tension. These rope sections had a length ranging from 1.7 to 2.1 m and were removed after being used to haul single snow crab traps one, five and six times. Before being tested, the ropes were soaked in fresh water at 15 to 25°C for a period of 22 to 26 hours to remove any salt crystals from dried sea water that could act as abrasive particles and make the rope weaker out of the water than when used for fishing. A hydraulic, horizontal, tensile strength testing machine (Wire Rope Industries Ltd., Canada) was used to measure the breaking force of ropes, recorded with a load measuring mechanism, during elongation at 0.5 s intervals. Differences between the breaking force of ropes used one, five and six times were determined using linear models separately for positively buoyant and sinking ropes, using the 'lm' function, implemented in R (R Core Team, 2021).

## 2.3 On-demand harvesting of snow crab using trawls of traps

### 2.3.1 On-demand fishing during the 2022 snow crab season

In 2022, in areas closed to gear using buoy lines with surface buoys, fishers used on-demand fishing gear to catch snow crabs for commercial sale under experimental licenses. Before the trials started, 19 vessel captains were individually trained by CORBO's team to use the 5112 EdgeTech on-demand fishing system. Training comprised in-house gear component descriptions, dockside demonstration of operability and instructions for at-sea data collection. Prior to the fishing season, one-to-one meetings were held with each fisher and their crew as well as group meetings with all participants. This enabled the sharing of experiences between fishers and personalised training for participants with specific questions or concerns. Real-time technical support was also available for all fishers throughout the season, comprising an essential tool to address the steep learning curve associated with high-tech systems. As an incentive for their participation, captains were granted permission by DFO to use 55 snow crab traps in closed areas for scientific trials in addition to their regular 150 traps under their commercial license. They also received partial funding for the purchase of up to five on-demand systems.

The EdgeTech fishing system consists of a release cage holding an acoustic release and a coiled buoy line. Hard plastic buoys, which do not collapse under pressure, are attached to the top of the release cage and to the buoy line inside. In the vessel, there is a deck box which communicates with the on-demand unit on the seabed via a transducer. This system uses a GPS-based gear marking application called Trap Tracker that displays the cage location in a chart plotter and a release code. Using the application, it is possible to 'trigger' the detachment of the cage's top cover that will float to the surface to be hauled. To do so, the application communicates the release information with the deck box in the vessel, which then communicates via a transducer with the acoustic release cage on the seabed (Fig. 5). Fishers have to be within a five nautical mile (9.26 km) radius of their trawl to view it on the system. Trawl locations can only be viewed in the mobile application chart plotter by the trawl's owner.

The tests of on-demand fishing gear in CFA 12 began on 11 May 2022 when the first closure occurred due to right whale detection. A total of 78 fishing trips were made in this closed area with 10–21 trap trawls and on-demand fishing gear, ranging between two to eight trips per fisher. For the sea trials, cameras were installed on each vessel to document the process, and fishers filled out data sheets that recorded parameters, such as

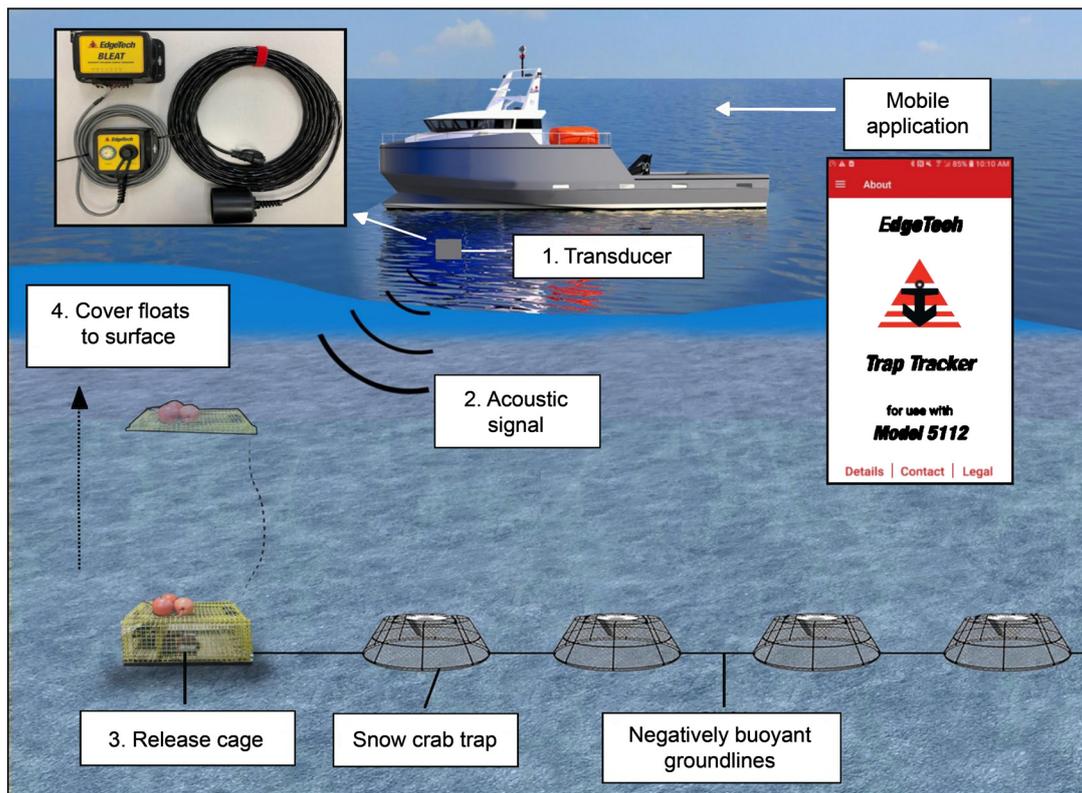


Figure 5. Unscaled illustration of the on-demand fishing system used in this study. Using a mobile application, it is possible to trigger the transducer on deck to send an acoustic signal to the transducer on the release cage that will release the cage cover and permit the hard plastic buoys and buoy line to float to the surface for hauling and retrieval of the trawl.

weather conditions, crab catch per trawl, number of traps per trawl and gear deficiencies. During several sea trips, we accompanied vessel crews to provide support and observe the process of using on-demand gear.

From the videos recorded on the selected vessels' decks, we determined the timing and sequence of steps involved in fishing snow crab. Video footage from three vessels was used to describe snow crab fishing using conventional gear. One vessel provided two videos, so there were four videos in total. For on-demand gear, we analysed videos from two vessels (three videos per vessel), plus a video recorded by onboard technicians. All the videos were recorded between 12 May and 30 June 2022.

### 2.3.3 Estimating arc height of model groundlines in trawls

To explore the existing compromise between using groundlines between traps made of positively buoyant rope (more available and less expensive) and sinking ropes that are safer for whales, we used scaled-down models to quantify and compare groundline profiles of different proportions of sinking and positively buoyant ropes, current speed and percentage proportion of excess length (the length of rope divided by the distance between two anchors), referred to as 'slack percentage'. On 30 July 2019, we tested seven different groundline model configurations (15 m total length) comprising different proportions of positively buoyant and sinking rope, using a pre-determined length of each type of rope within each configuration. The tests were conducted in flume tank trials at the Marine Institute, Memorial University, St. John's, Newfoundland (Table S1 in SM3). The flume tank is 4 m deep and 22 m long and includes a viewing gallery on one side, where it was possible to observe the behaviour of our scaled-down fishing gear. The viewing gallery also incorporates a video camera-based measuring system with a camera mounted on linear rails capable of moving along horizontal and vertical axes, and a video monitor displaying crosshairs superimposed on the object being measured.

We used Proflex rope with a SG of 0.9 for the positively buoyant ropes and Delphinline lead with SG of 1.46 for the sinking rope, both with a diameter of 19 mm. The positively buoyant end was attached upstream to a

1:10 snow crab model with the proper height and the sinking end of the groundline to a downstream anchor. The groundline was oriented parallel to the water flow. The shape (curvature) of the positively buoyant section of the groundline models was measured using computer aided design software Autocad (Autodesk Corporation, San Francisco, CA, USA). The height of the arc between anchors was measured in reference to the flume tank floor as a function of slack percentage in the groundline (5, 12, 20, 28%; 75, 150, 300 and 420 cm, respectively), which relates to the distance between two anchors and total length of the rope (15 m) and current speed (scaled-up values between 0.1 and 0.77 m/s). Before the flume tank trials, ropes were submerged in water overnight to saturate them and drive out trapped air. From the viewing gallery, we filmed groundline profiles and used the camera-based measuring system to extract a minimum of 15 points (nodes) from various visible markers located on the ropes. All trials performed with groundline models were carried out between 30 July and 2 August 2019. The height of the arc of the positively buoyant section of the rope at full scale was estimated by multiplying the model results by a factor of 10.

## RESULTS

### 3.1 Snow crab fishing operation and tension of buoy lines

#### 3.1.1 Collecting fishers' knowledge to characterise the snow crab fishing operation

Responses provided by 25 snow crab fishers from ACA and APPCA were used to summarise buoy line characteristics (Table S2 in SM4). It was found that the most commonly used length of sinking rope is 46 m attached to the surface buoy followed by 91 m of positively buoyant rope to the trap bridle (1:2 ratio, in 50% of cases). For both types of ropes, the most common diameters were 19 and 16 mm. While some fishers used their ropes for up to 10 years, they mostly replaced them after four years. The maximum weight of a trap with catch among vessels ranged between 227 and 362 kg, while each fisher hauled between 1,500 and 2,100 times during the 2016 season. Most vessels in these two associations had a total length between 14.6 and 19.5 m. Seventy-nine percent of them were equipped with a conventional hydraulic hauler, while the remaining 21% had load sensing haulers enabling the user to fix the tension limit in the hauling line. The surveyed group consisted of fishers holding a captain license between four and 45 years, but most of them had captain experience of 22 to 32 years. Most fishers performed between 11 and 13 fishing trips during that year. During those sea trips, the most common seabed types fished were mud, sand and/or gravel. The minimum depth at which they fished ranged between 46 and 76 m, while the maximum depth was between 80 and 106 m.

#### 3.1.2 Tension profiles of buoy lines while hauling an actual snow crab filled trap and a simulated trap

We recorded tension data of buoy lines while hauling a trap loaded with 279 kg of snow crab and a SLT (272 kg) with a commonly used hauling speed of about 1.2 m/s (Fig. 6). We found no significant difference between tension readings from the actual loaded trap and the SLT when comparing maximum tension ( $t_{[2,56]} = -1.06$ ;  $P = 0.38$ ), median ( $t_{[2,56]} = -2.12$ ;  $P = 0.14$ ) and mean values ( $t_{[2]} = -2$ ;  $P = 0.18$ ) from tension measurements for

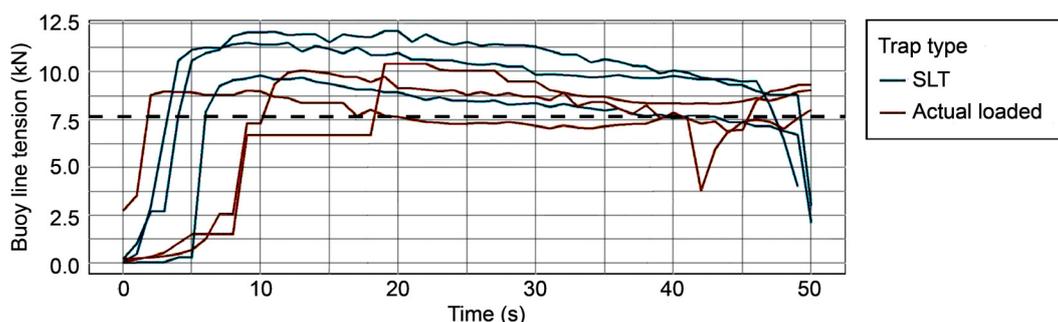


Figure 6. Tension profiles (kN) of buoy lines measured during the hauling of an actual trap loaded with 279 kg of snow crab (red line), and the simulated loaded trap (SLT, blue line) weighing 272 kg. Horizontal dashed line indicated the 7.56 kN threshold.

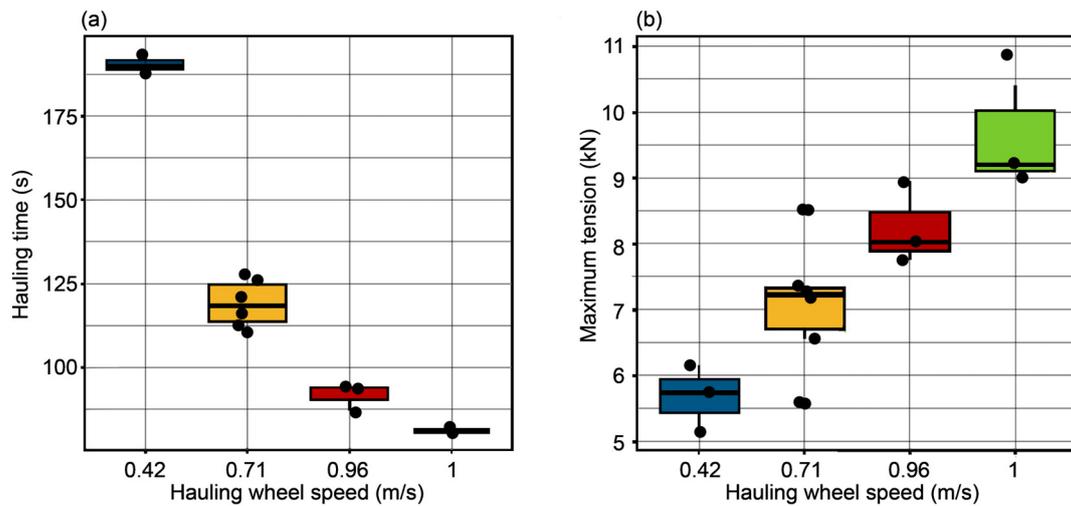


Figure 7. Boxplots for (A) hauling time and (B) maximum tension at four hauling speeds (m/s).

each hauling event. When averaging all readings for each trap type, the mean ( $\pm$  sd) buoy line tension was 8.94 kN ( $\pm$ 3.02) of the SLT and 7.32 kN ( $\pm$ 2.67) for the actual loaded trap. During all trap hauling events except one, the tensions reached higher than 7.56 kN. Given the similar profiles, the artificially weighted trap was used to analyse the effects of hauling speed on buoy line tension dynamics.

### 3.1.3 Effect of hauler speed on hauling time and maximum tension of buoy lines

We found that the hauler speed of the SLT had a negative relationship with hauling time ( $F_{[3,11]} = 260.49$ ;  $P < 0.001$ ) and a positive relationship with maximum tension of buoy lines ( $F_{[3,11]} = 12.34$ ;  $P < 0.001$ ) (Fig. 7). Time to haul the SLT decreased from  $190 \pm 2.5$  s when hauling at a speed of 0.42 m/s to  $81.3 \pm 0.58$  s at 1 m/s. By contrast, maximum tension of buoy lines increased from a mean value of  $5.68 \pm 0.51$  to  $9.69 \pm 1.02$  kN when traps were hauled at 0.42 and 1 m/s, respectively. By maintaining hauler speed under 0.71 m/s, it was possible to reduce buoy line tension below 7.56 kN when the total weight of the lifted trap and its catch did not exceed 272 kg.

### 3.1.4 Tension of hauled buoy lines in the 2022 snow crab season

Tension profiles of 5,075 trap hauling events were recorded using conventional buoy lines aboard nine vessels, with the support of the ACA and APPCA. From the maximum tension registered while hauling (before the trap reached the water surface), 40% of the hauling events reached above 7.56 kN (Fig. 8). Average maximum tension during hauling with conventional buoy lines was  $6.84 \pm 2.12$  kN.

## 3.2 Efficacy of low breaking-strength gear and hydraulic tension limiter

### 3.2.1 Effect of hydraulic pressure regulator on maintaining low tension during hauling

The implementation of the pressure regulator was effective at maintaining a stable tension in the buoy line while hauling the SLT (Fig. 9). It is important to note that, while the first sea trial was conducted under calm weather,

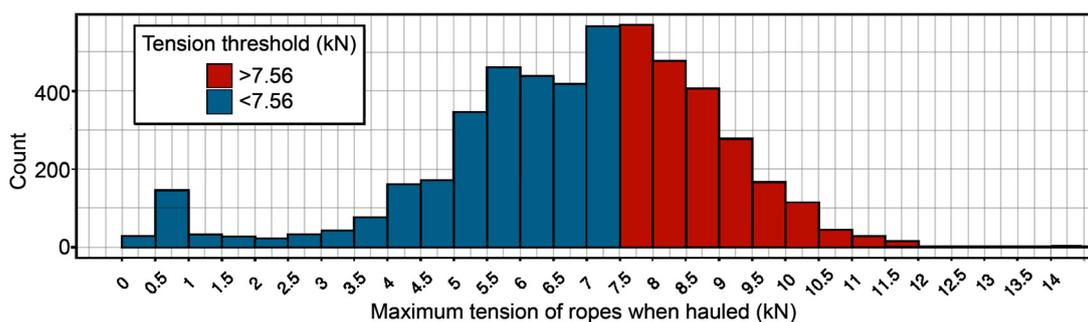


Figure 8. Frequency of maximum tension of buoy lines while being hauled for 5,075 hauling events using conventional buoy lines during the 2022 fishing season.

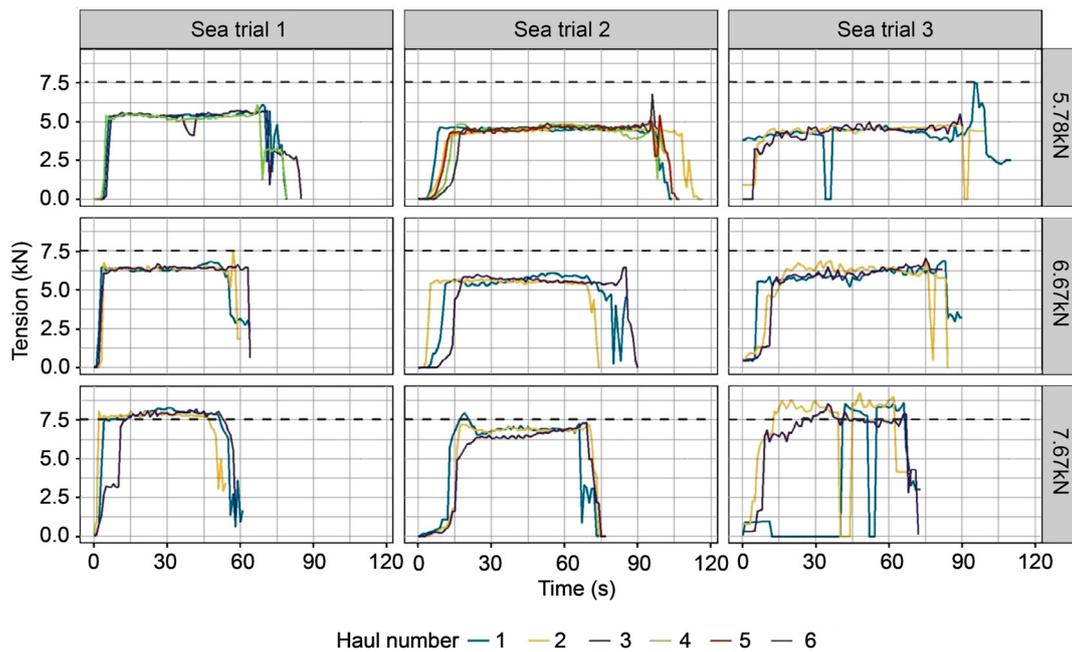


Figure 9. Buoy line tension profiles (kN) when hauling the SLT with a hydraulic pressure regulator set at 5.78, 6.67 and 7.56 kN (equivalent to 1,300, 1,500 and 1,700 lbf) during three sea trials. Horizontal dashed lines indicate the 7.56 kN threshold.

the Beaufort level increased to 3 during the second sea trial and 5 during the third trial, causing abrupt movements of the vessel that coincided with sudden declines in tension while hauling the SLT (Fig. 9). We found that as the regulator setting (tension limit) was increased from 5.78 to 7.56 kN, the average hauling time of 27 lifts decreased from 90 to 60 s.

### 3.2.2 Evaluation of low breaking-strength gear

The results from the fitted linear model showed that the greater number of times a buoy line (weak rope, Tufropes diameter 16 mm) was used to lift a trap, the lower the tension needed to part it (Fig. 10), for positively buoyant ( $F_{[2,12]} = 4.85$ ;  $P = 0.03$ ) and sinking ropes ( $F_{[2,18]} = 9.29$ ;  $P = 0.001$ ). For the positively buoyant weak ropes, the breaking strength decreased from  $9.8 \pm 0.83$  kN after lifting a trap once to  $8.35 \pm 0.89$  kN when used to lift traps six times (14.7% decrease). For sinking ropes, it decreased from  $10.1 \pm 0.67$  kN after lifting a trap once to  $8.27 \pm 1.38$  kN when used to lift traps six times (18.1% decrease).

During the sea trials conducted to test different low breaking-strength modifications, we found that the buoy line parted while lifting a trap only when it was fitted with Novabraid sleeves (Table 1). For this weak link, we

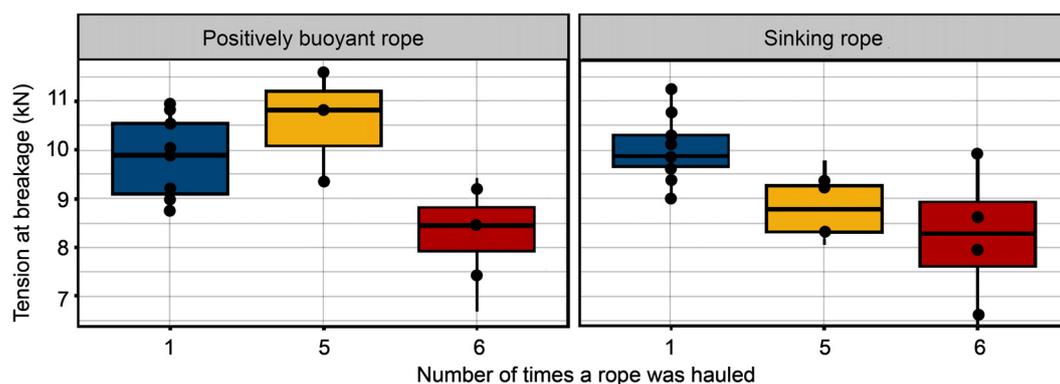


Figure 10. Boxplot indicating the relationship between the tension at breakage (kN) of Tufropes positively buoyant and sinking ropes after lifting snow crab traps on one, five and six occasions.

Table 1

Summary of the low breaking-strength modifications implemented in buoy lines and associated breaks during sea trials performed in 2022 in CFA 12. Buoy line sections that were not weakened consisted of conventional neutrally buoyant rope (HydroPro-Polysteel 16 mm breaking strength 49 kN).

Date	Weak rope/link	Position of weak rope/link (% distance from the buoy)	Coordinates	Fishing depth (m)	Gear break
08 May	Tufropes	Full length	47°32'N, 62°31'W	71	No
10 May	Tufropes	Full length	47°32'N, 62°31'W	73	No
15 May	Tufropes	Full length	47°32'N, 62°31'W	73	No
16 May	Tufropes	Full length	47°32'N, 62°31'W	73	No
26 May	Tufropes	Full length	47°32'N, 62°31'W	73	No
30 May	Tufropes	Full length	47°32'N, 62°31'W	73	No
04 June	Tufropes	Full length	47°32'N, 62°31'W	73	No
08 May	Tufropes	Top third	47°33'N, 62°31'W	73	No
10 May	Tufropes	Top third	47°33'N, 62°31'W	73	No
15 May	Tufropes	Top third	47°33'N, 62°31'W	73	No
16 May	Tufropes	Top third	47°33'N, 62°31'W	73	No
26 May	Tufropes	Top third	47°33'N, 62°31'W	73	No
30 May	Tufropes	Top third	47°33'N, 62°31'W	73	No
04 June	Tufropes	Top third	47°33'N, 62°31'W	73	No
08 May	CoastLine Break-Away Links	33, 50 and 75	47°33'N, 62°31'W	71	No
10 May	CoastLine Break-Away Links	33, 50 and 75	47°33'N, 62°31'W	73	No
15 May	CoastLine Break-Away Links	33, 50 and 75	47°33'N, 62°31'W	73	No
16 May	CoastLine Break-Away Links	33, 50 and 75	47°33'N, 62°31'W	73	No
26 May	CoastLine Break-Away Links	33, 50 and 75	47°33'N, 62°31'W	73	No
30 May	CoastLine Break-Away Links	33, 50 and 75	47°33'N, 62°31'W	73	No
04 June	CoastLine Break-Away Links	33, 50 and 75	47°33'N, 62°31'W	73	No
08 May	Novabraid Sleeves	33, 50 and 75	47°33'N, 62°31'W	73	Yes (33%)
10 May	Novabraid Sleeves	33, 50 and 75	47°33'N, 62°31'W	73	Yes (50%)
18 May	Tufropes	Full length	47°08'N, 62°48'W	64	No
18 May	Tufropes	Top third	47°08'N, 62°48'W	64	No
18 May	CoastLine Break-Away Links	33, 50 and 75	47°08'N, 62°48'W	64	No
18 May	Novabraid Sleeves	33, 50 and 75	47°08'N, 62°47'W	64	Yes (50 and 75%)

observed that the 16 mm diameter buoy line parted at the sleeves fitted at 68 m from the surface in the first haul during the first trial (8 May 2022); at 68 m in the first haul and at 102 m in the second haul during the second trial (10 May 2022); and at 68 and 102 m in the first haul during the third trial (18 May 2022).

### 3.3 On-demand harvesting of snow crab using trawls of traps

#### 3.3.1 On-demand fishing during the 2022 snow crab season

With the collaboration of 19 fishers, 300 trawls were hauled with a total harvest of 203 tonnes of snow crab using on-demand fishing gear in areas closed due to the detection of right whales in snow crab fishing area (CFA) 12. Trawls ranged in size from 10 to 22 traps with 88% having 10 or 11 traps. Trawls were set at mean depth  $74 \pm 5.5$  m – 96% of traps were set in good conditions (Beaufort 0–1). There was a slight deterioration in weather conditions at the time of hauling (93% were hauled at Beaufort 0–1). Trawls were set in seabeds composed mainly of mud (65.7%), followed by gravel (22.3%) and sand (12%). Groundlines were either sinking or neutrally buoyant rope with a diameter of 16 mm (87.7%) and ascending lines were mostly 16 mm positively buoyant (31%) or 16 mm sinking (31.4%), with both types of rope also used in the same buoy line (18%).

The horizontal distance between the on-demand system set on the seabed and the vessel’s location where the gear release was triggered averaged  $170 \pm 280$  m, with values ranging from 4 m to 3,000 m. The successful release of the system after a single triggering attempt in the application was achieved in 64.7% of the sets, whereas more than one attempt was required to lift 15.3% of sets. In 13.3% of cases, when triggering the release, it was indicated that the release was not successful, but the system did still surface. The remaining 6.6% of sets were retrieved by grappling, mainly due to hardware or software problems and tangled ropes (stowed buoy lines were tangled within the rope containment cages). In general, the problems reported by fishers while operating

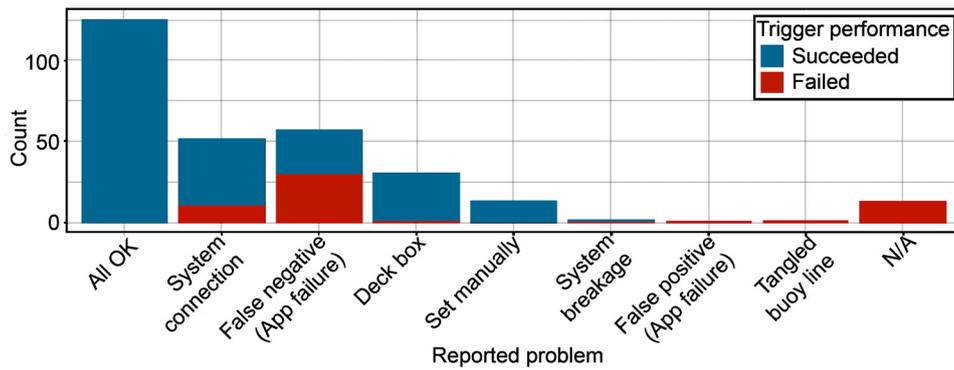


Figure 11. Problems reported by fishers while using on-demand fishing gear in closed areas during the 2022 snow crab fishing season.

on-demand fishing gear (Fig. 11) included: poor system connection preventing proper synchronisation and update of gear location; application failing to correctly indicate gear that did actually deploy (false negative); deck box issues; steps to set the system had to be done manually; system breakage; the application indicated successful recovery deployment but system did not actually deploy (false positive); and packing and movements of ropes causing knots and tangled ropes inside the seabed cage.

During meetings with fishers regarding their use of on-demand gear, we found that fishers’ main concerns related to at-sea internet connection and multiplication of tasks for crew members. We summarised the opinions of the fishers between 2021 and 2023 (Table 2).

Using the conventional method of fishing crab in CFA 12, hauling a single trap took an average of 317 seconds, while the first trap in an on-demand trawl required 456 seconds to haul, and each subsequent trap (second, third, etc.) added another 154 seconds. (Table 3). Once fishers became familiar with the on-demand gear, fishing a 10-trap trawl line took roughly the same amount of time as deploying 10 individual traps in open areas, about 10 minutes to set and 45–50 minutes to haul. When using conventional fishing gear, fishers often set a series of single traps near each other. In this case, the time between lifts of successive single traps averaged 53 seconds, a period in which the trap stand in a vessel is lifted for the next hauling cycle (6 seconds), and the vessel moves to the position of the next trap (47 seconds). According to fishers, the steam time to move to another series of traps can take up to three hours, as their pots are spread out in various sections of the fishing grounds, whether they fish singles or trawls.

Table 2  
Outcome(s) of meetings held with fishers after using on-demand fishing gear in the years 2021 to 2023.

Date	Meeting type	Number of participants	Main outcome
2–11 June 2021	Individual interviews	6	Majority of fishers had issues with the application (lines did not appear on charts, sync/update didn't work) due to poor internet connection. It takes time to get used to fishing with trawls for those not familiar with this technique.
28–29 June 2021	Group meetings	13	Fishers are concerned due to poor internet connection. An adjustment period is needed for fishing with trawls. The majority would prefer to use a computer rather than a tablet.
14 June–24 August 2022	Individual interviews	19	Fishers reported issues with internet connection, the App's GPS accuracy, Bluetooth connection from the tablet to the Deck box. Fishers noted that the time to fish with on-demand gear is similar to traditional fishing gear, but that it has to be used in good weather for safety. Some fishers reported that it helped to catch a significant part of their quota.
14 September 2022	Group meetings	13	Fishers reported that on-demand gear needs improvements and is not reliable enough yet. It's more challenging to fill the trawls with crab. Fishers can't safely use on-demand gear in winds greater than 25 km/h. Also noted the multiplication of tasks for captains.
29–31 July 2023	Individual interviews	6	Fishers plan to upgrade their internet to Starlink (which will improve the performance in the App). They are more comfortable fishing with trawls and the on-demand systems, but they reported that on-demand gear is still not viable for commercial use.

Table 3  
Sequence of activities and their duration when retrieving conventional fishing gear (four videos recorded on three vessels) and on-demand fishing gear (six videos recorded on two vessels).

Conventional (single trap and buoy line)		On-demand (trawls of traps and groundline)	
Activity description	Time (s)	Activity description	Time (s)
1. Catch main buoy and kicker	13	1. Do deployment steps on <i>Trap Tracker</i> application in the tablet	14
2. Lifting main buoy over small pulley and haul the buoy line	8	2. Send signal to on-demand gear	20
3. Lifting buoy line over boom pulley and hauler wheel	8	3. On-demand gear reaching the surface	60–90
4. Hauling the buoy line until trap is on the gunwale	59	4. Catch and lift main buoy over small pulley and haul the buoy line	11
5. Moving trap to above stand and open net to empty trap	23	5. Lifting buoy over boom pulley and hauler wheel	14
6. Lowering empty trap to the stand	2	6. Hauling the rope until on-demand gear is on the gunwale	60
7. Throwing empty trap overboard (buoy line is unrolling)	52	7. Move on-demand gear until it's on the stand	15
8. Sorting crabs by size	88	8. Unhook on-demand gear and position it on the deck	25
9. Emptying and refilling bait bags	11	9. Use small winch on the groundline rope following the on-demand gear	10
10. Lifting the stand for the next hauling cycle	6	10. Place rope slack on boom pulley and winch until trap is out of water	90
11. Move to the next trap position	47	11. Move trap on stand and unhook from mainline	15
		12. Pick crab off netting and open netting to empty net	42
		13. Close netting, move trap to stern and sort crab (simultaneously) while hauling next trap with boom pulley	50
		14. Repeat steps 10 through 13 until last trap on the trawl	–
		15. Move to the next trawl position	–
<b>Total time</b>	<b>317</b>	<b>Total time</b>	<b>456</b>

### 3.3.2 Estimating arc height of model groundlines in trawls

The flume tank trials showed arc height increased at lower current, higher slack percentage and lower proportion of sinking rope (Fig. 12). Increases in current generated forces moved the position of the slack rope downstream, towards the tank floor regardless of slack percentage.

When scaling up the flume tank results to a 150 m groundline (commonly used in on-demand trawls), maximum heights of arcs above the seafloor containing only positively buoyant ropes are predicted to range from 13.7 to 29 m when increasing the slack from 5 to 28%. When increasing the proportion of sinking rope in

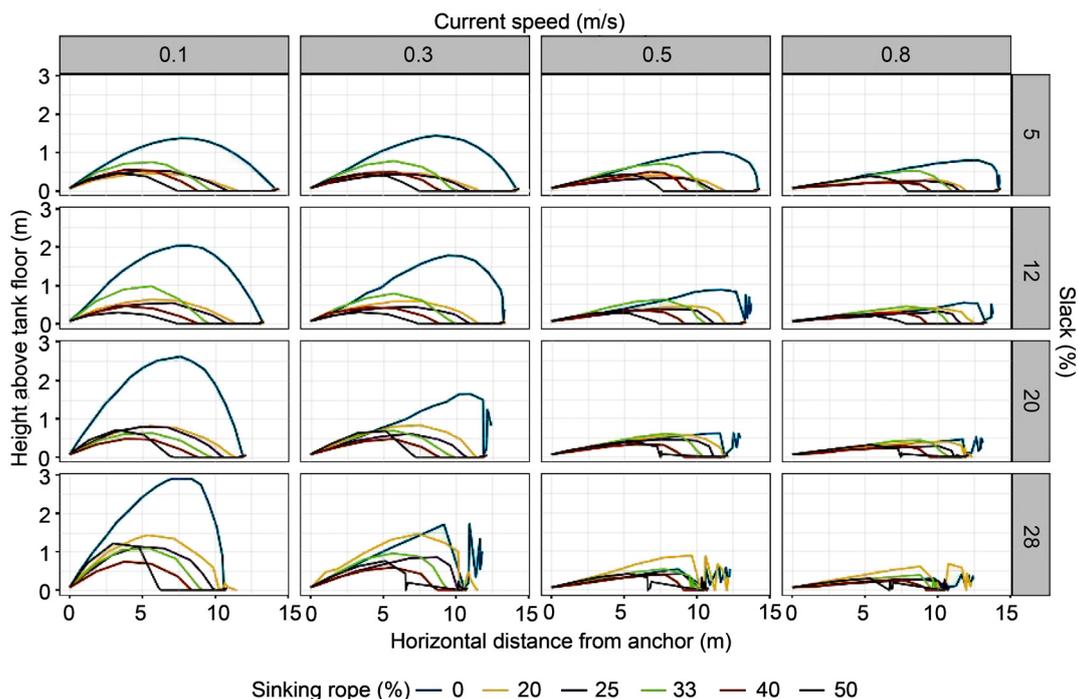


Figure 12. Arc height of a 15 m groundline (1:10 model) above the tank floor under different slack percentage, current speed and proportion of positively buoyant and sinking rope.

Table 4  
Arc height above the tank floor of 15m model groundlines and scaled-up values above the seafloor under a current speed of 0.1m/s, for groundlines containing 0, 33 and 50% sinking rope at one end and using different slack percentages (groundline between traps)

Sinking rope (%)	Slack (%)	Arc height in model groundline (m)	Scaled up arc height of a 150 m groundline (m)
0	5	1.37	13.7
	12	2.04	20.4
	20	2.62	26.2
	28	2.90	29
33	5	0.75	7.5
	12	0.99	9.9
	20	0.65	6.5
	28	1.12	11.2
50	5	0.46	4.6
	12	0.3	3
	20	0.71	7.1
	28	1.22	12.2

the groundline to 50%, scaled-up arc height values reduced from 12.2 to 4.6 m (Table 4). For reference, the scaled-up values for the distance between traps for 5, 12, 20 and 28% slack corresponded to 3.3, 8, 13.3 and 18.6 m, respectively. A few observations were inconsistent with these trends, such as 33% sinking rope and 20% slack (Table 4).

## DISCUSSION

By integrating the practical knowledge of fishers into our research, we were able to test fishing gear that could potentially reduce the risk and severity of large whale entanglements in the snow crab fishery in the sGSL. This approach follows collaborative efforts worldwide, showing that stakeholder engagement is critical for advancing fisheries management by incorporating diverse perspectives and building trust among stakeholders and government agencies (Hendriks, 2022; Murua *et al.*, 2023). Our findings further advance the knowledge base, particularly for fisheries that use buoy lines with breaking strengths > 40 kN (8,992 lbf). In addition to questionnaires, meetings regularly held among fishers, engineers and researchers provided a feedback loop, ensuring that the fishing methods were properly understood and updated in light of real-world experiences.

When comparing tensions of buoy lines while hauling the simulated loaded trap (SLT; 272 kg) and a trap loaded with crab (279 kg), we found that the average line tension for the SLT was higher than that for the actual trap. This moderately higher tension could have resulted, at least in part, from the use of plywood at the bottom of the trap, increasing its hydrodynamic drag. However, we did not find significant differences when comparing the maximum, median and mean tension values between trap types. In this study, the use of the SLT allowed us to isolate and examine a number of factors influencing buoy line tension, such as the relationship between maximum tension, hauling speed and time to haul. Our findings indicated that, by maintaining hauler speed under 0.71 m/s, it was possible to keep buoy line tension under 7.56 kN when the total weight of the lifted trap and its catch did not exceed 272 kg, at least in favourable weather and current conditions. It is important to note that this finding relates to the specific crab pots commonly used by the fishers that participated in this study. Reducing hauling speed also leads to more time needed to retrieve each trap, which, in turn, leads to a longer work schedule, reducing fishing efficiency.

In our study, the average maximum tension of buoy lines, measured until the trap emerged, exceeded 7.56 kN in 40% of hauls during commercial operations. In the deep-water snow crab fishery off Newfoundland, buoy line tensions were measured while hauling trawls of 50 snow crab traps (1.33 m diameter set 33 m apart) with catches averaging 1,024 kg per trawl (Peck *et al.*, 2024). In their study, maximum tension in the buoy line during hauling ranged from 0.116 to 8.99 kN before the first trap came aboard, and for groundlines between traps from 8.22 to 11.8 kN after the first trap came aboard, indicating that the implementation of low breaking-strength buoy lines would not be feasible (Peck *et al.*, 2024). In contrast, the tension values measured here for single traps indicate

that the use of low breaking-strength gear at reduced hauling speeds < 0.71 m/s remains a potential mitigating option for the mid-shore snow crab fleet in the sGSL.

Buoy line tension while hauling fishing gear may be controlled by a tension limiter as the Hydraulic Pressure Regulation System (HPR) showed promising results in maintaining buoy line tension below the critical threshold of 7.56 kN during lifting operations of traps weighing 272 kg. This reduction in tension provided by the HPR lends support to the potential adoption of low breaking-strength links/rope, combined with regular rope at the end of the buoy line (e.g., last 10 m). Although not tested, a strong terminal end would maintain the current tensile strength in this buoy line section, which is subject to increases in load once the trap surfaces and is brought onto the vessel, a period when the line tension tends to increase as the trap is no longer supported by the water. The consistent performance of the HPR suggests it can effectively manage and control buoy line tension, thereby enhancing the safety and sustainability of fishing operations (Mangel *et al.*, 2013; Werner *et al.*, 2015). The HPR is relatively easy to retrofit to existing vessels, albeit at a cost of increased hauling time. For reference, lifting a single trap weighing 272 kg from a 60 m depth at a hauler speed of 1 m/s takes on average 60 seconds, and when limiting the buoy line tension to 7.56 kN, the process takes 74 seconds, adding 35 minutes to the hauling of 150 single traps each with very large catches (200 kg). Note, requiring a quarter more time (74 vs 60 seconds) to retrieve a heavily loaded trap with the HPR does not include the time required to haul the initial slack rope of a buoy line which would not be subject to significant tensions and is retrieved rather quickly). Twenty snow crab harvesters from the ACA and APPCA are currently equipped with this hauler technology; they are reporting satisfactory performance (D. Gionet, Solutions Plus, pers. comm.)

Of the four weakened buoy line configurations tested, namely (1) sinking and positively buoyant weak rope, and three others having neutrally buoyant rope with the addition of either (2) a 1/3 section of sinking weak rope, (3) three CoastLine Break-Away links or (4) three Novabraid sleeves, only the latter configuration was reported to part. In our study, we only tested a single weak rope brand which was developed by Tufropes Pvt Ltd. which had an unused breaking strength of 8.23–9.56 kN. Recently, Polysteel Atlantic Ltd. received NOAA-approval for a newly developed, large diameter weak rope (< 7.56 kN) that is being used in the U.S. offshore lobster fleet in Lobster Management Area 3 (LMA 3) as a substitute for conventional 16 mm rope (Willse *et al.*, 2022; NOAA, 2023b). It is also being piloted by Canadian snow crab and lobster harvesters. The results of our trials using weak rope provided valuable insights into its durability and performance under repeated use, which is related to the environmental impact of the fleets (Deshpande *et al.*, 2023). The low breaking-strength configurations that parted during sea trials were those fitted with a 16 mm diameter Novabraid sleeve, pointing to material-specific and design vulnerabilities. However, a smaller diameter Novabraid sleeve proved to be effective for lighter lobster gear for which it was originally designed (McCarron & Tetreault, 2012; Knowlton *et al.*, 2018). We observed that wear and tear of the tested Tufropes product occurred at a much faster rate than conventional rope when used with existing rope haulers. Wear accumulation has been observed in another weak rope formulation using barium sulphate as a filler (Trippel *et al.*, 2008). We believe this will severely limit the useful lifespan of this particular weak rope. Further trials are recommended to explore the durability of other large diameter, low breaking-strength ropes that are more resistant to stretching, wear and chaffing (NOAA, 2023b). Implementing weak rope to harvest snow crab will likely require a change in hauler technology, from conventional hauler systems to those that incorporate load sensing to accommodate this type of rope. Experimental trials with improved versions of weak rope (and other weak gear modifications) in combination with tension limiters are worth considering for other challenging fisheries, such as the deep-water snow crab fishery off Newfoundland and Labrador and the offshore lobster fisheries in eastern Canada and the northeast U.S. Willse *et al.* (2022) reported buoy line tensions in commercial lobster fisheries attained 13.4 kN in offshore 40-pot trawls in the Gulf of Maine, whereas the present study's maximum tensions were < 12 kN. Also worth consideration is the time tension line cutter which acts to sever the buoy line after a pre-set duration above a specific line tension, enabling fishers to haul conventional rope at regular speeds (Peck, 2024). This whale-release system is under investigation for the snow crab fishery deploying 50–100 trap (diameter 1.33 m) trawls in Newfoundland. Weak gear implementation needs to minimise safety risks to fishers and lost gear (Goodman *et al.*, 2021), highlighting the importance of line tension and innovative gear evaluations prior to setting regulations (Knowlton *et al.*, 2018; Willse *et al.*, 2022; DFO, 2023e; Peck *et al.*, 2024).

Given that the conventional gear configuration for the snow crab fishery in CFA 12 are single traps, it was concerning that the deployment of positively buoyant groundlines connecting traps along the seafloor in on-demand trawls could increase the probability of whale entanglements. Recognising this potential risk, DFO conditions of experimental licenses to commercially fish snow crab using on-demand trawls in the sGSL required the use of neutrally buoyant or sinking groundline (each having SG > 1.03) (DFO Gulf Region Scientific License). Findings from our flume tank assessments were limited to sinking groundlines (beaded lead properties, SG = 1.46). It is recommended that arc heights of neutrally buoyant rope (polyester properties, SG = 1.04–1.05) be similarly evaluated. Presently, snow crab fishers in closed areas are connecting successive traps in on-demand trawls using 150–183 m groundlines made of neutrally buoyant or sinking rope (M. Noel, President, APPCA, pers. comm.). These long groundlines permit fishers to safely bring one trap onboard before lifting the next trap off the seabed, an important practice for these large traps, particularly in high wind and waves. Using depth sensors and/or underwater video to assess groundline arc profiles for ropes having a SG > 1.03 would provide field observations to further understand the risk of whale entanglements in lengthy groundlines used with on-demand snow crab gear. For positively buoyant 22–37 m groundlines used by the lobster fishery in the Bay of Fundy, it was determined that the mean maximum arc height was 3.8 m, when using a ratio of separation between traps to groundline length ranging from 0.72 to 1 (Brillant & Trippel, 2010). In the octopus (*Octopus vulgaris*) fishery in South Africa, the mean arc height of groundlines between traps set 20 m apart was 5.5 m (Daniel, 2022). In the langoustine (*Nephrops norvegicus*) fishery in Scotland, the maximum arc height of positively buoyant groundlines ranged between 0.5 to 7.2 m (averaging 3.7 m), between traps placed 12 m apart and under different tide conditions (Calderan *et al.*, 2024).

On-demand fishing systems have gained considerable interest from government agencies and NGOs as a novel fishing practice to remove buoy lines from the water column to prevent large whale entanglements while also maintaining commercial fishing activities (Moore, 2019; Hutchings, 2022; Matzen *et al.*, 2025). While we recovered 93.7% of the set gear, we only achieved a success rate of 64.7% when trying to trigger the release of the on-demand system from the tablet application once. The tested system showed that, in 13.3% of the ascents, the system could not be recovered in the application, but it surfaced, and in 6.3% of cases, hardware and software problems prevented the use of the application, so that the gear had to be recovered by grappling (no gear loss occurred). For this technology to be widely adopted, the trigger success rate must be significantly improved. However, our tests with on-demand gear were performed at a restricted range of depths, and mainly under good weather. Different results could be achieved with fisheries outside the sGSL at different depths and in weather conditions. Ongoing work, such as by the CanFISH Gear Lending Program (Canadian Wildlife Federation, 2024), which provides detailed feedback to developers on the performance of their systems, will be crucial for refining and increasing their reliability in commercial fisheries. In the U.S. since 2020, a 'lending library' of different on-demand systems from multiple manufacturers has been developed at the Northeast Fisheries Science Centre in Woods Hole, MA (NEFSC, 2022), providing experimental data from over 5,000 hauls by 38 captains using 431 on-demand systems with notable challenges occurring when fishing in deep water or high currents (Matzen *et al.*, 2025). Since 2017, annual meetings of the Ropeless Consortium have also provided an excellent forum for innovators, fishers, NGOs and government agencies to identify constraints and future opportunities to overcome these challenges (Ropeless Consortium, 2024).

The use of on-demand fishing systems in our study came with notable challenges. Fishers' comments highlighted the need for adaptation to this new technology and a requirement for computer literacy. Additionally, transitioning to on-demand fishing means adjusting to trawl fishing methods, which posed a significant learning curve. Fishers could have set single traps using on-demand gear, though it would have been much more expensive to outfit numerous single traps compared with a trawl of traps (Alkire, 2022). From the fishing trips conducted in closed areas using on-demand systems, more than 203 tonnes of snow crab were harvested by the study's 19 fishers in closed areas during 2022. Some fishers noted that, in 2022, the on-demand gear was crucial for meeting their quotas after the fishing grounds were closed due to the detection of right whales. The time required to fish a trawl line of 10 traps was comparable to conventional methods once fishers became comfortable with the gear. However, adapting to trawl fishing was challenging, particularly when locating crab concentrations, as trawls

covered less area than single pots. Moreover, various issues arose with the on-demand system, including hardware problems, wiring issues, rope entanglements, poor system connectivity, low GPS accuracy and human errors. Fishers also found the additional tasks required for trawl fishing cumbersome, and the 35% failure rate when triggering the release of the gear was a source of frustration. We managed these challenges by tracking trawl locations and preventing gear overlay using a master key provided by EdgeTech's database, giving us the underwater units' real-time coordinates that we could then map using a software developed by CORBO. This facilitated coordination and ensured that fishers' trawls were properly uploaded to the database. Overall, as a first experimental large-scale effort, the perspective of fishing with on-demand gear seems promising, with most fishers reporting a positive experience after becoming accustomed to it. The system itself was found to be user-friendly and catch rates in closed zones with on-demand gear were comparable with those in open zones using conventional traps. These findings highlight the pioneering nature of this study, as it integrates innovative technologies with conventional fishing practices to achieve sustainable outcomes. Recognising its value, the Fishery (General) Regulations were amended in June 2023 to permit commercial fishing without surface buoys in order to minimise marine mammal entanglements (DFO, 2023f). The sGSL snow crab fishery has provided an excellent opportunity to test on-demand gear, as the fishery operates in the absence of both co-occurring mobile gear and strong currents which are challenging elements in the integration of on-demand gear in the Bay of Fundy. Mobile fleets can unknowingly drag their gear through untethered on-demand trawls, while strong currents increase the time required for small, hard, plastic buoys to surface. Once there, they can be quickly pulled down again by hydrodynamic drag on the buoy and buoy lines. Inclement weather and high waves also add complexity to deploying on-demand gear in all fisheries.

It is of interest to explore the potential for diving right whales to encounter groundlines in the sGSL. Our modelling results from flume tank trials indicate that, in areas with low current (e.g., low tidal amplitude), arcs above the sea floor could range from 17 to 29 m for a 150 m positively buoyant groundline with 5–28% slack at currents  $\leq 0.30$  m/s. During the 2022 fishing season, current speeds in CFA 12 were mostly  $< 0.15$  m/s (maximum 0.25 m/s) in the 30 m stratum above the sea floor (A. Drozdowski, DFO Science, pers. comm.; Brickman & Drozdowski, 2012). This indicates that if on-demand trawls had been deployed in the area using positively buoyant groundlines at these slow current speeds, persistent arc heights would have posed an entanglement risk to right whales descending to this zone to feed (Chabot *et al.*, 2021). For reference, an average of 77% of daylight and 43% of nighttime dives by right whales approached within 30 m of the seafloor, with the greatest occurrence in 2022 of three years of monitoring (2019, 2022 and 2023; V. Lesage, DFO Science, pers. comm.). Fishers' practices when setting trawls can also influence groundline height as those that are set with the current maintained tautness in the groundline reduce the elevation caused by slack rope between traps landing on the seafloor close to each other (Brillant & Trippel, 2010; Calderan *et al.*, 2024).

The iterative learning process implemented here, facilitated by comprehensive training sessions, enabled fishers to develop a positive attitude towards exploring these new fishing technologies. These sessions served as a platform for mutual exchange, allowing feedback from fishers to refine and improve gear design and functionality, consistent with findings from other studies, where participatory workshops and cooperative research actions have been instrumental in developing sustainable fishing practices (Holm *et al.*, 2020). This collaborative framework has proved to be essential in addressing the complex challenges of mitigating whale entanglements *and* maintaining fishing efficiency (Yochum *et al.*, 2011; Ebel *et al.*, 2018; Holm *et al.*, 2020). The engagement of fishers in the research process not only increased the credibility and acceptance of new technologies but also highlighted the importance of co-management approaches in marine conservation. Moreover, the implications of this study extend beyond the specific context of the sGSL. The lessons learned and the technologies tested here have the potential to benefit other fisheries facing similar conservation challenges. Future research should focus on refining these technologies and exploring their potential applications in different marine environments to enhance the impact on global whale conservation. By fostering collaborative relationships in order to address the practical and environmental challenges identified here, we can make significant progress towards more sustainable and whale-friendly fishing practices.

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## Supplementary Material

### SM1: ESTIMATION OF BUOY LINE TENSION FROM DYNAMOMETER READINGS

The pulley tension readings measured with the Dillon dynamometer placed between the boom and redirect pulley were converted to rope tension in Newtons, using a subtended angle between the two rope segments around the redirect pulley attached to the Dillon dynamometer ( $\theta = 97^\circ$ ) using:

$$Ropetension(N) = \frac{Pulleytension}{2 \times \cos \frac{\theta}{2}}$$

where the value used for  $\theta$  was determined by measuring the variation of this angle during a hauling event in previous sea trials, where we found a subtended average angle of  $97^\circ (\pm 16, n = 292; \text{Fig. S1})$ .

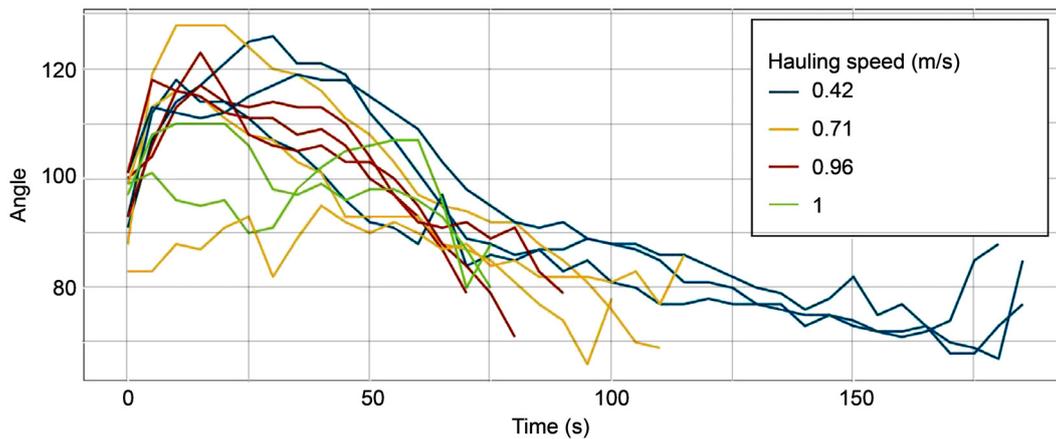


Figure S1. Variation of the subtended angle of the buoy line as it passes through the hauler while retrieving the simulated loaded trap (SLT) at four different hauler speeds.

## SM2: DESCRIPTION OF DYNAMOMETER DEVELOPED TO MEASURE BUOY LINE TENSION DURING THE 2022 FISHING SEASON

A shackle dynamometer prototype developed by CORBO Consulting Engineering was used to measure the buoy line tension on fishing vessels (Fig. S2). This dynamometer has three main components (Fig. S2a):

1. A display unit that recorded a log of unitless force measurements (converted to the required force units during post processing) with a timestamp. The data were recorded on SD memory cards along with parameters such as logging frequency and load cell calibration.
2. A shackle load cell inserted at the end of the boom at the pulley attachment point, between the davit and hanging redirect block pulley (Fig. S2b). The force measured by the load cell on the pulley was the vectorial sum of the load (trap) on the rope and the hauling force (hauler). The force applied on the load cell was converted into an electrical signal with an amplitude proportional to the force applied.
3. The amplifier was installed between the shackle load cell and display unit. The amplifier converted the electrical signal from the load cell into a voltage signal for the display unit.

During the sea trials, the captain or a crew member could monitor the load on the buoy line being hauled by watching the dynamometer display. For convenience, the display could be set to show the load in Newtons, pound-force or kilogram-force units, and the display could be tared to deduct the weight of the pulley from the value shown on the display. These functions had no effect on the data recorded by the dynamometer that were used for analyses. Readings from the shackle dynamometer above the bidirectional redirect pulley were converted to kN, and tension was calculated using a subtended angle of  $97^\circ$  in the buoy line (Fig. S2c), maintaining consistency with previous angular vector force results.

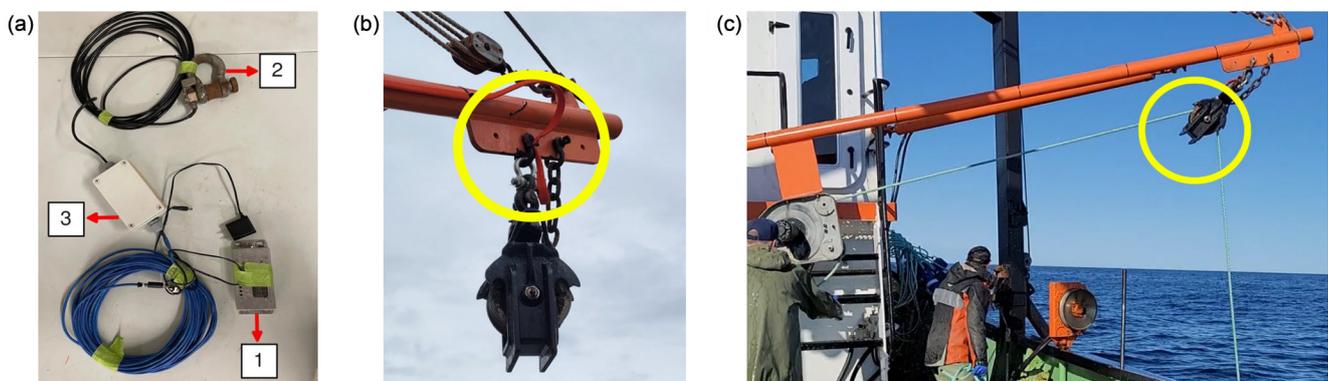


Figure S2. The tension of buoy lines while hauling a snow crab trap was measured using: (A) the shackle dynamometer, composed of the (1) display unit, (2) load cell and (3) amplifier. The dynamometer was installed on the vessel by inserting: (B) the shackle load cell at the pulley attachment point. When hauling a trap, (C) the buoy line forms an angle, highlighted with a yellow circle.

### SM3: PROPORTIONS OF SINKING AND POSITIVELY BUOYANT ROPES USED IN FLUME TANK TRIALS

Table S1

Groundline lengths with 1:10 model sinking rope at one end and positively buoyant rope at the other end (attached to two anchors) to achieve different proportions of these two rope types for a total length of 15 m.

Sinking rope (%)	Length sinking rope (m)	Length of positively buoyant rope (m)
0	0	15
20	3	12
25	3.8	11.2
33	4.9	10.1
40	6	9
50	7.5	7.5
100	15	0

## SM4: FISHERS' RESPONSES TO OUR SURVEY TO CHARACTERISE THEIR PRACTICES

Table S2

Frequencies (%) of responses to survey questions relating to buoy line characteristics, setting and usage, fishing boat equipment, capacity and operations, provided by 25 voluntary mid-shore CFA 12 snow crab fishers based on the 2016 season.

Question	Options	Frequency (%)
<b>Buoy line characteristics</b>		
Length of the sinking rope section (m)	46	58
	55–59	13
	60	21
	64	8
Length of the positively buoyant rope section (m)	46–82	21
	91	50
	128–137	25
	165	4
Diameter of sinking rope (mm)	19	48
	16	40
	17.5	12
Diameter of positively buoyant rope (mm)	19	56
	16	32
	17.5	12
<b>Buoy line usage</b>		
Age of ropes (y)	1–3	28
	4	32
	5	24
	6–10	16
Maximum weight of a loaded trap (kg)	227–261	32
	272	32
	295–362	36
Number of trap lifts in the 2016 fishing season	130	5
	1,158–1,349	21
	1,520–1,650	42
	1,698–2,100	32
Times rope has broken in the last 10 years	1–2	39
	3–5	39
	6–10	22
How often are ropes replaced (y)	4–8	13
	10	44
	12–15	43
<b>Fishing boat equipment and capacity</b>		
Overall boat length (m)	14.6–19.5	20
	19.8	64
	20.4–21.6	16
Type of hydraulic system	Standard	79
	Load sensing	21
How long have you been a captain (y)	4–10	25
	14–20	29
	22–32	29
	33–45	17
Type of buoys used (primary and secondary)	Sea-Alex Buoy (20 cm)	8
	Polyform A-0 (20 cm) / A-2 (38 cm)	71
	Polyform HL-2 (30 cm)	21
<b>Fishing operation</b>		
Did you have any landing limits in 2016?	Yes	56
	No	44
Number of sea trips in 2016	9–10	33
	11–13	53
	15–20	14
Type of seabed where you fish (Mud: M; Rocks: R; Sand: S; Gravel: G)	ALL	17
	M	8
	M, G	8
	M, R	4
	M, R, S	4
	M, S	25
	M, S, G	26
	S	4
	S, G	4
	Minimum depth at which you fish (m)	46–55
59–62		44
64–77		12
Maximum depth at which you fish (m)	80–88	20
	91	44
	95–106	36