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Ghost fishing by self-baited lost, abandoned or discarded pots in snow crab (*Chionoecetes opilio*) fishery

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ABSTRACT

Unintended continuous capture or so-called “ghost fishing”, by abandoned, lost, or otherwise discarded fishing gear produces negative environmental impact on marine life and nature conservation. The risk of ghost fishing in pots could be high due to potential self-baiting resulting from mortality of ghost fished catch. Self-baiting may increase ghost fishing by further attracting marine organisms, including cannibalistic conspecifics. However, self-baiting effect in pot fisheries is seldom investigated. Pot fisheries targeting snow crab (*Chionoecetes opilio*) in the Arctic have high risk of gear loss due to harsh weather conditions. This study quantifies ghost fishing efficiency by simulated self-baited snow crab pots containing dead snow crab relative to catch efficiency of actively fished baited pots. On average, self-baited pots captured 0.4% of target-sized snow crab compared to actively fished pots. These results showed that the impact on marine environment caused by ghost fishing in pots is not always increasing due to self-baiting and can vary throughout the time pots are exposed to ghost fishing.

1. Introduction

Marine pollution by abandoned, lost or otherwise discarded fishing gear (ALDFG) causes considerable environmental and economic challenges for fisheries sustainability and environmental management (Gilman, 2015). These aspects are gaining more attention over the last decades (Brown and Macfadyen, 2007; Macfadyen et al., 2009; Gilman, 2015; Richardson et al., 2019; Gilman et al., 2021). A global increase in fishing effort and common use of more durable synthetic materials in different fishing gear types have led to both, increase and persistence, of ALDFG in the marine environment (Macfadyen et al., 2009; DelBene et al., 2019).

Pots and traps are considered being among the most abundant fishing gear types contributing to ALDFG in different fisheries (Miller, 1990; Matsuoka et al., 2005; Adey et al., 2008; Macfadyen et al., 2009; Gilman et al., 2021). Such gear often is made as a durable structure consisting of a frame often covered with netting that is made of slowly degrading plastic materials, for example polyethylene, polyamide and polyester. This fishing gear type is believed to pose high ecological and economic impacts through potential to continue capturing marine animals when left at sea unattended, so-called “ghost fishing” (Del Bene et al., 2019). The capture principle in pots relies on animals approaching the pot based on the odour of the bait with limited subsequent escape depending on gear design. Ghost fishing implies that the ALDFG continues capturing target and non-target animals in cases when pots are lost, abandoned or discarded at sea (Miller, 1990) negatively affecting biological conservation. This process can continue for long time after the gear has been lost at sea (Breen, 1987; Bullimore et al., 2001; Hébert et al., 2001; Adey et al., 2008), in some instances potentially lasting up to several years (Stevens et al., 2000; Goodman et al., 2001; Arthur et al., 2014). Ghost fishing by pots or traps can stop after considerable time when they are broken up by harsh weather or degrade to a state where all animals can escape (Miller, 1990) which depends on both, the marine environment where the gear is lost and its configuration and material.

Furthermore, in case of ghost fishing in pots, it is believed that the rates of capture by ALDFG can be significantly affected over time due to mortality of entrapped ghost-fished animals. This in the literature is called “self-baiting” of such ghost fishing gear (Miller, 1990). Specifically, after pot loss at sea, animals that enter the gear and cannot subsequently escape, eventually die. Such mortality can further attract different scavenger species to the gear acting as a bait. The scavengers entering the gear also risk being trapped depending on their morphology

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and size and the configuration of the lost gear (i.e., mesh size and presence or absence of other escape mechanisms). Pots are commonly used fishing gear in different crustacean fisheries such as for lobsters and crabs. Many of those species are opportunistic scavengers that often are cannibalistic. Cannibalism is defined as animals preying upon other conspecifics, including dying or dead individuals (necrophagy) (Polis, 1981; Romano and Zeng, 2017). This means that there can be an additional risk that such target species could be subjected to both, ghost fishing and subsequent self-baiting risk. Species that are scavengers would naturally consider dead individuals trapped in ALDFG as potential food source. Therefore, it could act as bait, leading to a continuous cycle of capture, mortality and attraction of other animals as long as the pots remain intact (Bullimore et al., 2001) continuously negatively affecting marine environment.

Mortalities caused by ALDFG can have a negative effect on the marine environment, conservation and sustainable management of commercial fisheries (Guillory, 1993; DelBene et al., 2019) and negatively affect efficiency of commercial fisheries (Scheld et al., 2015). Ghost fishing risk has been investigated in some pot and trap fisheries (Breen, 1987; Bullimore et al., 2001; Hébert et al., 2001; Adey et al., 2008; Butler and Matthews, 2015; Cerbule et al., 2023). However, self-baiting cycles can result in varying ghost fishing rates. Without accounting for these potential variations in ghost fishing, it is not possible to correctly estimate the effect caused by ALDFG based on only initial results without presence of dead conspecifics (Cerbule et al., 2023) or results that are based only on few observations during whole ghost fishing cycle (Hébert et al., 2001; Humborstad et al., 2021).

Several studies have mentioned self-baiting risk associated with ALDFG in case of different trap gear, including in crustacean fisheries (Bullimore et al., 2001). Some studies have shown varying rates of ghost fishing caused by self-baiting with dead conspecifics in lost pots or traps (Goodman et al., 2021). However, some other sources in the literature mention that even for cannibalistic species such as some crab species, dead conspecifics in pots could potentially act as repellent (Miller, 1990). Specifically, live animals could consider the presence of dead conspecifics as a threat and, therefore, display avoidance behaviour. For example, Ferner et al. (2005) and Moir and Weissburg (2009) showed that for cannibalistic blue crabs (*Callinectes sapidus*) injured or dead conspecifics can function as repellent. Thus, the presence of dead conspecifics due to self-baiting could result in reduced ghost fishing efficiency for periods where there is presence of such in ghost fishing pots.

One of such large-scale examples of pot fisheries is targeting snow crab (*Chionoecetes opilio*). Snow crab fisheries are conducted in Arctic areas, including in Canada, U.S., Greenland, Russia and Norway. These fisheries are often performed in harsh weather conditions and large depths in areas partly covered with pack-ice which increases the risk of gear loss (Cerbule et al., 2023). Furthermore, often a large number of pots are deployed and hauled. For example, in Norwegian snow crab fisheries, each fishing vessel can operate up to 9 000 pots. Snow crab pot fisheries in east Canada, Greenland and Norway are using conical pots that are deployed baited (Winger and Walsh, 2011; Cerbule et al., 2022; Government of Greenland, 2024). These fisheries can result in large numbers of pots being lost at sea, and the subsequent retrieval of such gear can be time consuming, complicated and involve large costs due to large distances from the coast and large fishing depths. For example, drift-ice may cut the buoy-lines or move the entire pot-string which complicates subsequent finding of such fleet. Further, presence of lost gear can cause collisions with newly deployed gear, resulting in potential gear losses and operational challenges. Fishers operating bottom trawls in the Barents Sea in the same areas where snow crab fisheries are conducted, have reported retrieval of lost or discarded pots with live and dead crabs several weeks after the snow crab fishery had stopped (Fiskeribladet, 2023). In snow crab fishery, similarly as many other pot fisheries, the risk of such dead crabs to increase the ghost fishing rate through potential self-baiting is to date unknown. Thus, the estimated rate of ghost fishing can be subject to changes over time as the pots initially lost at sea attract snow crab and result in crab mortality. Furthermore, bycatch of other non-target species in these fisheries is generally low (Dutil et al., 1997; Addison et al., 2013; Nguyen et al., 2019). Therefore, the self-baiting in this fishery primarily relates to dead conspecifics.

Previous studies in the Barents Sea have demonstrated that ALDFG in snow crab fishery is contributing to ghost fishing (Humborstad et al., 2021; Cerbule et al., 2023). For example, Cerbule et al. (2023) quantified the initial ghost fishing risk in snow crab fisheries by simulating lost pots where the smell of bait odour has been depleted. The results showed that such lost gear has a potential to initiate ghost fishing even without bait present and a capture rate over 8.3 % (CI: 4.33–13.73 %) of target sized snow crab compared to commercial snow crab pots that are deployed in the fishery using squid (*Illex* spp.) as bait (Cerbule et al., 2023). The pot design in this fishery consists of a metal frame that is covered with plastic netting, i.e., made from 4 mm diameter braided polyethylene twines. The entrance of the conical pots is located at the top with a high-density polyethylene entrance cone with diameter 535 mm (Cerbule et al., 2022). The mesh size used in pot netting allows escape of undersized snow crab (Herrmann et al., 2021) which in Norwegian snow crab fishery corresponds to $<$ 95 mm carapace width (CW). Larger target sized snow crab that have entered the ghost fishing pots would remain trapped and subsequently die.

Snow crab similar to several other decapod crabs are cannibalistic species (Dutil et al., 1997; Lovrich and Sainte-Marie, 1997; Squires and Dawe, 2003). However, it is unknown whether such dead conspecifics in the lost gear would attract other snow crab as suggested in some studies (Hébert et al., 2001; Humborstad et al., 2001) and if so to what extent can this affect the ghost fishing efficiency of ALDFG. Such results could provide an important knowledge about the unaccounted mortality, effect on the marine environment and further potential economic losses in the fishery.

The aim of this study was to estimate self-baited snow crab pot ghost fishing efficiency compared to the catch efficiency of actively fished baited pots as used in commercial snow crab fishery. Cerbule et al. (2023) quantified the initial ghost fishing efficiency in snow crab pot fishery by comparing efficiency of simulated ghost fishing pots to the relative catch efficiency of actively fished baited pots applying a relative catch efficiency estimation. Such estimate is not dependent on snow crab abundance, or the specific soak time (Cerbule et al., 2023). In this study we adapted a similar approach to investigate the self-baiting effect in ghost fishing efficiency of snow crab pot fisheries.

2. Materials and methods

To estimate the efficiency of self-baited snow crab pots to continue ghost fishing, we used standard baited snow crab pots as used in commercial fisheries as baseline (actively fished pots) and simulated self-baited ghost fishing pots as test gear (self-baited pots). The pot design for both, test and baseline pots, in these experiments was identical. The only difference between both setups was the presence of dead snow crab in self-baited pots while baseline pots contained bait (i.e., squid) typically used in commercial snow crab fishery.

2.1. Ethics statement

The animals used in this study were not an endangered or protected species. All experiments followed standard commercial fishing practices in snow crab fishery, and the animals were not exposed to any additional harm. Therefore, no specific permits were required for conducting the study described here.

2.2. Experimental setup and data collection

Cerbule et al. (2023) estimated initial ghost fishing efficiency in snow crab pot fishery by applying a new method. Specifically, the ghost fishing efficiency was estimated between simulated ghost fishing pots without bait and catch efficiency of gear with squid as used in commercial snow crab fishery. To investigate the self-baiting effect in ghost fishing of snow crab, this study applied similar experimental design and analysis methods as in Cerbule et al. (2023) which is described in following sections.

Test pots were baited with one target-sized (> 95 mm CW) dead snow crab to simulate mortality of a captured snow crab in lost pots. The snow crab samples for test pots were collected during previous research trials during March 2022 in the Barents Sea following commercial fishing practice. Snow crab samples were frozen as whole animals directly after capture and kept packed and frozen (−20° C) until these experiments. Before the experiments, one snow crab was attached to each test pot at the upper part of the pot frame using a mesh bag to avoid losing the crabs from the pots during deployments through pot entrances. Prior deployments, each snow crab was measured for the CW to ensure that only target sized individuals were used for our experiments, thus simulating the crabs that under a ghost fishing scenario would be retained in the gear due to not being able to pass through the netting meshes (Herrmann et al., 2021). Therefore, the size of the crabs that were used for self-baiting experiments ranged between 97 and 130 mm CW. The actively fished pots were baited similar as practiced in the commercial snow crab fishery, i.e., using approximately 800 g of squid (*Illex* spp.). The bait was divided into two parts, one placed in a small mesh bait bag and the other in a perforated plastic bait container, following the commercial fishing pattern. Both bait containers were hanging under the entrance cone of the pot.

The conical pot frame design and dimensions corresponded to that used in commercial snow crab fisheries and were identical for both test and baseline pots (Cerbule et al., 2022). In the commercial fisheries, conical pot frames are covered with plastic netting made of 4 mm polyethylene twine. Mesh sizes range from 120 mm to 140 mm, which aims to allow undersized snow crab pass through netting meshes to escape the gear during pot deployment while larger snow crab are retained in the gear thus determining size selectivity for the snow crab (Herrmann et al., 2021). In this study similar as in Cerbule et al. (2023) small-mesh netting with nominal mesh size of 52 mm in both test and baseline pots was used to retain snow crab of all sizes. Therefore, such approach allows comparing the entry probability of all sizes of snow crab (Herrmann et al., 2021).

In studies comparing fishing gear performance of different configurations, including in pot fisheries, it is common to alternate deployment of the test and baseline gear to ensure that both configurations are in proximity to each other, accounting for abundance and size structure variability of the target species (Olsen et al., 2019a; Cerbule et al., 2021, 2022). However, such experimental design is not suitable for studies comparing pots using different types of odour attractions such as in this study. A suitable experimental setup must ensure sufficient distance between test and baseline pots. This is due to the specific setup comparing test pots with dead snow crab and catch efficiency of baited baseline pots with squid. In our experiment, odour of both sources could potentially affect the results by attracting crabs away from other setup fishing pots (i.e., squid bait odour in close proximity to test pots). However, too large distance between the test and baseline pots could lead to differences in snow crab abundance and size structure between fishing areas which could potentially affect the results. To address these challenges, the experimental design proposed by Cerbule et al. (2023) named the “triplet design” was used for these experiments.

The triplet experimental design consists of pot deployment using three parallelly deployed mainlines where each contain a single pot configuration (either test or baseline gear) (Cerbule et al., 2023). Further, the two outer mainlines contain the same configuration (both being either test or baseline gear). When using the triplet design, it is expected that the snow crab abundance available for the middle line approximates the mean of the two outer fishing lines based on simple linear interpolation (Cerbule et al., 2023). Thus, the catch comparison is made between the middle and outer lines which should reduce the risk for bias due to potential variation in snow crab abundance.

Following this approach, in our study, we used the two outer pot mainlines to deploy test pots and the middle mainline contained only baseline pots. We used two lines with 30 test pots each (self-baited pots) and one line with 30 baseline pots (actively fished pots). Fishing trials were performed with the research vessel “Helmer Hanssen” (63.8 m LOA and 4.080 HP) between 6th – 14th of December 2023. The fishing grounds were in the central Barents Sea (74°34.040 N — 74°36.300 N / 35°29.500 E — 35°31.700 E) (Fig. 1A) at depths of around 265 m. We applied similar distance between the three pot lines as used in Cerbule et al. (2023) by separating the pot lines by approximately 0.5 nautical miles (nm) which equals 926 m (Fig. 1B-C).

The pots were attached to each mainline every 30 m with a 2 m long branch line (gangion) by a quick-link system. The deployment and recovering time for the three pot lines was kept the same resulting in 8 days of soaking time. This pot deployment time corresponds to typical soak time used in commercial snow crab fishery in the Barents Sea (Olsen et al., 2019a); therefore, it was considered suitable for these experiments. Each of the three lines was hauled on board separately. The CW (i.e., the largest distance across the carapace, including spines (Jadamec et al., 1999)) of all snow crab in each pot separately was measured to the nearest millimetre below using callipers.

2.3. Estimation of mean number of snow crab captured in test and baseline pots

To compare the efficiency of test pots to capture snow crab with the catches of the baseline gear, we first estimated the mean number of snow crab retained in test pots and baseline pots (Cerbule et al., 2023). We expressed the mean number of snow crab as catch per unit of effort (*CPUE*):

$$\begin{aligned} CPUE_S &= \frac{\sum_{i=1}^{KS} nS_i}{KS} \\ CPUE_A &= \frac{\sum_{i=1}^{KA} nA_i}{KA} \end{aligned} \tag{1}$$

In Equation (1), nS_i is the number of crabs in test (self-baited) pot i while nA_i is the number of snow crabs retained in the baseline (actively fished) pot i. KS and KA are the number of pots on fishing lines with test and baseline pots, respectively. Uncertainties for $CPUE_S$ and $CPUE_A$ were obtained using a bootstrap approach where groups of test and baseline pots were resampled separately with replacement, leading to a set of values for $CPUE_S$ and $CPUE_A$ (Cerbule et al., 2023). We applied 1000 resampling repetitions and obtained a population of 1000 results for $CPUE_S$ and $CPUE_A$, respectively. These were applied to obtain Efron 95 % percentile confidence intervals (CIs) (Efron, 1982).

CPUE estimations depend on the specific abundance and size structure of snow crab on the fishing ground at the time and location the experiments are conducted (Olsen et al., 2019b; Cerbule et al., 2023). Therefore, $CPUE_S$ and $CPUE_A$ for test and baseline pots are specific for the abundance and size distribution of snow crab during the experiment and cannot be extrapolated to other fishing areas and seasons (Cerbule et al., 2023).

In contrast to the *CPUE* estimation, relative catch efficiency between test and baseline pots can be estimated based on catch data and does not require the information on either abundance or size structure of snow crab (Cerbule, Herrmann, Grimaldo, Grimsmo, & Vollstad, 2021; Olsen et al., 2019b, 2022, 2023). Furthermore, it can provide a more generalizable estimate for quantifying the self-baiting effect on ghost fishing efficiency.

2.4. Estimation of ghost fishing efficiency of test pots

Similar to the experiments assessing the initial ghost fishing effi-

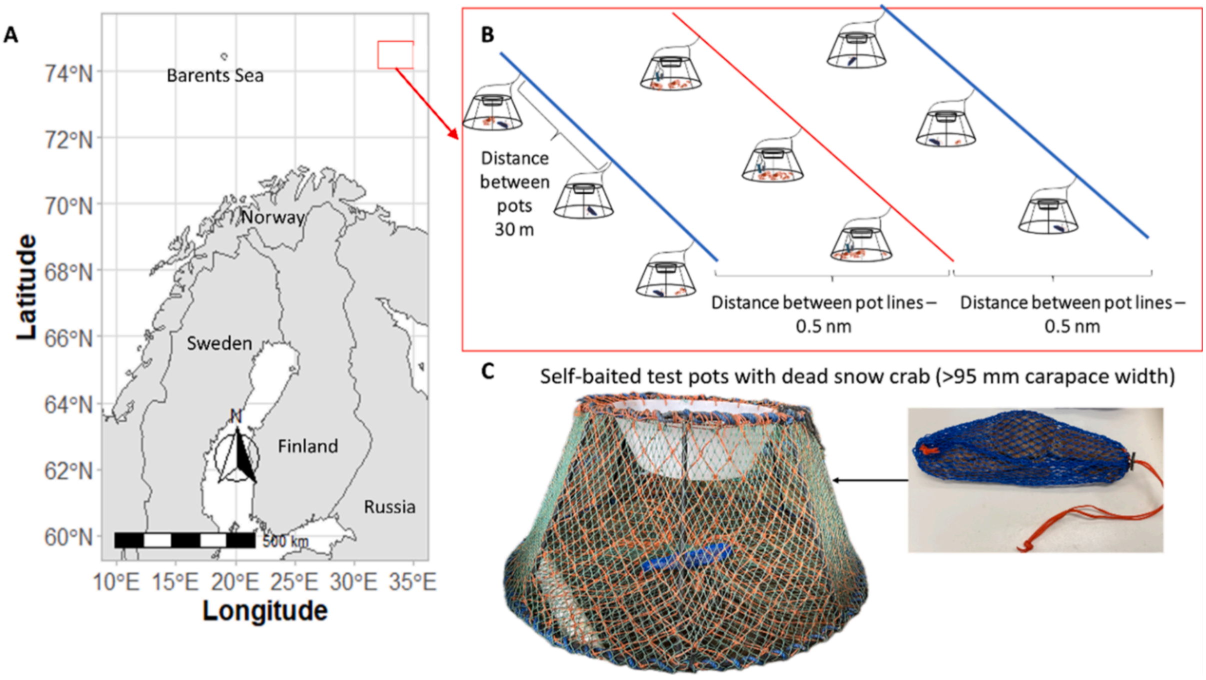

Fig. 1. **A:** Map of the area where the trials were conducted. **B:** the experimental design used during the trials where blue lines denote lines with test (self-baited) pots containing dead snow crab while the red line in the middle – baseline (actively fished) pots equipped with squid (*Illex* spp.) bait. The distance between the pots along the mainline was 30 m. The distance between the three parallel deployed lines was 0.5 nm (equals to 926 m). **C:** example of test pot and placement of a dead snow crab in a mesh bag that was attached to the bottom netting of each test pot.

ciency (Cerbule et al., 2023), the relative size-dependent catch efficiency between test pots and baseline pots was estimated by applying catch comparison and catch ratio analyses (Herrmann et al., 2017). The catch comparison method as presented in Cerbule et al. (2023) utilizes the experimental triplet design (Fig. 1). We assumed that the snow crab abundance for the baseline pots (middle line) is approximately half of the abundance which is summed over the two self-baited mainlines (outer lines) according to the experimental design used in this study (Fig. 1). Further, we assumed that the capture in a pot is proportional with the local abundance where the pots are deployed. The experimental catch comparison rate was estimated using the following equation (Equation (2) (Cerbule et al., 2023)):

$$CC_{cw} = \frac{\sum_{i=1}^{q} nS1_{cw,i} + \sum_{i=1}^{q} nS2_{cw,i}}{\sum_{i=1}^{q} nA_i \sum_{i=1}^{q} nS1_{cw,i} + \sum_{i=1}^{q} nS2_{cw,i}} \tag{2}$$

In Equation (2), $nS1_{CW,i}$, $nS2_{CW,i}$ and $nA_{CW,i}$ are the numbers of snow crab with carapace width *CW* being captured in pot *i* in test pots in outer mainlines *S1* or *S2* or baseline pots, respectively. *q* represents the number of pots deployed on each of the three lines.

The functional form of the catch comparison rate (the experimental rate expressed by Equation (2)) was estimated based on the catch data summed over the *q* pots by minimizing the following expression (Cerbule et al., 2023):

$$-\sum_{CW}\left\{\sum_{i=1}^{q}\{nS1_{CW,i} \times ln(CC(\boldsymbol{v},CW)\} + \sum_{i=1}^{q}\{nS2_{CW,i} \times ln(CC(\boldsymbol{v},CW)\} + \sum_{i=1}^{q}\{nA_{CW,i} \times ln(1.0 - CC(\boldsymbol{v},CW)\}\right\} \tag{3}$$

In Expression (3), $\boldsymbol{v}$ is a vector representing the parameters of the function describing the catch comparison curve. The outer summation in the equation is the summation over the snow crab CW size classes.

If the catch efficiency of test and baseline pots was equal with equal number of test and baseline pots deployed, the expected value for the summed catch comparison rate would be equal to 0.5 with catch comparison rate ranging from 0.0 to 1.0. However, due to the experimental design used in this study consisting of pot deployment on three mainlines resulting in deployment of twice as many test than baseline pots, the baseline for identical catch efficiency between test and baseline gear is 0.67 (Cerbule et al., 2023). The experimental CC_{cw} is modelled by the function $CC(\boldsymbol{v}, CW)$ (Cerbule et al., 2023):

$$CC(\boldsymbol{v}, CW) = \frac{exp(f(CW, v_0, \cdots, v_k))}{1 + exp(f(CW, v_0, \cdots, v_k))} \tag{4}$$

where *f* is a polynomial of order *k* with coefficients from v_0 to v_k. We considered an *f* of up to an order of 4 with parameters v_0–v_4. Leaving out one or more of the parameters $v_0 \ldots v_4$ led to 31 additional models that were also considered as potential models for the catch comparison $CC(\boldsymbol{v}, CW)$ between test and baseline pots (Cerbule et al., 2023). Estimations of the catch comparison rate were made using multi-model inference to obtain a combined model to represent the trend in the experimental data (Burnham and Anderson, 2002; Herrmann et al., 2017).

We evaluated the ability of the combined model to describe the experimental data based on the *p*-value. *p*-value quantifies the probability of obtaining by coincidence at least as big a discrepancy between the experimental data and the model as the one observed. The *p*-value should not be < 0.05 for the combined model to describe the experimental data sufficiently well (Wileman et al., 1996).

Uncertainties for $CC(\boldsymbol{v}, CW)$ were estimated by using the double bootstrapping approach (Herrmann et al., 2017). Each of the three pot lines (*S1*, *S2* or *A*) were treated separately by conducting resampling independently (Cerbule et al., 2023). Specifically, for each line separately the pots were resampled with replacement in an outer loop to account for the variation in capture between the pots. Further, each time a pot was selected in this outer loop, the captured population in that pot was resampled in an inner resampling loop. This inner resampling accounted for uncertainty in size structure in the pot catches due to finite number of crab in a pot. For each of the three lines 1000 bootstrap repetitions were applied leading to three bootstrap populations. Next, these three bootstrap populations were aggregated. This was done for each bootstrap by aggregating the data for the individual bootstrap resamples. Thereafter, the resulting data was used to minimize Expression (3) and provide a bootstrap population of results for $CC(\boldsymbol{v}, CW)$ (Cerbule et al., 2023). Efron 95 % confidence intervals were obtained from this bootstrap population (Efron, 1982).

The catch comparison rate $CC(\boldsymbol{v}, CW)$ cannot be used to quantify directly the ratio between the ghost fishing efficiency of self-baited pots to that of catch efficiency by actively fished pots for snow crab of specific size CW. Therefore, catch ratio estimations $CR(\boldsymbol{v}, CW)$ are applied. We used the estimated catch comparison function $CC(\boldsymbol{v}, CW)$, to obtain the relative catch efficiency $CR(\boldsymbol{v}, CW)$ between the test and baseline pots by the following equation (Cerbule et al., 2023):

$$CR(\boldsymbol{v}, CW) = \frac{1}{2} \times \frac{CC(\boldsymbol{v}, CW)}{1 - CC(\boldsymbol{v}, CW)} \tag{5}$$

The factor ½ in Eq. (5) account for the double number of test pots to baseline pots applied to provide an estimate that is valid for a balanced number of pots. The resulting catch ratio values range are >=0 where $CR(\boldsymbol{v}, CW)$ of 1.0 show equal catch efficiency. Confidence intervals for $CR(\boldsymbol{v}, CW)$ were obtained by incorporating Equation (5) in the bootstrap population estimation.

Size-integrated average values (in percentage) for catch ratio ($CR_{average}$) (in percentage) were estimated directly from the experimental catch data as follows (Cerbule et al., 2023):

$$\begin{aligned}
CR_{average-} &= 100 \times \frac{\frac{1}{2}\sum_{CW<MLS}\left\{\sum_{i=1}^{q} nS1_{CW,i} + \sum_{i=1}^{q} nS2_{CW,i}\right\}}{\sum_{CW<MLS}\left\{\sum_{i=1}^{q} nA_{CW,i}\right\}} \\
CR_{average+} &= 100 \times \frac{\frac{1}{2}\sum_{CW\geq MLS}\left\{\sum_{i=1}^{q} nS1_{CW,i} + \sum_{i=1}^{q} nS2_{CW,i}\right\}}{\sum_{CW\geq MLS}\left\{\sum_{i=1}^{q} nA_{CW,i}\right\}} \\
CR_{average} &= 100 \times \frac{\frac{1}{2}\sum_{CW}\left\{\sum_{i=1}^{q} nS1_{CW,i} + \sum_{i=1}^{q} nS2_{CW,i}\right\}}{\sum_{CW}\left\{\sum_{i=1}^{q} nA_{CW,i}\right\}}
\end{aligned} \tag{6}$$

In Equation (6), the outer summations include the snow crab CW size classes under MLS ($CR_{average-}$) and over MLS ($CR_{average+}$) observed during the experimental fishing trials. Therefore, in contrast to the size-dependent evaluation of the catch ratio $CR(\boldsymbol{v}, CW)$, $CR_{average}$ is specific for the snow crab population structure encountered during the experimental sea trials. Therefore, these average values cannot be directly applied to other scenarios as the size structure of the population could differ (Olsen et al., 2019b; Cerbule et al., 2021).

2.5. Estimation of variation in snow crab abundance within the fished area

To check for potential variations in snow crab abundance within the fishing area of our experiments, we used a standard catch comparison method between the two outer mainlines that consisted of test pots (Herrmann et al., 2017; Cerbule et al., 2023). Specifically, both outer lines would be expected to retain similar numbers of snow crab in each CW size class, if there were no significant differences in snow crab abundance. Therefore, if the confidence intervals for all sizes of snow crab include 0.5 baseline value, there is no proof of any significant abundance variations within the area and time of these experiments.

For these estimations, we used unpaired catch comparison ($CC(\boldsymbol{v}, CW)$) and catch ratio ($CR(\boldsymbol{v}, CW)$) analyses (Herrmann et al., 2017). Further, the size-integrated average catch ratio ($CR_{average}$) and size-integrated catch ratio values for undersized ($CR_{average-}$) and target sized ($CR_{average+}$) snow crab were estimated from the catch data. Details about the estimation of $CC(\boldsymbol{v}, CW)$, $CR(\boldsymbol{v}, CW)$ and $CR_{average}$ between the two outer mainlines in the triplet design setup can be found in Supplementary material of Cerbule et al. (2023). Equations and descriptions regarding the details for estimation of $CC(\boldsymbol{v}, CW)$, $CR(\boldsymbol{v}, CW)$, and $CR_{average}$ are provided in Herrmann et al. (2017).

Finally, to formally test whether both outer pot mainlines are catching equally all sizes of snow crab, we further applied a hypothesis testing with null hypothesis test pots for all sizes of snow crab. This implies that $CC(\boldsymbol{v}, CW)$ would be 0.5 value for all CW size classes of snow crab. We tested whether this hypothesis could be rejected based on the collected data by setting $CC(\boldsymbol{v}, CW)$ to 0.5 for all CW size classes, and then calculating the corresponding p-value for obtaining at least as big discrepancy as observed between the experimental catch comparison data and the model by chance. If this p-value was below 0.05, we then would reject the null hypothesis.

The data analysis described in sections 2.3-2.5 were conducted using SELNET data analysis software (Herrmann et al., 2012).

3. Results

During the experiments, two lines with 30 test pots each and one line with 30 baseline pots were deployed simultaneously following the triplet experimental design (Fig. 1). However, upon pot recovery, in two self-baited mainlines the last pot on the line was open (i.e., opening at the underside of the pot netting that is used for emptying the pots when the gear is retrieved). Therefore, one pot in each self-baited mainline was excluded from the analysis resulting in 29 deployed pots in both $S1$ and $S2$. Therefore, to balance the number of pots within the three mainlines, we considered 29 pots by excluding the last pots on each mainline $S1$, $S2$ and A, respectively. After 8 days of soaking time, a total of 2199 snow crab were captured and measured by CW size (Table 1).

3.1. Mean number of snow crabs in test compared to baseline pots

The results showed significantly different mean numbers of crab captured in test and baseline pots since the CPUE of the baseline pots ($CPUE_A$) was significantly higher compared to the mean number of crabs captured in test pots ($CPUE_S$). Specifically, the $CPUE_S$ and $CPUE_A$ were estimated to 0.60 (CI: 0.43–0.77) and 77.29 (CI:71.93–82.71), respectively.

3.2. Estimating test pot ghost fishing efficiency relative to catch efficiency of baseline pots

The fit statistics of the analysis showed that the deviation between the experimental data and the modelled catch comparison rate could be coincidental as the p-value was larger than 0.05 (Table 2). Therefore, we were confident in modelling the experimental catch comparison

Table 1
Details from the three deployed pot lines (one line with baited baseline snow crab pots (A) and two lines of self-baited test pots ($S1$ and $S2$)) showing position of the lines, depth, number of pots in each line and number of crabs retained. MLS – minimum landing size.

	Actively fished baseline pots (A)	Self-baited test pots ($S1$)	Self-baited test pots ($S2$)
Start position	N74°35.70; E35°30.20	N74°36.40; E35°29.50	N74°35.02; E35°30.04
End position	N74°35.72; E35°31.50	N74°36.30; E35°31.50	N74°34.04; E35°31.70
Depth at start position (m)	270	263	268
Depth at end position (m)	270	268	257
Number of pots	29	29	29
Total number of crabs	2164	21	14
Number of crabs below MLS	436	13	7
Number of crabs above MLS	1728	8	7

Table 2
Fit statistics and catch ratio values (in %) obtained for test pots against baseline pots for undersized (< 95 mm carapace width) (*CRaverage-*) and target-sized snow crab (*CRaverage +*) and averaged over all snow crab sizes (*CRaverage*). Values in parentheses represent the 95 % confidence limits. DOF = degrees of freedom.

p-value	0.4960
Deviance	66.45
DOF	67
CRaverage-	2.20 (1.35–3.30)
CRaverage+	0.42 (0.24–0.60)
CRaverage	0.80 (0.58–1.00)

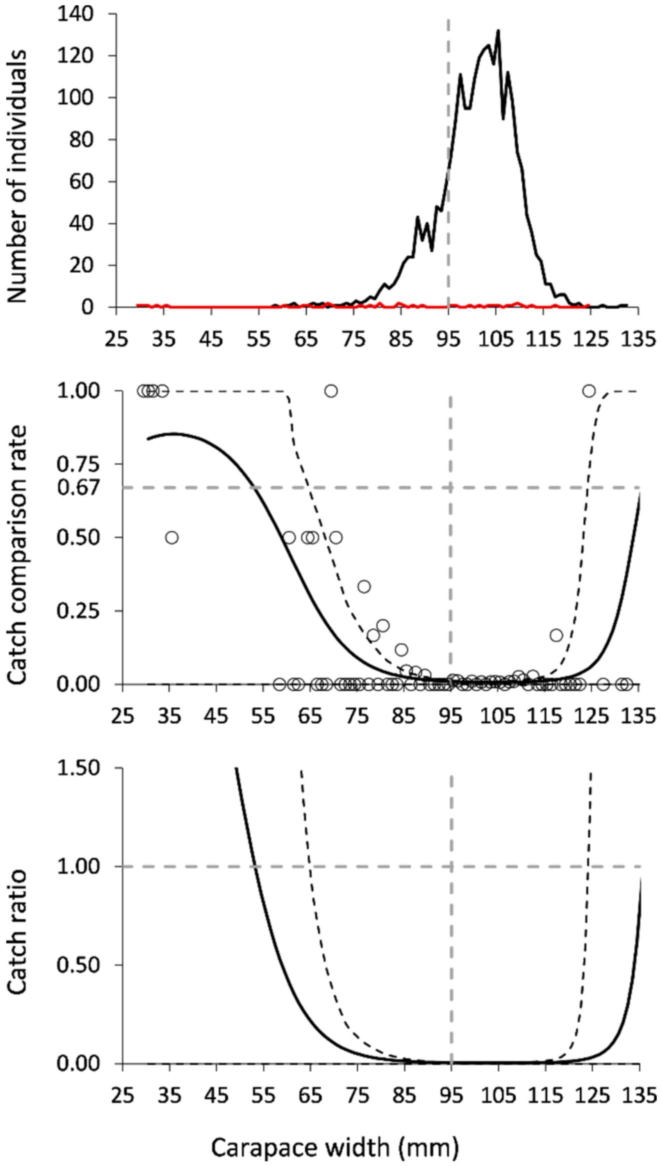

Fig. 2. Upper plot: populations caught in actively fished baseline (black) and self-baited test (red) pots. Middle plot: catch comparison rate (black curve, with experimental catch comparison rates (circles). Lower plot: catch ratio. Stippled lines represent 95 % CIs. The horizontal grey stippled lines are the baseline of no significant difference between the test and baseline pots investigated. The stippled vertical lines represent the minimum landing size of the snow crab (95 mm carapace width).

rate by Equation (4).

The efficiency of test pots regarding ghost fishing of snow crab was significantly lower for all sizes of snow crab (Fig. 2). The average efficiency of test pots regarding ghost fishing of snow crab over all CW sizes was 0.8 % compared to the catch efficiency of the baseline pots (*CRaverage* = 0.80 % (CI: 0.58–1.00 %)). Therefore, the efficiency of test pots on average was significantly lower compared to the catch efficiency of baited baseline pots (Table 2; Fig. 2). Further, for target sized individuals, the average catch efficiency was as low as 0.42 % (CI: 0.24–0.60 %) compared to baseline pots.

3.3. *Variation in snow crab abundance within the fished area*

The comparison of the catch efficiency between the two outer pot mainlines, i.e., the self-baited lines *S1* and *S2*, allowed to infer whether there were any differences in snow crab abundance in the fishing area. The fit statistics of the catch comparison analysis showed that the *p*-value was > 0.05 (Table 3) showing that the deviation between the experimental data and the modelled catch comparison rate could be coincidental.

The results showed no significant differences for the average catch ratio (*CRaverage*), including when comparing the average catch ratio for undersized (*CRaverage-*) and target sized snow crab (*CRaverage+*) (Table 3). Due to small number of individuals captured in test pots, (21 and 14 individuals in lines *S1* and *S2*, respectively) the confidence intervals in these estimates were wide and not showing any significant differences in catch ratio between the two test pot lines for all CW sizes of snow crab (Fig. 3). This also resulted in wide confidence intervals observed for average catch ratio values (Table 3). These results showing no significant differences between the two outer mainlines provide an additional indication that there should be no considerable variations in snow crab abundance in fishing area during our trials. Therefore, variation in snow crab abundance would not have affected the estimation of the test pot ghost fishing efficiency in this study.

Finally, the results of hypothesis testing for equal catch efficiency between the two outer lines (null hypothesis) had a *p*-value that was larger than 0.05 (*p*-value = 0.0746). Therefore, the null hypothesis was not rejected, thereby implying that we cannot rule out that there are no significant differences between catch efficiency of the two outer lines (Supplementary information S1) and thus the snow crab abundance of the fished area.

4. Discussion

In this study, we investigated how ghost fishing can affect marine environment and sustainable marine resource conservation considering ghost fishing by self-baited pots. The results showed that self-baited pots with dead conspecifics had significantly lower ghost fishing efficiency when compared to the catch efficiency of actively fished baited pots, resulting in very low catch rates. For the target sized snow crabs above 95 mm CW, self-baited pots captured only 0.4 % of crabs compared to actively fished baited pots. The results regarding entry efficiency by

Table 3
Fit statistics and average catch ratio values (in %) between the two outer self-baited pot lines (*S1* and *S2*) for snow crab below and above minimum landing size (*CRaverage-* and *CRaverage+*, respectively), and averaged over all sizes (*CRaverage*). Values in parentheses represent the 95 % confidence limits. DOF = degrees of freedom.

p-value	0.1524
Deviance	34.49
DOF	27
CRaverage-	185.71 (70.00–750.00)
CRaverage+	114.29 (33.33–366.67)
CRaverage	150.00 (68.18–350.00)

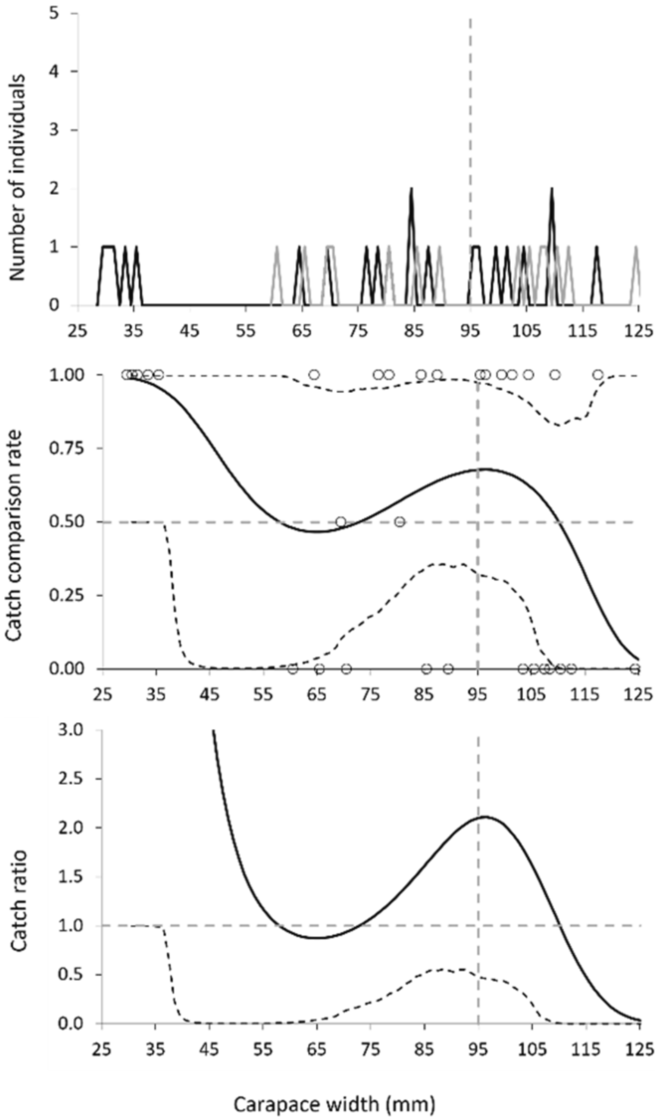

Fig. 3. Upper plot: population caught in two outer self-baited pot lines (S1 – black line and S2 – grey line). Middle plot: catch comparison rate where circles represent experimental catch comparison rates. Lower plot: catch ratio results. Stippled curves are 95 % confidence intervals. The grey horizontal stippled lines show the expected catch comparison rate in case of no difference between the pots investigated. The vertical stippled lines represent the minimum landing size of the snow crab (95 mm carapace width).

undersized snow crab showed slightly higher catch rate of 2.2 % compared to actively fished pots. Ghost fishing implies that the animals that enter or otherwise contact ALDFG (i.e., trap or pot) are unable to subsequently escape (Matsuoka et al., 2005). In case of undersized snow crabs, such individuals when entering commercial snow crab pots would most probably be able to escape through meshes of the pot netting which in commercial fishery are made of sufficient size to allow escape of small individuals (Herrmann et al., 2021). For example, snow crab pots used by Norwegian vessels are built with 120–140 mm mesh netting. Thus, entry of small crabs in such pots would not further contribute to ghost fishing catches while the opposite would be expected for larger individuals.

The results of this study differed from those observed for initial ghost fishing efficiency in this fishery. Cerbule et al. (2023) quantified initial ghost fishing efficiency by lost snow crab pots by simulating the situation when the bait odour is depleted over time. The results showed that initial ghost fishing by lost snow crab pots without bait present was 8.3 % (CI: 4.3–13.7 %) for target sized individuals when compared to actively fished pots (Cerbule et al., 2023). The present study using self-baited gear thus showed significantly lower average catch efficiency for target-sized crabs since $CRaverage+ = 0.42$ % (CI: 0.24–0.60 %). However, *CRaverage* values should be interpreted with caution since they are specific for the snow crab population structure encountered during the specific experimental sea trials (Olsen et al., 2019b; Cerbule et al., 2021). Since the size structure of the population may be different considering the time period the two studies were conducted, the comparison of size-dependent catch ratio curves can be used comparing results of this and previous study by Cerbule et al. (2023). These results of both studies are comparable due to application of the same method of quantifying ghost fishing by comparing the ghost fishing efficiency to catch efficiency of commercial fishery and applying the same experimental design. The low ghost fishing by self-baited pots in this study could indicate that the presence of dead conspecifics can reduce the ghost fishing efficiency by ALDFG in this fishery compared to initial ghost fishing (Cerbule et al., 2023).

Several studies so far have emphasized that pots and traps could have a high negative impact on marine environment and resource conservation when ghost fishing is considered due to potential of self-baiting (Havens et al., 2011; DelBene et al., 2019). Self-baiting includes attraction of cannibalistic target species towards pots of dead conspecifics such as in snow crab pot fisheries where bycatches of species other than snow crab are not common throughout the different areas where these pot fisheries are being conducted (Addison et al., 2013; Nguyen et al., 2019; Nguyen et al., 2020). Crabs are often cannibalistic species that also feed upon dead or dying conspecifics. This could suggest that self-baiting in such fisheries could increase ghost fishing rates (i.e., above the estimated 8 % compared to baited actively fished pots (Cerbule et al., 2023)).

However, presence of dead conspecifics in the gear can also cause an opposite effect as shown in this study. Even though the odour of dead crabs may represent an attractive odour due to indication of food to other crabs, it can as well serve as an indication of potential threat that has caused previous mortality in same species. Such odour of dead conspecifics can cause an avoidance behaviour by acting as a warning signal of potential danger. Some studies examining the behaviour of different cannibalistic crustacean species in presence of dead conspecifics have found that dead individuals can act as repellent (Ferner et al., 2005; Moir and Weissburg, 2009). Thus, for some species, the response on self-baiting could act as repellent that would explain decreased ghost fishing efficiency.

Such avoidance of dead snow crabs would be contrary to earlier results regarding cannibalism in snow crab including analyses of snow crab stomach contents (Dutil et al., 1997; Squires and Dawe, 2003; Zakharov et al., 2021; Fisheries and Oceans Canada, 2022; Holte et al., 2023). However, the results of study by Dutil et al. (1997) suggested that cannibalism was more frequent in crabs when other food sources were scarce. This could indicate that considering sufficient food availability in the area, snow crab odour would not act as bait for other individuals. However, in such case we would not expect that the capture rate in self-baited pots would be significantly lower than that of initial ghost fishing by empty pots (Cerbule et al., 2023). Therefore, the present result is more in line with avoidance behaviour than that of availability of other food sources. Furthermore, even though snow crab is scavenging species feeding upon also dead material, stomach content analyses that are often used to conclude the cannibalism in snow crab, cannot determine whether snow crab prey was obtained through predation or through necrophagy, i.e., feeding on dead snow crab (Lovrich and Sainte-Marie, 1997). Considering the above mentioned, we could speculate that some crab species such as snow crab could as well not be attracted to dead conspecifics. The ability of snow crab to detect dead conspecifics over the distance based on odour is not estimated. However, other studies have showed that snow crab are capable of detecting odour over large distances. For example, in study by Brêthes et al. (1985), the results of tagged and recaptured crabs showed that the radius of the prospected area following smell ranged between 100–140 m.

Our observations are in contrast to earlier results by Hébert et al. (2001) stating that snow crab pots continued to catch crabs after bait depletion due to self-baiting effect. However, the results by Hébert et al. (2001) were based on limited number of observations of limited number of pots. This implies a possibility that the catch rates of ghost fishing pots varied over time. We can speculate that after pot loss at sea, several ghost fishing cycles could include initial attraction phase due to bait presence of lost pots and following mortality of large crabs that cannot escape the gear. The time the crabs can survive without food was estimated to exceed 3 months (100 days) in captivity in laboratory conditions (Siikavuopio et al., 2019). However, survival and injuries can also depend on captured snow crab density (Siikavuopio et al., 2017). This implies that live crab in ghost fishing pots could be present potentially for several months and the mortality of the crabs could take place gradually. Thus, the effect of presence of both, live animals and dead snow crab in pots regarding ghost fishing efficiency is unknown, and the time until pots are empty (i.e., all pots contain no snow crab) can take several months.

The present study combined with the former results on initial ghost fishing efficiency (2023) demonstrated that snow crab can be repelled from pots with dead conspecifics, implying that subsequent mortality of ghost fished snow crab could for a period reduce ghost fishing efficiency, eventually leading to empty gear due to depletion of dead crabs. This, however, could again increase the ghost fishing cycle in empty pots up to rates presented in Cerbule et al. (2023).

The results suggest that snow crab, similar to few other decapod crab species, may be repelled from odour of dead conspecifics as the observations showed low ghost fishing risk in self-baited pots. This could indicate avoidance behaviour due to potential danger. These results implies that self-baiting by dead snow crab in these fisheries would not increase the ghost fishing risk in lost pots. However, lost pots still could cause a considerable risk to the marine environment and conservation as discussed in Cerbule et al. (2023). Specifically, decay of dead individuals in pots would imply that more crabs could again be attracted to these pots, either due to seeking shelter, due to random movements, or due to being attracted to live conspecifics in the gear (Miller, 1990; Skajaa et al., 1998; Anderson and Alford, 2014). Moreover, it is also important to note that functionally both empty pots and self-baiting pots should be considered under ALDFG since snow crab entrance in empty gear can result in self-baited pots.

The precise number of pots being lost at sea in Barents Sea snow crab fishery is unknown. However, considering the information from lost gear retrieval operations and accidental snow crab pot retrieval during other fishing operations, this amount can be considerable. Considering the large numbers of pots lost in different fisheries targeting snow crab in the Arctic and the fact that such gear can continue fishing for long periods (i.e., before breaking down to a state where snow crab of all sizes can escape the gear), the effect on the marine environment and unaccounted snow crab mortality can be considerable.

Therefore, the present study showed that ghost fishing in snow crab pots can have varying efficiency over the time pots are exposed to ghost fishing. These factors would be important to consider when further discussing risk posed by ALDFG in this pot fishery regarding both, effect on the marine environment, conservation and management of commercial fisheries due to unaccounted mortality. The environmental challenges of snow crab pots that lead to ghost fishing and gear conflicts are issues that have been a major challenge in economically important snow crab fishery challenging sustainable use of marine resources. Accounting for ghost fishing requires information on number of lost gears, the period they are subjected to ghost fishing and rate of entry and escape by the targeted animals (Miller, 1990). However, due to this complex nature of attraction and subsequent potential repellence caused by self-baiting with dead snow crab, this study shows that estimations of ghost fishing potential in this fishery are complex. Furthermore, attraction to live conspecifics in pots and possible predation upon smaller live individuals by larger snow crab (Humborstad et al., 2021) could further contribute to difficulties when assessing ghost fishing risk.

Potential negative effects of ALDFG in such pot fishery can be mitigated by removing such ALDFG. However, pot removal programs often are expensive due to large distances and large depths that complicate gear retrieval especially in these pot fisheries. Therefore, alternative solutions to limit negative effects caused by lost pots should be considered. Some of the examples include incorporation of biodegradable twine in pot netting (Winger et al., 2015). Alternatively, use biodegradable escape mechanisms are suggested for different pot fisheries (Goodman et al., 2021; Scheld et al., 2015; Winger and Walsh, 2007; 2011). However, biodegradable material used should provide a reasonable time for degradation when the pots are lost at sea. For example, the study by Goodman et al. (2021) in lobster pot fishery found that degradation time for such biodegradable components can take up to four years, implying that ghost fishing can take place for prolonged periods even when such mechanisms are being used.

ALDFG in snow crab fishery is causing complex challenges for fisheries sustainability and marine environment. Due to the same target species and fishing gear type used, similar results as presented here would also apply to other snow crab fisheries. Furthermore, similar approach can be used when estimating ghost fishing and associated self-baiting risk in other pot fisheries and for other species as the effect of self-baiting can vary between species. Furthermore, in other pot fisheries, self-baiting can include other bycatch species (Goodman et al., 2021), thus not being limited mainly to conspecifics such as in snow crab fisheries. Therefore, the effect of self-baiting on the ghost fishing efficiency should be estimated in other fisheries to have a broader overview of the implications of ghost fishing in different pot fisheries.

The results in this study should be interpreted with caution as they are based on a limited number of pot deployments during one fishing season. The limited number of pot deployments and the amount of crab captured leads to uncertainties in the ghost fishing estimations. However, such uncertainties are reflected in the confidence intervals provided with the results. As long as these confidence intervals are considered when interpreting the results, the limited number of pot deployments used in this study should not affect the results (Herrmann et al., 2016). Furthermore, the time of the year and the area in which the experiments were conducted represent typical conditions for the snow crab fishery. Therefore, we consider that our results are representative of a comparable snow crab fishery in the region.

Ethical approval.

We confirm that this manuscript has not been published and is not under consideration by another journal. Ethical approval and informed consent are not applicable for this study.

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CRediT authorship contribution statement

Kristine Cerbule: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Bent Herrmann:** Writing – original draft, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Roger B. Larsen:** Writing – original draft, Conceptualization. **Mengjie Yu:** Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jnc.2024.126764.

Data availability

Data will be made available on request.

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