DTU Library

Ghost fishing efficiency by lost, abandoned or discarded pots in snow crab (Chionoecetes opilio) fishery

Cerbule, Kristine; Herrmann, Bent; Grimaldo, Eduardo; Brinkhof, Jesse; Sistiaga, Manu; Larsen, Roger B.; Bak-Jensen, Zita

Published in:
Marine Pollution Bulletin

Link to article, DOI:
10.1016/j.marpolbul.2023.115249

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Marine Pollution Bulletin 193 (2023) 115249

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

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

Kristine Cerbule[a,b,*], Bent Herrmann[a,b,c], Eduardo Grimaldo[a,b], Jesse Brinkhof[a,b], Manu Sistiaga[a,d], Roger B. Larsen[a], Zita Bak-Jensen[c]

[a] UiT The Arctic University of Norway, Tromsø, Norway
[b] Department of Fisheries Technology, SINTEF Ocean, Trondheim, Norway
[c] DTU Aqua, Technical University of Denmark, Hirtshals, Denmark
[d] Norwegian Institute of Marine Research, Bergen, Norway

ARTICLE INFO

Keywords:
Marine pollution
ALDGF
Derelict pots
Barents Sea

ABSTRACT

Marine pollution by lost, abandoned or otherwise discarded fishing gear (ALDFG) often has negative impact on the ecosystem through plastic pollution and continuous capture of marine animals, so-called "ghost fishing". ALDFG in pot fisheries is associated with high ghost fishing risk. The snow crab (*Chionoecetes opilio*) pot fishery is conducted in harsh weather conditions increasing the risk of fishing gear loss. Due to plastic materials used in the pot construction, lost gear can most likely continue fishing for decades. This study presents a method to quantify ghost fishing efficiency relative to catch efficiency of actively fished pots. On average, the ghost fishing pots captured 8.29 % (confidence intervals: 4.33–13.73 %) target-sized snow crab compared to the actively fished pots, demonstrating that lost pots can continue fishing even when the bait is decayed. Given the large number of pots lost each year, the ghost fishing efficiency is a considerable challenge in this fishery.

1. Introduction

Marine pollution by lost, abandoned or discarded fishing gear (ALDFG) results in environmental and economic challenges for fisheries sustainability (Gilman, 2015a). Globally, pots constitute a large part of derelict fishing gear contributing to the marine litter (Macfadyen et al., 2009; Gilman, 2015a; Scheld et al., 2016; DelBene et al., 2019). In various fisheries pots can be made of different designs and using different materials (He et al., 2021). In cases when decay-resistant materials are used in the pot design, such gear can have significant negative ecological impacts on the marine environment, such as macro- and micro-plastic pollution and continuous capture of marine animals for long periods after being lost at sea, so-called "ghost fishing" (Miller, 1990; Matsuoka et al., 2005; Scheld et al., 2016; Humborstad et al., 2021).

In pot fisheries, the general mechanism of capture is based on the attraction of the target animals by bait, which then approach and enter the gear following the bait odour (Miller, 1990; Cerbule et al., 2023). After some time when the gear is deployed at sea, the bait odour is decayed (Miller, 1990). The absence of bait would suggest that the target animals are no longer attracted to the pots and would not have any incentive to enter the gear (Miller, 1990). However, in the literature, other mechanisms regarding entry efficiency of the pot gear are described, indicating that the ALDFG pots can continue fishing after the bait has decayed as, for example, seeking shelter (Skajaa et al., 1998; Anderson and Alford, 2014), random movements, attraction to live conspecifics in the gear (Miller, 1990), or attraction by dead animals acting as bait in the gear, which again would be causing continued mortality by attracting more conspecifics (Hébert et al., 2001; Havens et al., 2008; Anderson and Alford, 2014). Such ALDFG pots can continue ghost fishing until they are recovered, broken by natural forces like storms, or degraded to a state that all captured animals can escape (Miller, 1990), which, depending on the gear characteristics and deployment, can take long time.

One fishery associated with high risk for gear loss and thus ghost fishing is the pot fishery targeting snow crab (*Chionoecetes opilio* Fabricius 1788) (Hébert et al., 2001; Winger et al., 2015; Humborstad et al., 2021). The snow crab fishery in the Barents Sea started in 2012 (Huse and Bakketeig, 2018); however, the population and subsequently the fishery in this area continues to expand. Currently, the snow crab fishery

* Corresponding author at: UiT The Arctic University of Norway, Tromsø, Norway.
E-mail address: kristine.cerbule@uit.no (K. Cerbule).

https://doi.org/10.1016/j.marpolbul.2023.115249
Received 4 May 2023; Received in revised form 14 June 2023; Accepted 1 July 2023
Available online 7 July 2023

has become substantial in the Barents Sea with catches reaching 7.428 t in 2022 (Norwegian Directorate of Fisheries, 2022a). The fishery is characterized by the large numbers of conical pots employed by each vessel. Specifically, each vessel is allowed to operate up to 9000 pots. The fishery is often performed in harsh weather and ice conditions. The pots are deployed in lines with up to 400 pots per line, concentrated in limited areas, causing potential entanglement with each other as well as other fishing gears such as bottom trawls, subsequently increasing the risk for pot loss. In this fishery, the deployment time varies due to, for example, the weather conditions. However, the maximum pot soaking time according to the Norwegian fishery regulations is three weeks (Norwegian Directorate of Fisheries, 2020). The pots in the Barents Sea snow crab fishery originate from Canada and are made of a metal frame covered with a diamond mesh polyethylene (PE) netting with mesh sizes ranging from 120 to 140 mm, which allow escape of undersized snow crab. The minimum legal size (*MLS*) for snow crab in the Barents Sea is 95 mm carapace width (CW) (Norwegian Directorate of Fisheries, 2020), and crabs under this size must be released. The same pot design is used for targeting snow crab in other areas, including Canada (Newfoundland and Labrador fisheries) and Greenland.

The plastic materials used in the snow crab pot netting does not deteriorate easily (Welden and Cowie, 2017), which prolongs the period ALDFG pots can potentially continue ghost fishing. Conical snow crab pots are robust, and due to that they are deployed in deep water (i.e., around 200–300 m depth in the Barents Sea snow crab fishery) and relatively stable seabed and water current conditions, ALDFG pots can continue ghost fishing for long periods (Hébert et al., 2001; Pawson, 2003; Stevens, 2021). The Norwegian Directorate of Fisheries carries out an annual gear retrieval program, and about 1200 and 2400 snow crab pots were retrieved in the Barents Sea in 2019 and 2020, respectively (Norwegian Directorate of Fisheries, 2022b). Knowledge about the ghost fishing efficiency of ALDFG in this developing fishery would provide valuable information to estimate unaccounted mortality and potential economic losses in the fishery.

The records of lost and recovered snow crab pots in the Barents Sea show that such ALDFG can contain large numbers of snow crab (Humborstad et al., 2021). However, this provides only a limited information about the ghost fishing efficiency in snow crab pots. Specifically, the extent to which snow crab resources are subject to ghost fishing by lost pots is unknown because such estimate would depend on the abundance of snow crab in the specific fishing ground, and knowledge on the number of pots lost annually. Thus, to quantify the ghost fishing efficiency, it can be compared to the catch efficiency of actively (intentionally) fishing pots following commercial practices. Such a comparison would provide a relative estimate of the ghost fishing efficiency that is not dependent on snow crab abundance, or the specific soak time applied. Therefore, our study aimed at first estimating the initial catch efficiency of pots that could take place in such ALDFG when bait odour is decayed over the time the pots are lost at sea. To quantify this initial ghost fishing efficiency, we considered this scenario by comparing simulated ghost fishing pots containing no bait with actively fished pots deployed according to the commercial fishing practice.

The abundance of animals at sea is subject to temporal and spatial variations. Therefore, in studies assessing relative catch efficiency between two different fishing gears, the gears are usually deployed in the same area to account for these possible variations. However, one of the challenges to estimate ghost fishing efficiency in a pot fishery relative to what is being captured by the actively fished pots, is related to potential effect of the bait from the actively fished pots towards the ghost fishing pots without bait when the two different types of gear are deployed in proximity to each other. In this study, we present a method to investigate and quantify the ghost fishing efficiency in the Barents Sea snow crab fishery by comparing it to the catch efficiency of actively fished snow crab pots.

Knowledge of the ghost fishing efficiency would provide information to understand the extent of the negative effect pots have on snow crab mortality as well economical losses for the fishery. Therefore, this study was designed to answer the question regarding catch efficiency of ALDFG in pot fishery (i.e., ghost fishing) relative to pots actively fishing for snow crab.

2. Materials and methods

2.1. Experimental design and data collection

Fishing trials were performed with the research vessel "Helmer Hanssen" (63.8 m LOA and 4080 HP) between 25th of February – 6th of March 2022. The fishing grounds were in the central Barents Sea (74°34.122 N — 74°34.918 N / 33°29.655 E — 35°33.863 E) (Fig. 1) at depths of around 265 m. During the trials, we used standard baited snow crab pots as baseline (hereafter, actively fished pots) and snow crab pots without any bait to simulate ghost fishing (hereafter, ghost fishing pots).

Both ghost fishing and actively fished pots in the trials were identical with the only difference being that the latter contained bait. These pots were baited similar as practiced in the commercial fishery, i.e., approximately 800 g of squid (*Illex* spp.) divided into two parts, one placed in a small mesh bait bag and the other in a perforated plastic bait container, both hanging below the entrance cone of the pot. The ghost fishing pots did not contain any bait when they were deployed.

Similar to the pots used in the commercial fishery, the diameter of top and bottom rings in the pots were 70 and 130 cm, respectively, and they were 60 cm high (Cerbule et al., 2022). In the commercial fishery, mesh sizes range from 120 mm to 140 mm, which affects the size selectivity of snow crab (Herrmann et al., 2021). In this study we used small-mesh netting in all pots, both actively fished and ghost fishing pots, to retain all sizes of snow crab. Therefore, this approach allows comparing the entry probability of snow crab of all sizes. The netting used to cover all pots had a nominal mesh size of 52 mm.

In studies assessing the efficiency of passive fishing gear such as pots, it is often deployed by alternating the test gear and the baseline gear. Thus, both configurations are placed in close vicinity to each other to account for possible variations in abundance of the target animals (Olsen et al., 2019; Cerbule et al., 2021, 2022). However, such an experimental design would not be optimal for this study comparing the ghost fishing and actively fished pots, because the actively fished pots containing bait potentially could attract crab from the areas around the ghost fishing pots, affecting their catch efficiency and biasing the results of the study. To minimize the risk for bias, it was necessary to leave sufficient distance between the ghost fishing and actively fished pots. At the same time, too large distance between the two pot configurations could lead to differences in the snow crab abundance regarding population density and size structure of crabs available for both pot configurations. Such potential differences could bias the estimation of the relative efficiency between the ghost fishing and actively fished pots based on catch data. To cope with these challenges, the experimental design proposed in this study, which we call the triplet design, consists of three lines of pots, each containing a single pot configuration (either ghost fishing pots or actively fished pots) and separated by 0.5 nautical miles (nm), which equals 926 m. In an earlier study in another crab fishery, DelBene et al. (2019) used a 260 m distances between pot types assuming that such distance is sufficient to provide independence between the designs. However, the optimal distance can vary between fisheries and species; therefore, we further increased this distance to 0.5 nm to ensure independency between the ghost fishing and actively fished pots. The two outer lines in the experimental design contained only ghost fishing pots while the middle line contained only actively fished pots (Fig. 1). Such a design provides independency in the entry probability between ghost fishing and actively fished pots.

The pots were attached to each line every 30 m with a 2 m long gangion and a quick-link system. The deployment and recovering time for the lines was kept the same resulting in 12 days of soaking time for the three lines. This soak time corresponds to a typical soak time used in

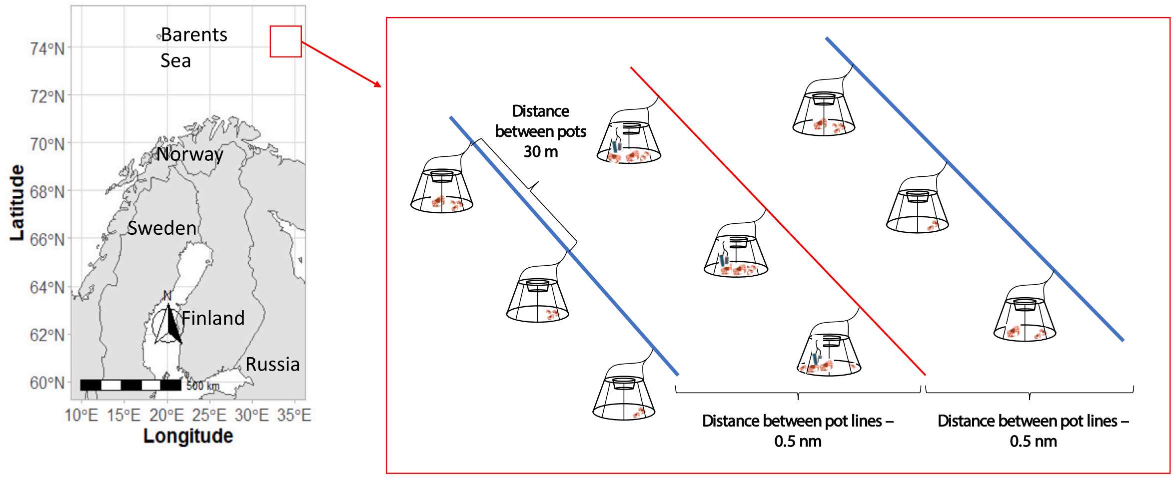

Fig. 1. Map of the area where the trials were conducted (left), and experimental design used during the trials (right). In the panel showing the experimental design, blue lines denote lines containing ghost fishing pots while the red line in the middle – actively fished pots with bait. The distance between the pots was 30 m. The distance between the three parallel deployed lines was 0.5 nm, which equals 926 m. Each of the three lines contained 30 pots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

commercial fisheries (for example, Cerbule et al., 2021), and, therefore, found suitable for the specific investigation. Each of the three lines was hauled on board separately. The CW (i.e., the largest distance across the carapace, including spines) of all snow crab in each pot was measured to the nearest millimetre below using callipers according to Jadamec et al. (1999).

The basic idea by using the triplet design is that the expected snow crab abundance available for the centre line with actively fished pots will be approximately the mean for the two ghost fishing outer lines based on simple linear interpolation. Therefore, the catch comparison is made between the middle line versus the two outer lines and the risk for bias due to abundance should be reduced. Thus, one only needs to account for differences in number of pots deployed.

2.2. Estimation of mean number of snow crab captured in ghost fishing and actively fished pots

To compare the ghost fishing efficiency with the catches of the actively fished gear, we first examined the mean number of snow crab retained in the ghost fishing and actively fished pots expressed as catch per unit of effort (*CPUE*):

$$CPUE_G = \frac{\sum_{i=1}^{KG} nG_i}{KG} \qquad CPUE_A = \frac{\sum_{i=1}^{KA} nA_i}{KA} \tag{1}$$

In Eq. (1), nG_i is the number of crab in ghost fishing pot i while nA_i is the number of snow crab retained in the actively fished pot i. KG and KA are the number of pots on ghost fishing and actively fished lines, respectively. Uncertainties for $CPUE_G$ and $CPUE_A$ were obtained using a bootstrap approach where groups of ghost fishing and actively fished pots were resampled separately with replacement, leading to a set of values for $CPUE_G$ and $CPUE_A$. Repeating this resampling 1000 times led to a population of 1000 results for $CPUE_G$ and $CPUE_A$, which were applied to obtain Efron 95 % percentile confidence intervals (CIs) (Efron, 1982). We used the software SELNET for the analysis of the data (Herrmann et al., 2012).

CPUE estimations depend on the spatial and temporal size-dependent availability of snow crab on the fishing ground at the time and location the experiments are conducted. Therefore, $CPUE_G$ and $CPUE_A$ for ghost fishing and actively fished pots, respectively, provide only limited insight on the potential differences between the configurations, and the results cannot be extrapolated to other fishing areas and seasons.

In contrast to the *CPUE* estimation, the relative catch efficiency between the ghost fishing and actively fished pots can be estimated based on catch data from the fishing experiments, not requiring the information on the size-dependent availability of snow crab (Olsen et al., 2019; Cerbule et al., 2021, 2022).

2.3. Estimation of the ghost fishing efficiency

The relative size-dependent catch efficiency between ghost fishing and actively fished pots was estimated using catch comparison and catch ratio analyses (Herrmann et al., 2017). The method uses the experimental design of the three mainlines of pots with two outer mainlines simulating the ghost fishing pots (Fig. 1). Due to this design, we assumed that the snow crab abundance for the actively fished pots is approximately half of that summed over the two outer ghost fishing mainlines. Further, we assumed that the capture in a pot is proportional with the local abundance where the pots are deployed. This allows using a catch comparison and catch ratio method to compare the ghost fishing and catch efficiency between the two. However, with this experimental design, the experimental catch comparison rate is estimated by using the following (Eq. 2):

$$CC_{cw} = \frac{\sum_{i=1}^{q} nG1_{cw,i} + \sum_{i=1}^{q} nG2_{cw,i}}{\sum_{i=1}^{q} nA_i + \sum_{i=1}^{q} nG1_{cw,i} + \sum_{i=1}^{q} nG2_{cw,i}} \tag{2}$$

In Eq. (2), $nG1_{CW,i}$, $nG2_{CW,i}$ and $nA_{CW,i}$ are the numbers of snow crab with carapace width *CW* being captured in pot i in ghost fishing pots in *G1* or *G2* or actively fished 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 Eq. (2)) was estimated based on the catch data summed over the q pots by minimizing the following expression:

$$-\sum_{CW}\left\{\sum_{i=1}^{q}\left\{nG1_{CW,i}\times ln\left(CC(\boldsymbol{v},CW)\right\}+\sum_{i=1}^{q}\left\{nG2_{CW,i}\times ln\left(CC(\boldsymbol{v},CW)\right\}+\sum_{i=1}^{q}\left\{nA_{CW,i}\times ln\left(1.0-CC(\boldsymbol{v},CW)\right\}\right\} \quad (3)$$

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 size classes of snow crab (*CW*).

If the catch efficiency of ghost fishing pots and active fishing pots was equal with equal number of pots deployed, the expected value for the summed catch comparison rate would be equal to 0.5 (Cerbule et al., 2021). In this case, due to this experimental design applied, the baseline for identical catch efficiency between the ghost fishing pots (test) and actively fished pots (baseline) is 0.67. The experimental CC_{cw} is often modelled by the function $CC(\boldsymbol{v}, CW)$, with the following form (Cerbule et al., 2021):

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

In Eq. (4), 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 ghost fishing and actively fished pots. Estimations of the catch comparison rate were made using multi-model inference to obtain the best combined model to represent the data (Burnham and Anderson, 2002; Herrmann et al., 2017).

The ability of the combined model to describe the experimental data was evaluated based on the *p*-value, which quantifies the probability of obtaining by coincidence at least as big a discrepancy between the experimental data and the model as the one observed. Therefore, this *p*-value, which was calculated based on the model deviance and the degrees of freedom, 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 method described in Herrmann et al. (2017). Specifically, each line of pots were treated separately, meaning that the resampling was conducted independent of the rest of the lines. Within a line (*G1*, *G2* or *A*, respectively), the pots on the line were resampled in an outer loop with replacement to account for the variation in capture between the pots along that specific line. Each time a pot was selected in the outer loop, the captured population in that pot was resampled in an inner resampling loop to account for uncertainty in size structure in the pot catch due to finite number of crab in a pot. For each of the three lines this bootstrap approach was applied with 1000 repetitions. Thus, the approach led to three separate bootstrap populations of data. Next, the three bootstrap populations were aggregated. This was specifically done for each bootstrap by aggregating the data for the individual bootstrap resamples. The resulting data was thereafter used to minimize Expression (3) and thereby provide a bootstrap population of results for $CC(\boldsymbol{v}, CW)$. Following, Efron 95 % confidence intervals were obtained from this bootstrap population (Efron, 1982).

Based on the estimated catch comparison function $CC(\boldsymbol{v}, CW)$, we obtained the relative catch efficiency $CR(\boldsymbol{v}, CW)$ between the ghost fishing and actively fished pots by the following equation:

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

Estimation of the confidence intervals for $CR(\boldsymbol{v}, CW)$ were obtained by incorporating Eq. (5) in the bootstrap population estimation.

Finally, size-integrated average values (in percentage) for catch ratio ($CR_{average}$) (in percentage) were estimated directly from the experimental catch data by the following equations:

$$CR_{average-}=100\times\frac{\frac{1}{2}\sum_{CW<MLS}\left\{\sum_{i=1}^{q}nG1_{CW,i}+\sum_{i=1}^{q}nG2_{CW,i}\right\}}{\sum_{CW<MLS}\left\{\sum_{i=1}^{q}nA_{CW,i}\right\}}$$

$$CR_{average+}=100\times\frac{\frac{1}{2}\sum_{CW\geq MLS}\left\{\sum_{i=1}^{q}nG1_{CW,i}+\sum_{i=1}^{q}nG2_{CW,i}\right\}}{\sum_{CW\geq MLS}\left\{\sum_{i=1}^{q}nA_{CW,i}\right\}} \quad (6)$$

$$CR_{average}=100\times\frac{\frac{1}{2}\sum_{CW}\left\{\sum_{i=1}^{q}nG1_{CW,i}+\sum_{i=1}^{q}nG2_{CW,i}\right\}}{\sum_{CW}\left\{\sum_{i=1}^{q}nA_{CW,i}\right\}}$$

where the outer summations include the size classes for the catch during the experimental fishing period under *MLS* ($CR_{average-}$) and over *MLS* ($CR_{average+}$). In contrast to the size-dependent evaluation of the catch ratio, $CR_{average}$ is specific for the snow crab population structure encountered during the experimental sea trials, and it cannot be applied to other scenarios in which the size structure of the population may be different (Olsen et al., 2019; Cerbule et al., 2021).

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

To check for variation in snow crab abundance within the area fished, we used a standard catch comparison method between the two ghost fishing lines (Herrmann et al., 2017; Olsen et al., 2019; Cerbule et al., 2021). Specifically, we used the catch comparison analysis to determine whether there were differences in retention of snow crab of different sizes between the pots in the two outer ghost fishing lines. If there were no significant spatial differences in snow crab abundance, both lines would be expected to retain similar numbers of snow crab in each length class. Thus, in case the confidence intervals for all sizes of snow crab caught include 0.5, it is unlikely that the abundance varies within the area and time used in this study for the assessment of the ghost fishing efficiency.

We used unpaired catch comparison ($CC(\boldsymbol{v},CW)$) and catch ratio ($CR(\boldsymbol{v},CW)$) analyses (Herrmann et al., 2017) for these estimations. Further, the size-integrated average catch ratio ($CR_{average}$) and size-integrated catch ratio values for snow crabs under ($CR_{average-}$) and above ($CR_{average+}$) *MLS* were estimated directly from the catch data. We used the statistical software SELNET to conduct the analysis (Herrmann et al., 2012). Further details about the estimation of $CC(\boldsymbol{v},CW)$, $CR(\boldsymbol{v},CW)$ and $CR_{average}$ are provided in the Supplementary material (S1).

3. Results

During the experiments, one line with 30 actively fished pots and two lines with 30 ghost fishing pots each were deployed simultaneously in an area used by the commercial snow crab fishery following the triplet experimental design (Fig. 1). The depth on the fishing grounds was around 265 m (Table 1). After 12 days of soaking time, a total of 3427 snow crab were captured and measured (Table 1). More undersized compared to target sized crab were caught in both, actively fished and ghost fishing pots (Table 1).

Table 1
Details from the three deployed pot lines (one line with baited snow crab pots and two lines of ghost fishing pots pots) showing position of the lines, depth, number of pots in each line and number of crabs retained in each line.

	Actively fished pots (*A*)	Ghost fishing pots (*G1*)	Ghost fishing pots (*G2*)
Start position	N74°34.782; E35°32.115	N74°34.615; E35°33.863	N74°34.918; E35°30.303
End position	N74°34.320; E35°31.405	N74°34.122; E35°33.150	N74°34.511; E33°29.655
Depth at start position (m)	265	269	266
Depth at end position (m)	264	265	263
Number of pots	30	30	30
Total number of crabs	3245	90	92
Number of crabs below *MLS*	3058	78	73
Number of crabs above *MLS*	187	12	19

Table 2
Fit statistics and catch ratio values (in %) obtained for the ghost fishing pots against the actively fished pots for undersized and target-sized snow crab (*CRaverage-* and *CRaverage+*, respectively), and average over all sizes of snow crab (*CRaverage*). Values in parentheses represent the 95 % confidence limits. DOF = degrees of freedom.

p-value	0.1566
Deviance	92.72
DOF	80
CRaverage-	2.47 (1.95–3.11)
CRaverage+	8.29 (4.33–13.73)
CRaverage	2.80 (2.27–3.43)

3.1. *Mean number of snow crabs in ghost fishing pots compared to actively fished pots*

The results showed different mean numbers of crab captured in each pot when the retention by the ghost fishing pots and actively fished pots were compared. Specifically, there was a significant difference between the pots since the *CPUE* of for the actively fished pots ($CPUE_A$) was 108.17 (CI: 93.80–120.83), whereas for the ghost fishing pots the $CPUE_G$ was 2.98 (CI: 2.54–3.49).

3.2. *Estimating ghost fishing efficiency relative to catch efficiency of actively fished pots*

To estimate the ghost fishing efficiency while taking into consideration the possible spatial and temporal variability of snow crab abundance, we adapted methods used in fishing gear catch efficiency estimation as described in Section 2.3. The fit statistics of the analysis showed that the deviation between the experimental data and the modelled catch comparison rate could be coincidental (p-value >0.05) (Table 2).

During the experiment, the average ghost fishing efficiency of snow crab averaged over all sizes was 2.80 % compared to the catch efficiency of the actively fished pots (*CRaverage* = 2.80 % (CI: 2.27–3.43 %)). This ghost fishing efficiency was significantly lower compared to the catch efficiency of baited actively fished pots (Table 2; Fig. 2). However, the ghost fishing efficiency for all sizes of snow crab, both undersized and

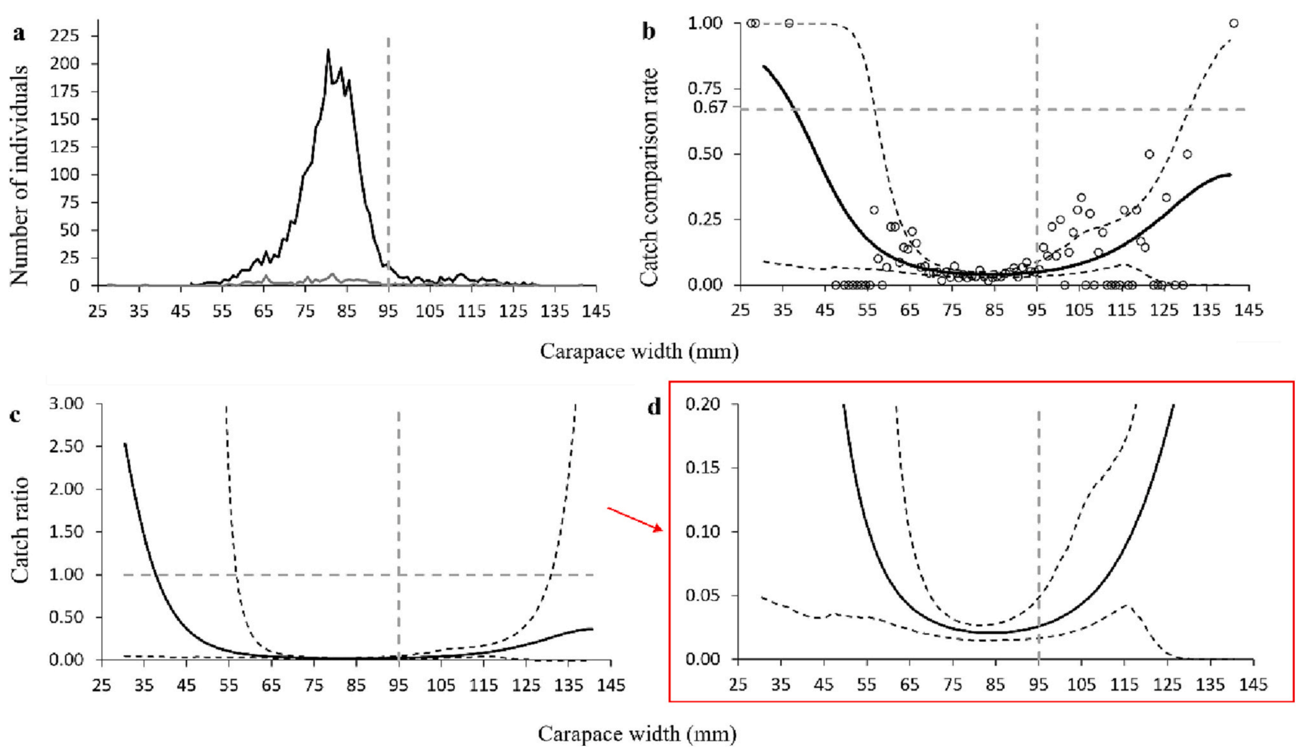

Fig. 2. a) Populations caught in actively fished (black) and ghost fishing (grey) pots; b) catch comparison rate (black curve, with experimental catch comparison rates (black circles); c) catch ratio, and d) scaled catch ratio of c) determining whether the ghost fishing efficiency is significantly different from zero. Stippled lines represent 95 % CIs. The horizontal grey stippled lines in b-c show the expected catch comparison rate in case of no significant difference between the pots investigated accounting for the number of units deployed for actively fished and ghost fishing pots, respectively. The stippled vertical lines represent the minimum legal size of the snow crab (95 mm carapace width).

Table 3
Fit statistics and average catch ratio values (in %) between the two ghost fishing lines for snow crab below and above *MLS* (*CRaverage-* and *CRaverage+*, respectively), and averaged over all sizes (*CRaverage*). Values in parentheses represent the 95 % confidence limits. DOF = degrees of freedom.

p-value	0.0654
Deviance	73.92
DOF	57
CRaverage-	106.85 (73.33–157.14)
CRaverage+	63.16 (20.51–184.61)
CRaverage	97.83 (71.17–138.96)

target sized individuals, was significantly different from 0.00 (Fig. 2c). This shows that there is a significant ghost fishing efficiency of ALDFG in the snow crab pot fishery.

Moreover, a significant size-dependent difference in ghost fishing efficiency was observed in this study. A larger fraction of the retained snow crab in the ghost fishing pots compared to actively fished pots were target-sized individuals over 95 mm CW with the catch efficiency around 8.3 % of what the actively fished pots are retaining (*CRaverage +* = 8.29 % (CI: 4.33–13.73 %)). Meanwhile, the capture of undersized individuals by ghost fishing pots was lower and constituted around 2.5 % compared to the actively fished pots (*CRaverage-* = 2.47 % (CI: 1.95–3.11 %)) (Table 2). Thus, the ghost fishing efficiency for target sized individuals (CW $\geq$ 95 mm) was around 8 % compared to the actively fished pots, and this result was significantly different from 0.00 (Table 2, Fig. 2). However, also the entry efficiency by undersized snow crab in the ghost fishing pots was significant (Table 2, Fig. 2).

3.3. Variation in snow crab abundance within the fished area

The comparison of the catch efficiency between the two outer lines, i. e., the ghost fishing pot lines (*G1* and *G2*), allowed to infer whether there were any differences in snow crab abundance in the fishing area covered during our trials. The fit statistics of the catch comparison analysis showed that the *p*-value was >0.05 (*p*-value = 0.0654) (Table 3) showing that the deviation between the experimental data and the modelled catch comparison rate could be coincidental. The results of the comparison showed no significant difference in catch efficiency for any of the CW size classes (*CRaverage* = 97.83 (CI: 71.17–138.96)) (Table 3, Fig. 3). Specifically, there was no significant difference in snow crab captured of either undersized (*CRaverage-* = 106.85 % (CI: 73.33–157.14 %)) or target-sized ($CRaverage_{+}$ = 63.16 % (CI: 20.51–184.61 %)) individuals. Therefore, this result gives additional support that there were no significant difference in snow crab abundance (density and size structure) in the area covered during these trials. Thus, this provides an additional support that the snow crab abundance would not have effect on the results estimating the ghost fishing efficiency in this study.

4. Discussion

In this study we investigated the ghost fishing efficiency by simulating ghost fishing of lost snow crab pots relative to the catch efficiency of actively fished baited pots in a field experiment. Although earlier studies have shown that in various pot fisheries there is a risk for ghost fishing after the gear has been lost, abandoned or discarded, the extent and implications of the ghost fishing have not been quantified. In this study, we used a method that allowed such quantification, accounting for potential spatial variation in snow crab density and potential differences in size structure. The applied approach estimated the ghost fishing efficiency of snow crab pots relative to the catch efficiency of actively fished pots, accounting for potential variation in snow crab availability between the pot lines due to the distance between them.

The results of this study show that the ghost fishing efficiency by simulated ghost fishing pots without presence of bait was significantly lower for all sizes of snow crab when compared to the efficiency of actively fished baited pots. This difference was likely due to the difference in attraction between the baited and non-baited pots. Generally, in a pot fishery, ghost fishing can be divided into a short phase of high catch rates due to the bait odour still attracting the target individuals to the gear. This is then usually followed by a phase of lower catch rates when the bait decays over time (Miller, 1990). Because the ghost fishing pots were not baited like the actively fished pots, the detection and attraction to the pots by the crabs over distance can, therefore, differ between them, thus explaining the observed differences.

The difference in ghost fishing efficiency was detected for both undersized and target sized snow crab. Specifically, the average entry efficiency of undersized crab (< 95 mm CW) in ghost fishing pots was 2.47 % (*CRaverage-* = 2.47 (CI: 1.93–3.11)), while the retention for target sized individuals reached 8.29 % (*CRaverage +* = 8.29 (CI: 4.33–13.73)). The entry of undersized individuals in lost snow crab pots would cause less concern compared to larger target-sized snow crab as the small crab would be able to escape through the meshes in pots used in the commercial fishery. The fisheries in the Barents Sea, Canada (where the *MLS* is 95 mm CW) and Greenland (where the *MLS* is 100 mm CW) are targeting large snow crab. These fisheries aim at excluding the undersized snow crab during the pot deployment at the seabed since it is believed to improve the survival of the non-target small individuals compared to when they are sorted on board and released back into the sea. Further, size selecting the crab at the seabed also reduces the workload of having to sort the crab onboard. The mesh size used in the pots is chosen to release undersized crab while maximizing the retention of large individuals. Therefore, the escape of large individuals once they enter the pot would not be possible. These individuals remain in the pots, and in the cases where the pots are not retrieved either because they are lost or abandoned, they end up dying and potentially acting as bait that attracts other animals to the pots. The novel approach used in current study allowed a quantification of the ghost fishing efficiency for conical pots in the Barents Sea snow crab fishery. Although earlier studies have reported ghost fishing in snow crab pot fisheries (e.g., Hébert et al., 2001; Humborstad et al., 2021) and it has been also observed during ALDFG recovery operations (Norwegian Directorate of Fisheries, 2022b), the extent of this marine pollution problem has not been scientifically quantified. Furthermore, we expect that these results would be similar for other snow crab pot fisheries like in Canada and Greenland since they apply the same pot design and bait. This extrapolation is also valid to other snow crab fisheries which might have another abundance pattern of snow crab due to that one of the advantages of the applied method is that it is based on estimating the relative fishing efficiency between ghost fishing and actively fished pots.

The time of the year and the area in which the experiments of this study were conducted represent typical conditions for the commercial snow crab fishery in the Barents Sea. Therefore, we consider that our results are representative for the snow crab fishery in the region. Furthermore, we consider that 12 days soak time is sufficient for addressing the aim of this study considering that sufficient number of crab were caught to estimate the relative catch efficiency with relatively narrow CIs. Also, 12 days is a relevant soak time for actively fished pots in this fishery and, therefore, it is relevant for comparing the catch efficiency between ghost fishing pots against actively fished pots. In addition, an advantage of using ratio based technique as the relative catch efficiency is that as long as we do not exceed typical soak time and as long we deploy the ghost fishing pots without bait, the actual soaking time is not important as long as sufficient number of crab is captured by both, ghost fishing and actively fished pots. Specifically, the simulated ghost fishing pots in this study were already deployed without using bait; therefore, no additional time for bait to decay is needed.

The results of this study show that the pots that are lost or abandoned with bait decaying over time, or pots that are just discarded with no bait present, have the potential to capture snow crab, especially individuals

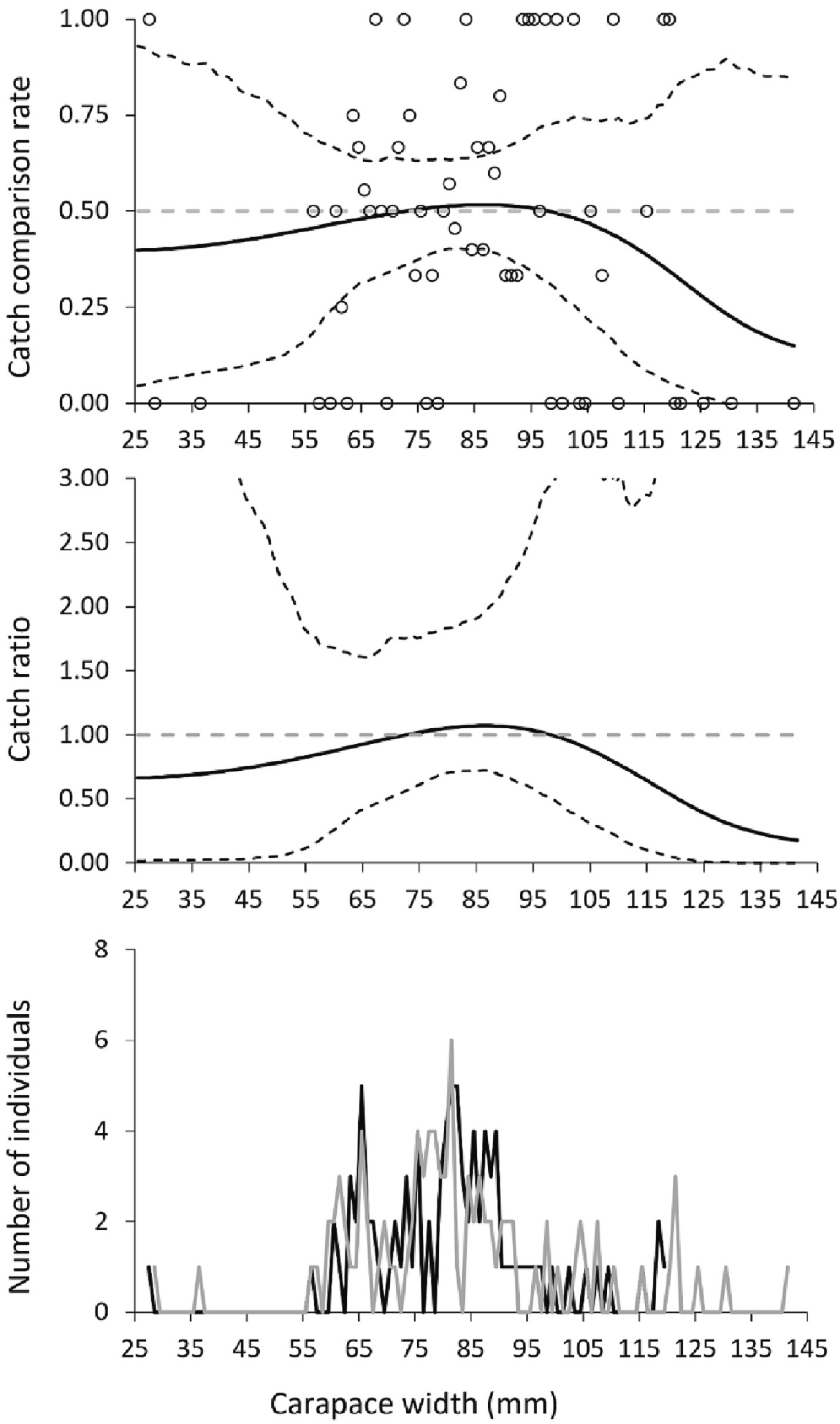

Fig. 3. Catch comparison rate (upper graph), catch ratio (middle graph) with 95 % CIs (stippled curves) and population caught in two ghost fishing pot lines (black and grey lines) (lower graph). Circles in the catch comparison graph represent experimental catch comparison rates. The horizontal grey stippled lines show the expected catch comparison rate in case of no difference between the pots investigated. The stippled vertical lines represent the minimum legal size of the snow crab (95 mm carapace width).

above *MLS*, which once entering the ghost fishing gear would not be able to escape. Although this ghost fishing efficiency is significantly smaller compared to the commercial snow crab fishery, it is not negligible and raises questions regarding the sustainability of the fishery. Furthermore, since all target-sized snow crab entering such ALDFG are likely retained, these pots have the potential to initiate a self-stimulating process of unintended snow crab retention due to self-baiting of the pots over time, which could create a ghost fishing cycle (Hébert et al., 2001). Specifically, the self-baiting of the gear can imply two processes where, first, live crab caught in the ALDFG pots can attract other conspecifics and, second, where moribund and decomposing organisms attract scavengers. Some of these scavengers are caught in the pots, die, and decompose acting again as bait for newcoming scavengers (Gilman, 2015b). Since this study demonstrated a significant ghost fishing risk by pots that would be lost without bait present or when bait has decayed over time, it should be further followed up by additional experiments estimating the potential effect of self-baiting that could follow such initial ghost fishing as demonstrated in this study. Specifically, if the catch efficiency of target-sized snow crab is significant and their subsequent escape is limited or impossible, then such trapped dead/dying animals could over time attract scavengers that in turn could affect the ghost fishing efficiency. Furthermore, the risk of such ALDFG to fall in this cycle emphasizes the need for escape mechanisms to avoid unnecessary mortality of snow crab and limiting the potential ghost fishing time.

Marine pollution by ALDFG including pots and resulting ghost fishing would be most efficiently mitigated by removing or preventing the occurrence of lost gear. However, initiatives and programs to remove ALDFG are expensive and require coordination among multiple parties to locate, remove, and then dispose such pots (DelBene et al., 2019). Furthermore, as all gear loss cannot be prevented, other measures, such as the incorporation of effective biodegradable escape mechanisms is necessary to limit the potential time for ghost fishing (Scheld et al., 2016). In the snow crab fisheries, pots are often equipped with a biodegradable (cotton) string in the pot netting that is supposed to degrade after a limited period of time in case the pot is lost at sea (Winger et al., 2015). In principle, once the string has degraded, the netting in the pot has a permanent opening that would allow all crab entering the gear to escape. However, such mechanism might not provide an optimal degradation time. For example, in an operation recovering abandoned snow crab pots that remained at sea for a period of 1.5 years, none of the cotton threads of 5 mm diameter used in those pots were broken; furthermore, the mean breaking strength of them was estimated to still be around 17 kg after recovery (Humborstad et al., 2021). Considering the ghost fishing efficiency by the ALDFG pots, it would, therefore, be necessary to use an appropriate animal release mechanism that provide an optimal degradation time in case the gear is left at sea unattended.

This study investigated the catch efficiency of non-baited pots to evaluate the potential for ghost fishing by such ALDFG in the Barents Sea snow crab fishery; however, the approach used here can also be applied to estimate the potential for ghost fishing efficiency in other fisheries using passive fishing gear. Further, studies estimating the effect of self-baiting in ghost fishing pots are necessary to better understand the ghost fishing efficiency that can result over time. This study demonstrated that lost, abandoned or discarded snow crab pots continue capturing snow crab of target sizes which are unable of escaping the pot using the commercial mesh sizes. However, the further resulting extent of self-baiting of the gear remains to be assessed.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.115249.

CRediT authorship contribution statement

Kristine Cerbule: Conceptualization, data gathering and investigation, formal analysis, visualization, writing – original draft, writing – review and editing.

Bent Herrmann: Conceptualization, software, data gathering and investigation, formal analysis, writing – original draft, writing – review and editing.

Eduardo Grimaldo: Data gathering and investigation, writing – original draft.

Jesse Brinkhof: Data gathering and investigation, writing – original draft.

Manu Sistiaga: Data gathering and investigation, writing – original draft.

Roger B. Larsen: Writing – original draft.

Zita Bak-Jensen: Data gathering and investigation, 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.

Data availability

Data will be made available on request.

Acknowledgments

This project was financed by the Research Council of Norway (Dsolve, grant number: RCN300008). We thank the crew of RV "Helmer Hanssen", Ivan Tatone, Jostein Saltskår, Ilmar Brinkhof, Nadine Jacques, Enis Kostak and Hanne Hjelle Hatlebrekke for valuable assistance during data collection on board. We are grateful to the editor and reviewers for their valuable comments, which we feel have improved our manuscript.

References

Anderson, J.A., Alford, A.B., 2014. Ghost fishing activity in derelict blue crab traps in Louisiana. Mar. Pollut. Bull. 79, 261–267. https://doi.org/10.1016/j.marpolbul.2013.12.002.

Burnham, K.P., Anderson, D.R., 2002. Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach, 2nd ed. Springer-Verlag, New York. ISBN 978-0-387-22456-5.

Cerbule, K., Herrmann, B., Grimaldo, E., Grimsmo, L., Vollstad, J., 2021. The effect of white and green LED-lights on the catch efficiency of the Barents Sea snow crab (*Chionoecetes opilio*) pot fishery. PLoS One 16 (10), e0258272. https://doi.org/10.1371/journal.pone.025872.

Cerbule, K., Herrmann, B., Grimaldo, E., Sistiaga, M., Brinkhof, J., Vollstad, J., 2022. Understanding and predicting the effect of entrance cone diameters on the catch efficiency of snow crabs (*Chionoecetes opilio*) in conical pots. Reg. Stud. Mar. Sci. 52, 102237 https://doi.org/10.1016/j.rsma.2022.102237.

Cerbule, K., Grimsmo, L., Herrmann, B., Grimaldo, E., 2023. Increasing sustainability in food production by using alternative bait in snow crab (*Chionoecetes opilio*) fishery in the barents sea. Heliyon 9 (3), e13820. https://doi.org/10.1016/j.heliyon.2023.e13820.

DelBene, J.A., Bilkovic, D.M., Scheld, A.M., 2019. Examining derelict pot impacts on harvest in a commercial blue crab *Callinectes sapidus* fishery. Mar. Pollut. Bull. 139, 150–156. https://doi.org/10.1016/j.marpolbul.2018.12.014.

Efron, B., 1982. The jackknife, the bootstrap and other resampling plans. SIAM Monograph No. 38, SBSM-NSF.

Gilman, E., 2015a. Highest risk of abandoned, lost and discarded fishing gear. Sci. Rep. 11, 7195. https://doi.org/10.1038/s41598-021-86123-3.

Gilman, E., 2015b. Status of international monitoring and management of abandoned, lost and discarded fishing gear and ghost fishing. Mar. Policy 60, 225–239. https://doi.org/10.1016/j.marpol.2015.06.016.

Havens, K.J., Bilkovic, D.M., Stanhope, D., Angstadt, K., Hershner, C., 2008. The effects of derelict blue crab traps on marine organisms in the Lower York River, Virginia. N. Am. J. Fish Manag. 28 (4), 1194–1200. https://doi.org/10.1577/M07-014.1.

He, P., Chopin, F., Suuronen, P., Ferro, R.S.T., Lansley, J., 2021. Classification and Illustrated Definition of Fishing Gears. In: FAO Fisheries and Aquaculture Technical Paper No. 672. Rome, FAO. https://doi.org/10.4060/cb4966en.

Hébert, M., Miron, G., Moriyasu, M., Vienneau, R., DeGrâce, P., 2001. Efficiency and ghost fishing of snow crab (*Chionoecetes opilio*) traps in the Gulf of St. Lawrence. Fish. Res. 52, 143–153.

Herrmann, B., Sistiaga, M., Nielsen, K.N., Larsen, R.B., 2012. Understanding the size selectivity of redfish (*Sebastes* spp.) in North Atlantic trawl codends. J. Northwest Atl. Fish. Sci. 44, 1–13. https://doi.org/10.2960/J.v44.m680.

Herrmann, B., Sistiaga, M., Rindahl, L., Tatone, I., 2017. Estimation of the effect of gear design changes on catch efficiency: methodology and a case study for a Spanish longline fishery targeting hake (*Merluccius merluccius*). Fish. Res. 185, 153–160. https://doi.org/10.1016/j.fishres.2016.09.013.

Herrmann, B., Grimaldo, E., Brčić, J., Cerbule, K., 2021. Modelling the effect of mesh size and opening angle on size selection and capture pattern in a snow crab (*Chionoecetes opilio*) pot fishery. Ocean Coast. Manag. 201, 105495 https://doi.org/10.1016/j.ocecoaman.2020.105495.

Humborstad, O.-B., Eliassen, L.K., Siikavuopio, S.I., Løkkeborg, S., Ingolfsson, O.A., Hjelset, A.M., 2021. Catches in abandoned snow crab (*Chionoecetes opilio*) pots in the Barents Sea. Mar. Pollut. Bull. 173, 113001 https://doi.org/10.1016/j.marpolbul.2021.113001.

Huse, G., Bakketeig, I.E., 2018. Resource overview 2018. Fisken og Havet 6–201.

Jadamec, L.S., Donaldson, W.E., Cullenberg, P., 1999. Biological Field Techniques for *Chionoecetes* Crabs. Alaska Sea Grant College Program, Fairbanks.

Macfadyen, G., Huntington, T., Cappell, R. (2009). Abandoned, lost or otherwise discarded fishing gear. FAO fisheries and aquaculture technical paper no. 523, Rome.

Matsuoka, T., Nakashima, T., Nagasawa, N., 2005. A review of ghost fishing: scientific approaches to evaluation and solutions. Fish. Sci. 71, 691–702.

Miller, R.J., 1990. Effectiveness of crab and lobster traps. Can. J. Fish. Aquat. Sci. 47, 1228–1251.

Norwegian Directorate of Fisheries (2020). J-213-2020: Forskrift om forbut mot fangst av snøkrabble. Available at: https://www.fiskeridir.no/Yrkesfiske/Regelverk-og-reguleringer/J-meldinger/Gjeldende-J-meldinger/j-213-2020 (accessed at 01.02.2021).

Norwegian Directorate of Fisheries (2022a). Catches of snow crab (in Norwegian). Available at: https://www.fiskeridir.no/Yrkesfiske/Tall-og-analyse/Fangst-og-kvoter/Fangst/fangst-av-snokrabbe (accessed at 17.09.2022a).

Norwegian Directorate of Fisheries (2022b). Gear retrieval (in Norwegian). Available at: https://www.fiskeridir.no/Areal-og-miljo/Marin-forsoepling/Redskapsopprensking (accessed at 13.10.2022b).

Olsen, L., Herrmann, B., Sistiaga, M., Grimaldo, E., 2019. Effect of gear soak time on size selection in the snow crab pot fishery. Fish. Res. 214, 157–165. https://doi.org/10.1016/j.fishres.2019.02.005.

Pawson, M.G., 2003. The catching capacity of lost static fishing gears: introduction. Fish. Res. 64 (2–3), 101–105. https://doi.org/10.1016/S0165-7836(03)00208-X.

Scheld, A.M., Bilkovic, D.M., Havens, K.J., 2016. The dilemma of derelict gear. Sci. Rep. 6, 19671. https://doi.org/10.1038/srep19671.

Skajaa, K., Fernö, A., Løkkeborg, S., Haugland, E.K., 1998. Basic movement pattern and chemo-oriented search towards baited pots in edible crab (*Cancer pagurus* L.). Hydrobiologia 371, 143–153. https://doi.org/10.1023/A:1017047806464.

Stevens, B.G., 2021. The ups and downs of traps: environmental impacts, entanglement, mitigation, and the future of trap fishing for crustaceans and fish. ICES J. Mar. Sci. 78 (2), 584–596. https://doi.org/10.1093/icesjms/.

Welden, N.A., Cowie, P.R., 2017. Degradation of common polymer ropes in a sublittoral marine environment. Mar. Pollut. Bull. 118 (1–2), 248–253. https://doi.org/10.1016/j.marpolbul.2017.02.072.

Wileman, D.A., Ferro, R.S.T., Fonteyne, R., Millar, R.B. (Eds.) (1996). Manual of Methods of Measuring the Selectivity of Towed Fishing Gears. In: ICES Coop. Res. Rep. No. vol. 215. ICES, Copenhagen, Denmark. ISSN:1017–6195.

Winger, P.D., Legge, G., Batten, C., Bishop, G., 2015. Evaluating potential biodegradable twines for use in the snow crab fishery off Newfoundland and Labrador. Fish. Res. 161, 21–23. https://doi.org/10.1016/j.fishres.2014.06.007.