Modelling the effect of mesh size and opening angle on size selection and capture pattern in a snow crab (Chionoecetes opilio) pot fishery

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A B S T R A C T

Size selection in commercial snow crab (Chionoecetes opilio) pot fisheries is important for reducing on-board sorting and unintended mortality of undersized individuals. In this paper, we tested whether snow crab of various sizes geometrically could pass through diamond meshes of different sizes and opening angles, to estimate a model for predicting the effect of mesh size and mesh opening angle on snow crab size selectivity. The model was able to explain the size selection results from earlier sea trials using commercial snow crab pots. Size selection was strongly dependent on mesh opening angle, making it less well-defined for the conical pots often used in snow crab fisheries where mesh opening angle varies. We predicted the optimal mesh size for the Norwegian snow crab fishery is 140 mm with a 65° opening angle, resulting in high capture efficiency for target size snow crab (larger than 100 mm carapace width) and low sorting effort, with approximately 10% of the catch consisting of undersized snow crab. Our model can potentially be used for other snow crab fisheries.

1. Introduction

Snow crab (Chionoecetes opilio) is distributed in the polar regions of the Northern Hemisphere and has become an important commercial species in the USA, Canada, Russia and Norway (Alvsvåg et al., 2009; Winger and Walsh 2011; Mathis et al., 2015; Olsen et al., 2019a, 2019b). Although seines are successfully used to catch this species in countries such as Japan (Yamasaki et al., 1990; Horie et al., 2001), in most fisheries snow crabs are harvested using pots. The design, size, and operation of the pots varies among regions, but the working principle of this fishing gear is basically the same. Snow crabs are attracted to the pot using bait that has been placed inside. Once the crabs enter the pot, they stay there until one or more mechanisms trigger their willingness to escape (Olsen et al., 2019b). These triggers vary from total or partial consumption of the bait, to behavioural patterns such as competition with other snow crabs or other species (Chiasson et al., 1993; Vienneau et al., 1993). However, a snow crab captured in a pot will not be able to escape unless it is able to pass through the meshes of the netting covering the pot. This means that apart from the size distribution of snow crabs in the fishing area, the size selective properties of the pot's netting affect the size distribution of the snow crabs ultimately captured by the pot.

For the Norwegian snow crab fishery crab in the Barents Sea, the minimum legal size (MLS) is 100 mm carapace width (CW). This means that in practice only male snow crabs can be harvested because females rarely exceed 90 mm in CW (Orensanz et al., 2007). All undersized snow crab must be returned to the sea. Sorting of the catch on-board a crab fishing vessel can be a labor-intensive operation. If not performed with care, it can result in the accidental processing of undersized snow crab and undesired mortality of undersized individuals. Snow crab fishing is often carried out in harsh weather conditions, and strong cold winds increase the mortality of snow crab being sorted on the vessel, as the risk of their internal organs freezing increases with decreasing temperature (Grant, 2003). Thus, optimal size selectivity at the seabed would decrease the labour required for sorting on deck and decrease unnecessary snow crab mortality.

The Norwegian snow crab fishery is relatively new. This species has been exploited commercially from the beginning of the present decade and the fishery has been expanding since (Olsen et al., 2019a, 2019b). Total snow crab landings in the Barents Sea increased from only 2,5 tonnes in 2012 to 10,430 tonnes in 2016, of which approximately 5200 tonnes were landed by Norwegian vessels (Norwegian Sales Organization 2016). The fleet consists of 40–70 m long vessels, each operating between 1000 and 2000 pots every day. In 2019, 62 vessels had permits

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to harvest snow crab in the Barents Sea, but only 11 of them participated in the fishery (Hjelset et al., 2019). Snow crab in the Barents Sea fishery is exclusively harvested using metal-framed conical pots which are covered with a diamond-mesh netting (Fig. 1). The pots are deployed in strings connected to the main line (longline). The technology and designs used have been adapted from the well-established snow crab fisheries along the east coast of Canada (Winger and Walsh 2007), using mesh sizes ranging from 120 to 140 mm. An advantage of using conical pots is that they are stackable and take up limited space on the deck of a fishing vessel (Fig. 1A). However, the disadvantage of these pots is the way the diamond mesh netting is mounted on the frame of the pot, which leads to differences in the mesh opening angles along the height of the pot (Fig. 1B). These differences in mesh opening angles affect the size selection of the pots (Olsen et al., 2019a). Therefore, it is highly relevant to have quantitative guidelines for the effect of mesh size and mesh opening angle on the size selection and catch pattern of snow crab pot fisheries.

The goals of the present study were to address the following research questions:

- How does snow crab size selection depend on mesh size and opening angle of the diamond mesh netting covering the conical pots?
- What is the most appropriate mesh size and opening angle for optimal size selection in the Norwegian snow crab fishery in the Barents Sea?

2. Materials and methods

In the past, size selectivity studies of fishing pots have mainly been carried out at sea following a trial and error procedure (Winger and Walsh 2011; Brčić et al., 2018a; Kalogirou et al., 2019; Olsen et al., 2019a). However, as sea trials are costly and time consuming, modelling and predictive work have become more common in this field to supplement experimental methods for active fishing gears (Herrmann 2005; Herrmann et al., 2009). For pot fisheries, Brčić et al. (2018b) introduced a method CREELSELECT based on laboratory experiments using dead specimens to obtain a model for the effect of mesh size and shape on the selectivity of the pot fishery. Brčić et al. (2018b) successfully applied CREELSELECT to explain pot size selection of Nephrops (*Nephrops norvegicus*) obtained during sea trials. Inspired by this success, we adapted this method to investigate the size selection of snow crab. We applied a six-step approach to investigate the effect of mesh size and opening angle on size selection and capture pattern in the Norwegian snow crab pot fishery in the Barents Sea as follows:

Step 1.   Collection of snow crab samples.

Step 2.   Laboratory experiments.

Step 3.   Estimation of a predictive model for the effect of mesh size and opening angle on snow crab size selection in pots based on laboratory experiments.

Step 4.   Examination of whether the predictive model can explain size selection results obtained at sea.

Step 5.   If Step 4 is successful, the model is applied to predict the effect of mesh size and mesh opening angle on size selection in conical pots used in the Norwegian pot fishery in the Barents Sea.

Step 6.   If Step 4 is successful, the model established in Step 3 is used to predict the effect of pot mesh size and shape on the catch pattern in the Norwegian snow crab fishery in the Barents Sea.

2.1. *Step 1: Collection of snow crab samples*

Snow crab samples for laboratory experiments were collected during a research cruise between the July 29 and the August 8, 2019 on the fishery research vessel Lance (LOA 60.7 m, GT 1380) in the central Barents Sea at three stations (N76°10′06″ E36°24′2″, N76°21′3″ E37°55′865 and N76°40′7″E32°20′58″). Experimental fishing was conducted with conical pots. Most pots had the commercially used mesh size (120 mm), but some had a smaller mesh (60 mm) to enable the capture of small snow crab. After emptying the pots on board, crabs were selected to cover the widest possible range of CWs to enable being able to establish predictions of size selectivity for the widest possible ranges of mesh sizes and opening angles.

2.2. *Step 2: Laboratory experiments*

The laboratory work consisted of conducting fall-through experiments (Brčić et al., 2018b) to test which size span of the sampled individuals can geometrically pass through mesh templates of different sizes and opening angles (Fig. 2). Before the fall-through experiments, the CW (the largest distance across the carapace including spines according to Jadamec et al. (1999)) of each snow crab was measured to the nearest millimetre using a calliper. For the fall-through experiments, a total of 56 rigid diamond mesh templates perforated in solid 5 mm thick nylon plates were used. The mesh sizes (MS) ranged from 100 mm to 160 mm and increased in increments by 10 mm. The opening angles (OA) ranged from 20 to 90° and increased in 10° increments (Fig. 2).

The plates were mounted horizontally in a frame and each snow crab was tested to see if it could geometrically pass through each of the mesh templates. Each snow crab was brought towards every mesh from above, lowering it sideways, and rotating it optimally to assess the potential to "fall through" the mesh (Fig. 3). The only force acting on the crabs was gravity. Whether or not each individual crab passed through each opening was recorded as either a "yes" (crab was able to pass through the mesh template) or a "no" (the crab was not able to pass through the mesh template).

2.3. *Step 3: Estimation of predictive model for the effect of mesh size and opening angle on snow crab size selection*

The fall-through data were treated as cover codend data (Wileman et al., 1996). For each mesh template separately, each snow crab that passed through the mesh template was considered to escape and all others were considered to be retained. Hence, each dataset contained information on the number of successful and failed passes for each width class (1 mm CW). The following logit size selection model was then fitted to each fall-through dataset for each mesh template to obtain a size selectivity curve (further in text referred to as "fall-through size selection curve"):

$$r(CW, CW50, SR) = \frac{\exp((CW - CW50) \times \ln(9)/SR)}{1 + \exp((CW - CW50) \times \ln(9)/SR)} \quad (1)$$
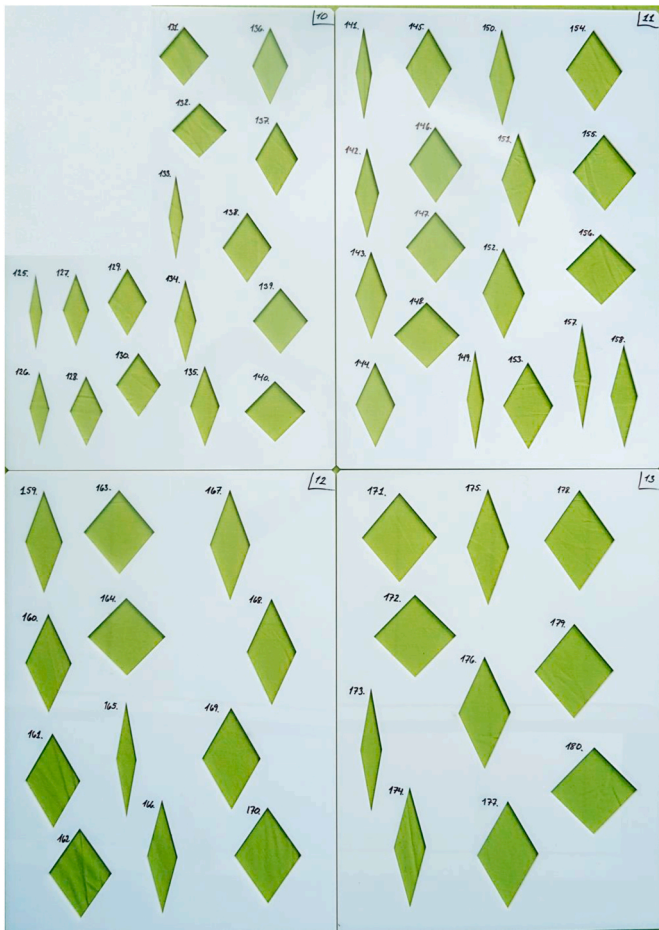

Fig. 1. A: Barents Sea snow crab vessel (MS North Eastern) on its way to the fishing grounds with the deck full of stacked conical pots (Photo: Opilio AS); B: differences in mesh opening angles along the height of the traditional conical pot.

Fig. 2. Mesh templates. Photograph of the 56 different diamond mesh templates that were used in the fall-through experiments. The mesh sizes were 100, 110, 120, 130, 140, 150 and 160 mm and the mesh opening angles were 20°, 30°, 40°, 50°, 60°, 70°, 80° and 90°.

Fig. 3. Fall-through tests with a snow crab. The images in the top row (from left to right) shows the fall-through process for a specific snow crab and mesh template. The images in the bottom row shows an unsuccessful "attempt" with a large snow crab (left) and a successful "attempt" with smaller snow crab (right).

and SR following the procedure described in Brčić et al. (2018b). This process generated 4096 models for consideration, from which the one with the lowest AICc value was selected as best for each species. AICc is the AIC (Akaike 1974) with a correction for finite sample size. The analysis described in this section was conducted using the statistical analysis tool SELNET (Herrmann et al. 2012, 2013a).

2.4. *Step 4: Examination of whether the predictive model can explain size selection obtained at sea*

Before applying the predictive model outlined in the previous section, we examined whether the predictive model would be able to explain the results obtained during commercial fishing by Olsen et al. (2019a). Olsen et al. (2019a) applied commercial conical pots that according to their study had mesh sizes between 130 and 140 mm and mesh opening angles between 64 and 84° for the three lowest rows of meshes which are most likely to affect size selection in the pots (Olsen et al., 2019b). Therefore, we had to consider this variation in mesh size and opening angle when testing the ability of our predictive model to obtain a similar size selection, as during the experimental fishing trials. In order to consider this variation, we used our model (based on Equation (2)) to estimate selection curves for mesh sizes from 130 to 140 mm in increments of 2 mm and mesh opening angles from 64 to 84° in in-

where CW represents the CW of the snow crab, CW50 is the CW at which a snow crab has 50% probability of being retained, SR is the selection range and is equivalent to CW75 – CW25. The estimated CW50 and SR values, their covariance matrix, together with the corresponding MS and OA value for each mesh template were used to estimate the parameters in the following predictive size selection model:

$$CW50(MS, OA) = \alpha_1 \times MS \times OA + \alpha_2 \times MS \times OA^2 + \alpha_3 \times MS \times OA^3 + \alpha_4 \times MS^2 \times OA + \alpha_5 \times MS^2 \times OA^2 + \alpha_6 \times MS^2 \times OA^3$$

crements of 4°. This was based on a hypothesis that snow crab selection (retention or escape) would be determined by contact with one of the

$$SR(MS, OA) = \beta_1 \times MS \times OA + \beta_2 \times MS \times OA^2 + \beta_3 \times MS \times OA^3 + \beta_4 \times MS^2 \times OA + \beta_5 \times MS^2 \times OA^2 + \beta_6 \times MS^2 \times OA^3 \tag{2}$$

where $\alpha_1 \dots \alpha_6$ and $\beta_1 \dots \beta_6$ are the model parameters that need to be estimated. All simpler sub-models obtained by leaving out one or more terms at a time from Equation (2) were considered for predicting CW50
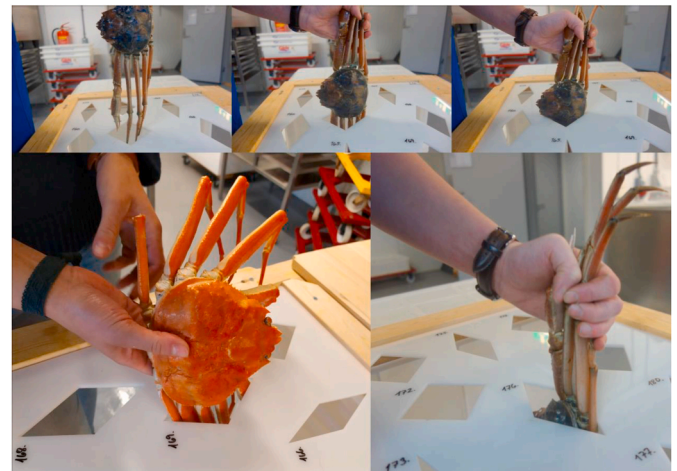
available meshes in the pots. The snow crab size selection curve obtained for 14 days soak time was considered most relevant, due to the typical fishing pattern in the Norwegian snow crab fishery and because this soak period provides sufficient time for snow crab to escape (Olsen

et al., 2019a). We applied the method outlined in Herrmann et al. (2013b, 2016) and used the FISHSELECT software framework (Herrmann et al., 2009) for this analysis. We first used CW05 to CW95 values in increments of 5% of snow crab retention likelihood between 5% and 95% to represent the experimental size selection curve from Olsen et al. (2019a), using the following equation (Krag et al., 2014):

$$CWxx = CW50 + \frac{SR}{ln(9)} \times ln\left(\frac{0.01 \times xx}{1.0 - 0.01 \times xx}\right) \qquad (3)$$

where xx represents the retention probability (05, …, 95%).

Once the experimental CW05, …, CW95 were obtained for the size selection curve, we tried to reproduce them based on the different combinations of contributions from the different meshes considered using the FISHSELECT software. The contributions were expressed in terms of weight factors that summed up to 100%. The values of the weight factors were estimated by minimizing a penalty function quantifying the difference in sum of squares between the experimental CW05, …, CW95 and the one obtained for a selection curve based on combining selection curves predicted by our model for meshes with different mesh sizes and opening angles (Herrmann et al., 2013b).

2.5. Step 5: Prediction of size selection

If the predictive model was found to be able to reproduce and explain the experimental selection curve obtained by Olsen et al. (2019a), the model could be applied to investigate the effect of mesh size and mesh opening angle on snow crab size selection in conical pots. We focused on meshes relevant to the Norwegian snow crab fishery and therefore we considered the mesh size range from 110 to 150 mm, with a special focus on 120–140 mm, as this range is currently used in the fishery. Regarding mesh opening angles, 20–90° were considered. We displayed iso curves for different constant retention probabilities at 05, 25, 50, 75, and 95%, respectively, depending on snow crab CW and pot mesh size and mesh opening angle. To obtain the iso curve, we first used our predictive model (based on Equation (2)) to obtain associated values for MS, OA, CW50 and SR for 36 meshes in the considered range. Next, the corresponding CW values were obtained by using Equation (3). The dataset resulting from the above procedure was processed using the statistical software tool R (version 4.0.0; (R Core Team 2020)). All plots were produced using the ggplot2 package (Wickham 2016).

2.6. Step 6: Prediction of capture patterns in the Norwegian snow crab pot fishery

To investigate how applying different mesh sizes and mesh opening angles would affect the capture pattern in the Norwegian snow crab pot fishery, we estimated the value of three exploitation pattern indicators, nP−, nP+ and nDRatio. These indicators are often used in fishing gear size selectivity studies to supplement assessment solely based on selectivity curves (Brčić et al., 2018c; Cheng et al., 2019; Kalogirou et al., 2019; Melli et al., 2020; Santos et al., 2016; Sala et al., 2016). The nP− and nP + quantifies the retention efficiency of the catch below and above the MLS (in %) for the population entering the fishing gear (Wienbeck et al., 2014). nDRatio quantifies the discard ratio, the fraction of snow crab below MLS in the total catch (in %). Ideally nP− and nDRatio should be low (close to 0), while nP + should be high (close to 100). The indicators were estimated by:
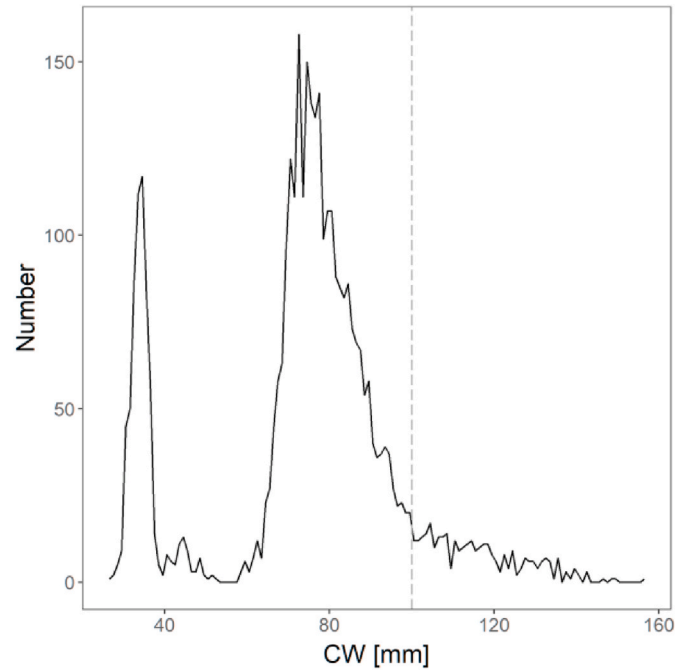

Fig. 4. Structure of the population caught in the small-meshed (60 mm) control pots from Olsen et al. (2019a). Vertical line represents MLS in the Norwegian fishery for snow crab.

$$nP- = 100 \times \frac{\sum\limits_{CW<MLS}\{r(CW, CW50, SR) \times nPop_{CW}\}}{\sum\limits_{CW<MLS}\{nPop_{CW}\}}$$

$$nP+ = 100 \times \frac{\sum\limits_{CW>MLS}\{r(CW, CW50, SR) \times nPop_{CW}\}}{\sum\limits_{CW>MLS}\{nPop_{CW}\}} \qquad (4)$$

$$nDRatio = 100 \times \frac{\sum\limits_{CW<MLS}\{r(CW, CW50, SR) \times nPop_{CW}\}}{\sum\limits_{CW}\{r(CW, CW50, SR) \times nPop_{CW}\}}$$

where $r(CW, CW50, SR)$ is the selection curve obtained by first predicting values for CW50 and SR for the specific mesh configuration (described by MS and OA) by using the predictive model resulting from Equation (2) and then using the values in the size selection model (Equation (1)). $nPop_{CW}$ represents the size structure for the snow crab entering the pots in terms of number of individuals in size class CW (1 mm wide) to the total number entering. $nPop_{CW}$ can be expected to vary to some extent with season and fishing area, which will be the case for the indicators in Equation (4). However, to get some idea of how different mesh configurations could affect the capture pattern in the Norwegian snow crab fishery, the size structure of snow crab retained in the small mesh (60 mm) pots obtained by Olsen et al. (2019a; Fig. 4) was used. All analyses described in this section were carried out with the software tool SELNET.

$$CW50(MS, OA) = \alpha_1 \times MS \times OA + \alpha_2 \times MS \times OA^2 + \alpha_3 \times MS \times OA^3 + \alpha_4 \times MS^2 \times OA + \alpha_5 \times MS^2 \times OA^2 + \alpha_6 \times MS^2 \times OA^3$$
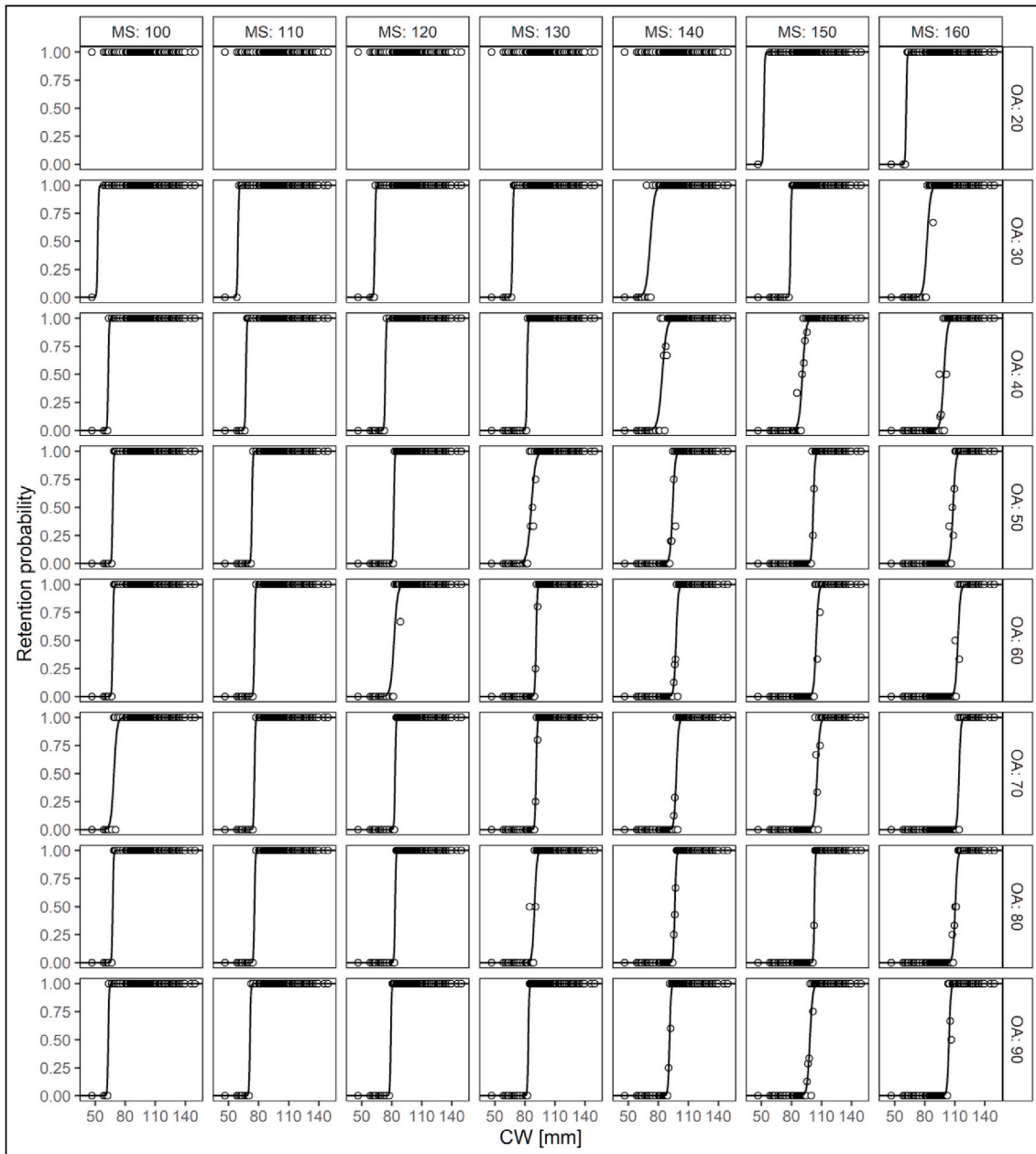
Fig. 5. Individual fall-through size selection curves for each mesh template. The circles show the fall through rates and the solid line shows the fitted logit size selection model.

Table 1
Results for fitting the best model to the fall-through size selectivity data. Values in brackets represent 95% confidence intervals.

Parameter	Factor	Value	p-value
CW50 [mm]	α_1	2.87E-02 (2.46E-02 - 3.29E-02)	<0.0001
	α_2	−4.11E-04 (−5.37E-04 to −2.86E-04)	<0.0001
	α_3	1.93E-06 (1.00E-06 - 2.85E-06)	8.52E-05
	α_4	−3.10E-05 (−5.93E-05 to −2.72E-06)	0.0321
	α_5	4.34E-07 (2.55E-07 - 1.98E-06)	0.0118
	α_6	−8.70E-09 (−1.51E-08 to −2.30E-09)	0.0084
SR [mm]	β_1	1.26E-03 (6.51E-04 - 1.86E-03)	<0.0001
	β_2	−2.46E-05 (−4.24E-05 to −6.79E-06)	0.0073
	β_3	1.36E-07 (9.10E-09 - 2.63E-07)	0.0359

3. Results

3.1. Fall-through results

In the fall-through experiment, we used a total of 157 snow crab with CWs between 46 and 149 mm to obtain fall-through size selection data for each of the 56 mesh templates (Fig. 2).

The logit size selection model (Equation (1)) was fitted to each of the fall-through size selection data to obtain the fall-through size selection curves (Fig. 5).

We were able to obtain estimates for selection parameters CW50 and SR for 50 of the 56 mesh templates (Fig. 5), making 50 sets of corresponding values for MS, OA, CW50 and SR. Those 50 sets of data were subsequently used to establish the predictive model for mesh size selection of snow crab for diamond meshes dependent on mesh size and mesh opening angle following the procedure described for Step 3. Based
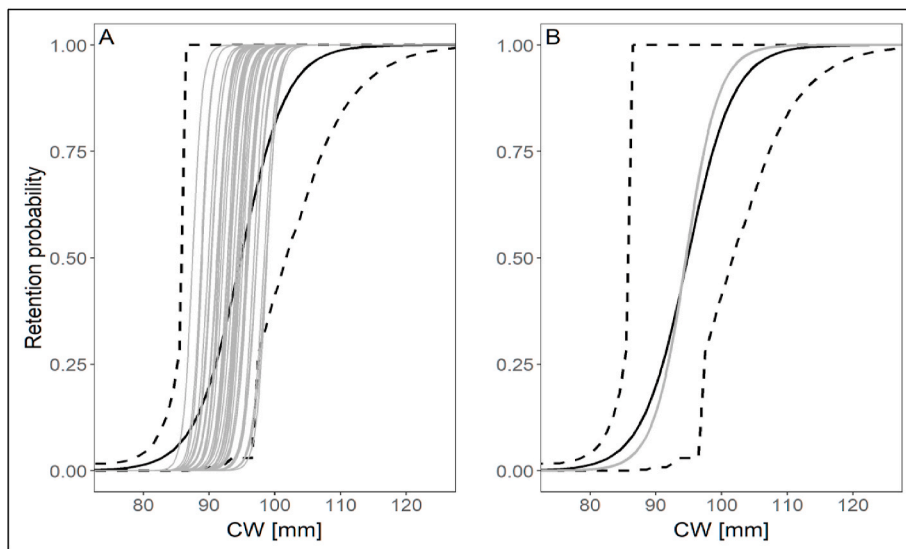
Fig. 6. Experimental vs. predicted pot size selection curve for snow crab. The experimentally obtained snow crab pot size selection curve (black line) with 95% confidence intervals (CI) (dashed line) for 14-day pot soak time from Olsen et al. (2019a) is compared to A: size selection curves predicted from model (Equation (5)) for MS between 130 and 140 mm in 2 mm increments and OA between 64° and 84° with 4° increments (grey lines) and B: the predicted mean pot size selection curve (grey line) based on the estimated contributions (Table 2).

Table 2
Estimated contributions (%) of each MS and OA considered for the modelling of the experimental size selection curve estimated by Olsen et al. (2019a). Olsen et al. (2019a) used snow crab pots with an average mesh size of 136.7 mm (range 130.4–139.7 mm) and average mesh opening angle of 79.2° (range 67.2–88.8°).

MS	OA (°)					
(mm)	64	68	72	76	80	84
130	0.53	0.27	0.00	0.00	0.00	17.08
132	10.53	4.35	1.14	0.01	0.00	0.01
134	0.00	0.31	3.15	2.39	0.39	0.20
136	0.00	0.00	0.00	0.23	4.31	6.14
138	0.00	0.00	0.00	0.00	0.00	0.56
140	17.11	15.01	14.16	0.00	0.00	2.12

on the full model (Equation (2)) a total of 4096 models were tested and the best model was found to be the following (Equation (5); Table 1):

$$SR(MS, OA) = \beta_1 \times MS \times OA + \beta_2 \times MS \times OA^2 + \beta_3 \times MS \times OA^3 \qquad (5)$$

3.2. Ability of the fall-through size selection model to explain the size selectivity of experimental pots

We wanted to investigate if the experimentally obtained size selection results reported in Olsen et al. (2019a) for conical pots with diamond mesh netting could be explained using our fall-through size selection model (Equation (5)). Following the procedure outlined in Step 4, we used the model (Equation (5)) to estimate selection curves for individual diamond meshes with mesh sizes of 130, 132, 134, 136, 138 and 140 mm for opening angles ranging from 64 to 84° in 2° increments, making a total of 36 meshes and corresponding size selection curves (Fig. 6A). Next, they were combined with individual contributions to create the best possible reproduction of the experimentally obtained curve from Olsen et al. (2019a) (Fig. 6B; Table 2). Our model predicted that the largest individual contributions to size selectivity of snow crab were caused by meshes of 140 mm with opening angles between 64 and 72° (Table 2).

By combining the fall-through size selection curves, it was possible to obtain a mean predicted selection curve that was similar to the experimental selection curve obtained by Olsen et al. (2019a) as shown in Fig. 6B. The difference between the two curves were within the confidence intervals of the experimental curve for all size classes of the snow crab, meaning that the differences were not significant. Based on this result, we concluded that it was possible to explain the experimental size selection based on the established fall-through model.

3.3. Predicting the effect of mesh size and mesh opening angle on size selectivity of snow crab

Fig. 7 (top) shows the predicted iso curves for 5, 25, 50, 75 and 95% retention probability depending on the mesh opening angle and on snow crab CW for pot mesh sizes of 120 and 140 mm, respectively. This figure showed that the retention probability had a nonlinear dependency on the mesh opening angle, with lowest retention probabilities for angles ranging from 60 to 70°. It demonstrated that for a mesh size of 120 mm, all target size snow crabs (>100 mm CW), were retained because the 95% retention iso curve was below the MLS line for all values of the mesh opening angle. The figure also demonstrated that a significant size range of undersized snow crab was retained, because the 5% retention iso curve was even further below the MLS line (maximum at 82 mm CW). If the mesh size was increased to 140 mm, a mesh opening of approximately 70° will lead to a reduced capture efficiency for some of the snow crab in the size range just above the MLS, because the iso curve for 75% retention reached a CW value at 100 mm. However, even with a mesh size of 140 mm there was a risk of retaining undersized snow crab because the iso curve for 5% retention was below the MLS line. Fig. 7 demonstrates the importance of mesh opening angle on size selectivity when designing pots for snow crab fisheries.

Another way of illustrating the importance of mesh opening angle on size selectivity of the snow crab is shown in Fig. 7 (bottom). This shows the predicted iso curves for 5, 25, 50, 75 and 95% retention probability in pots with mesh opening angles of 45°, 65° and 85° for mesh sizes between 110 mm and 150 mm. A mesh size of 140 mm with an OA of 45° would retain most of the snow crabs below the MLS, while the same mesh size with an OA of 65° would provide a 75% retention probability for crabs at MLS. Increasing the OA to 85°, decreases the retention probability of a 100-mm snow crab. Fig. 7 shows a clear interaction between mesh opening angle and mesh size regarding the size selective range for snow crab for conical pots covered with diamond mesh netting.

The size selective range can vary between CW0 to CW100, where CW0 means that a snow crab has no probability of being retained by a mesh size (with a certain OA) and CW100 means 100% retention probability. Fig. 8 shows the predicted iso curves for CW (mm) for 5%, 50% and 95% retention probability as a function of mesh size and mesh
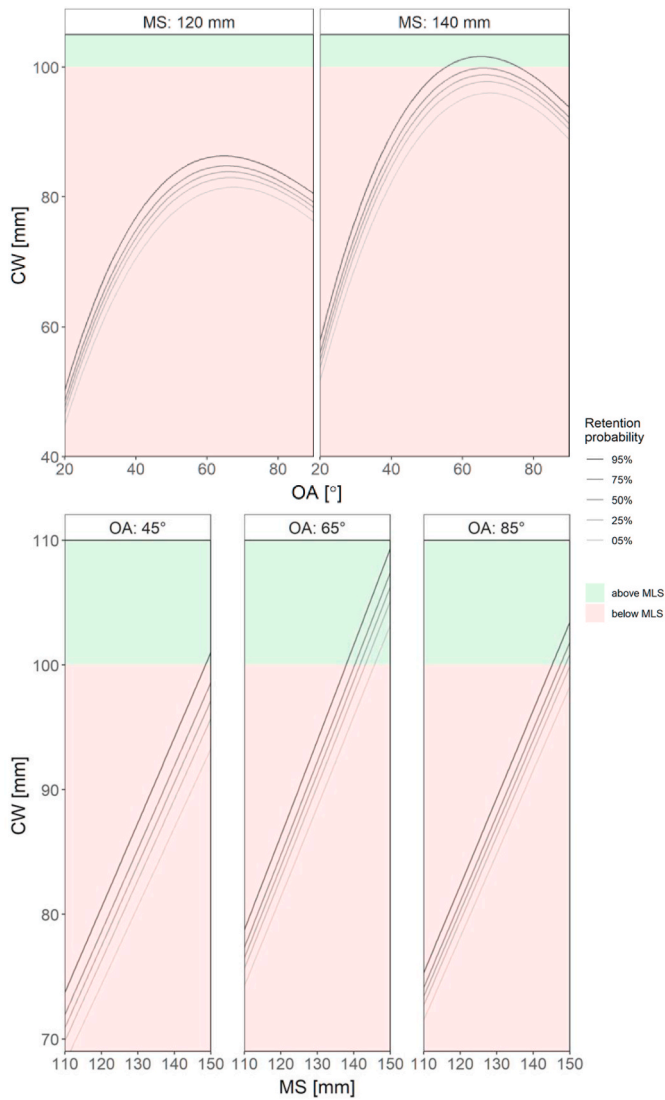
Fig. 7. Predicted iso curves for retention probabilities of 5%, 25%, 50%, 75% and 95% for snow crab (CW in mm). In top row for pots with mesh sizes of 120 mm and 140 mm and mesh opening angles between 20° and 90°. In bottom row for pots with mesh opening angles at 45°, 65° and 85° for mesh sizes between 110 mm and 150 mm.

Fig. 8. Predicted iso curves for CW (mm) for 5%, 50% and 95% retention probability dependent on mesh size and mesh opening angle. Red iso curves represent the situation where the predicted CW matches the MLS in the Norwegian fishery. . (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

opening angle (Fig. 8). Fig. 8 can be used as a design guide to evaluate the effect of changing mesh size and mesh opening angle on the selectivity of snow crab pots to find the optimum combination with regards to MLS. From this figure for instance, a mesh size of 138 mm (and OA of 65°) would provide a CW50 at around 97 mm CW and would release nearly all snow crabs below 95 mm as CW05 obtain this value.

3.4. Predicting the effect of mesh size and mesh opening angle on snow crab exploitation pattern

The resulting exploitation pattern from applying a specific mesh configuration (size and opening angle) in conical pots in the Norwegian snow crab fishery was predicted in terms of the value for the indicators nP-, nP+ and nDRatio following the procedure outlined for Step 5 (Fig. 9). This figure shows that a mesh size of 138 mm and mesh opening angle at 65°, would retain almost all target size snow crab (nP+ > 95%) and release almost all undersized snow crab (nP- < 10%). However, the predicted discard ratio would be approximately 20% if exposed to a snow crab population similar to that of Olsen et al. (2019a) with very large numbers of small snow crab entering the pots (Fig. 4). If the mesh
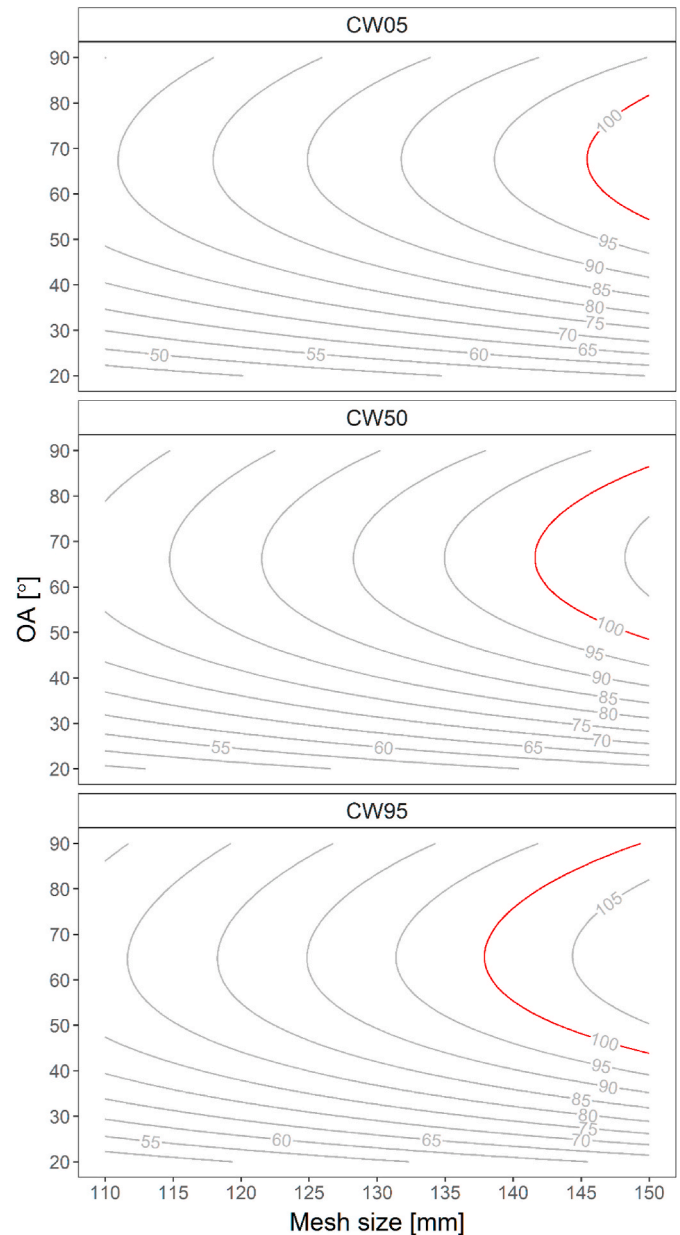
size were reduced to 120 mm, which is the smallest mesh size used in the Norwegian snow crab fishery (Olsen et al., 2019a), the discard ratio would increase to at least 70%. This means that 7 out of every 10 snow crabs caught would need to be returned to sea.

4. Discussion

We constructed and applied a model to predict the effect of mesh size and mesh opening angle on the size selection of snow crab in pots with a diamond mesh netting. Instead of being built based on expensive and time-demanding sea trials using different pot designs (different mesh sizes and OAs), our model was constructed based on fall through experiments in the laboratory, using dead snow crabs collected during a research cruise. This method has previously been successfully applied to investigate size selection of Nephrops in the Adriatic pot fishery (Brčić
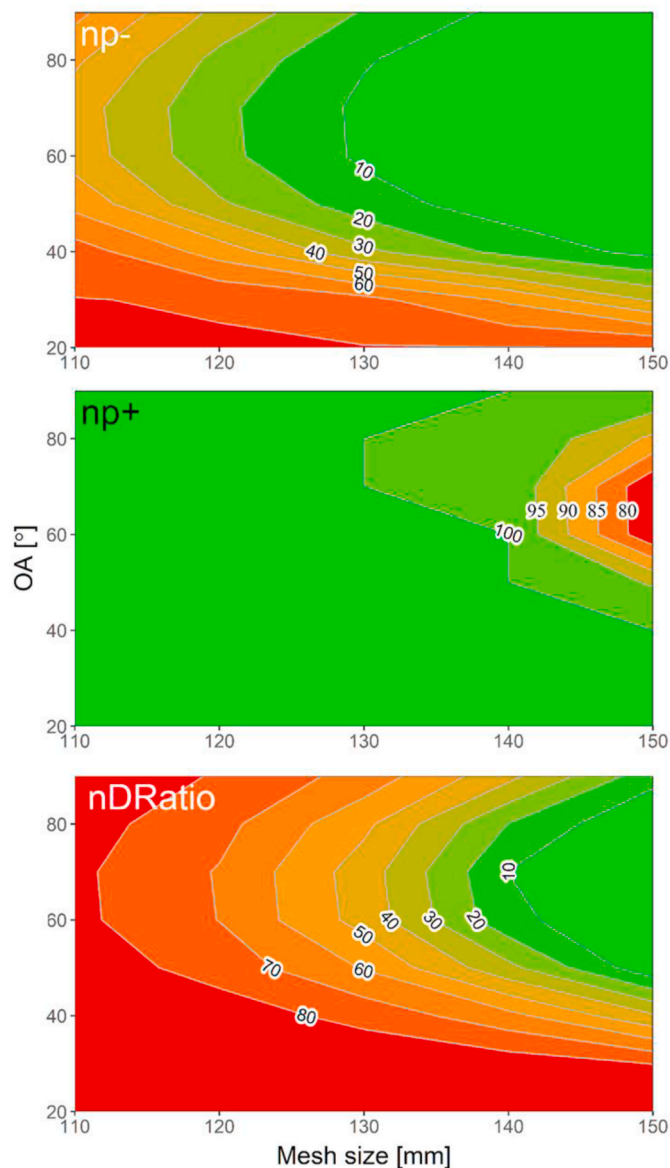
Fig. 9. Exploitation pattern indicators. Isolines showing nP-, nP+ and nDRatio indicator values for combinations of mesh sizes ranging from 110 mm to 150 mm and mesh opening angles ranging from 20° to 90°. nP− and nP + quantify the retention efficiency of the catch below and above the MLS (in %) for the population entering the fishing gear. nDRatio quantifies the discard ratio, the fraction of snow crab below MLS in the total catch (in %).

et al., 2018b). In this study, we demonstrated that the same method can also be applied to the snow crab pot fishery and that our predicted model was able to explain the size selectivity results obtained from earlier pot fishery experiments carried out at sea by Olsen et al. (2019a). We used the model to further investigate the effect of mesh size and mesh opening angle on the size selectivity of pots used in the snow crab fishery.

Our results showed that the size selection of snow crab was highly dependent not only on mesh size, but also on the mesh opening angle in the pots, with the highest release potential for mesh opening angles around 65°. The strong dependency on mesh opening angle could imply that the large variation of mesh opening angles in traditional conical pots, which are the most common type of pot used by the Norwegian fleet, results in a sub-optimal size selection. This makes it difficult to obtain a sharp size selection curve around the MLS by only adjusting mesh size. To ensure a higher retention efficiency, fishermen often use smaller mesh sizes than necessary (i.e. 120 or 130 mm). This is often

associated with the capture of larger numbers of undersized crabs leading to increased sorting time and reduced efficiency of the fishery. It can also increase the probability of unintended snow crab mortality, since all undersized crabs should be returned to the sea and, therefore, go through two decompression processes and are exposed to abrupt temperature changes.

We estimated that the optimal mesh size and shape for releasing undersized crabs from the Norwegian pot fishery would be a mesh size of 140 mm combined with a mesh opening angle of 65° which results in a minimal number of undersized snow crabs being retained by the pots. Further, our model showed that there is no risk of losing target sized snow crabs if the mesh size was reduced to 130 mm, while keeping the same OA. However, in this case the discard ratio (undersized snow crab sorted out on deck and returned to the sea) would increase from 10 to 40%. Using pots with mesh sizes of 120 mm would increase the discard ratio even further, up to 70% (Fig. 9), and lead to unnecessary catch sorting on the fishing vessel. Considering that an nP + at 100% implies no loss of targeted sizes of snow crab with a mesh size at 130 mm, there should be no reason to consider mesh sizes below this value (Fig. 7). However, the same figure showed that if the mesh size is increased to over 145 mm, then depending on mesh opening angles, the fishery begins to lose efficiency due to size selection. Again, a good compromise to improve size selection and reduce the discard ratio of small snow crabs seems to be the use of 140 mm mesh size and a mesh opening angle of 65°, as this ensures nP + above 95% alongside a nDRatio of approximately 10%. Note that some caution needs to be taken as our model predictions are based on the snow crab size distribution found on one fishing trip in one fishing area and the size distribution of snow crabs in the Barents Sea may differ in time and space. In that respect, Prozorkevich et al. (2018) found during an ecosystem survey in the Barents Sea that the most abundant size groups of the snow crab population were juveniles with a mean carapace width of 20–30 mm and adult male with carapace width of 70–90 mm.

It is also important to note that our method was solely based on geometrical/morphological considerations regarding pot size selection and does not consider parameters other than mesh size and mesh opening angle. However, if the pot soak time is sufficiently long as in Olsen et al. (2019a), the results showed that this simple modelling method provided relevant results for the fishing situation.

In this study, we solely used fall-through experiments to construct a predictive model for size dependent snow crab release potential for diamond shaped meshes. However, our approach can easily be applied to predict size selection and capture efficiency of other shapes of pots mounted with different types of netting (i.e. rectangular or circular openings), with or without the presence of escape gaps (Winger and Walsh, 2011). We believe that our approach is simple and cost effective and that it could provide useful information to fisheries managers and fishing gear designers in choosing the optimum design for a specific fishery. Specifically, we believe that our model and approach can potentially be used for other snow crab fisheries including the well-developed Canadian fishery that also uses conical pots.

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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