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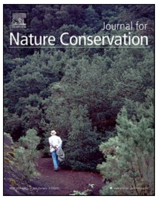

Selectivity in snow crab (*Chionoecetes opilio*) pot fishery: Effect of escape gap shape and size for conservation of fishery resources

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ABSTRACT

Conical pots are commonly used fishing gear for capturing snow crab (*Chionoecetes opilio*). In these fisheries, optimal snow crab size selection is important for reducing unintended mortality of undersized individuals aiming at conserving fisheries resources and reducing sorting time onboard fishing vessels. Size selection in snow crab pot fisheries commonly takes place through pot netting meshes during deployment. The diamond mesh netting has varying opening angles affecting retention of snow crab of different sizes, and often large proportions of catches consist of undersized crab challenging natural resource conservation. Some commercial snow crab fisheries use rigid escape gaps in addition to mesh selection to improve size selectivity. In this study, we predict the size selection potential of escape gaps with different shape and size and investigated whether such additional size selection mechanism can have a potential to improve selectivity compared to mesh selection. Results showed that circular escape gaps have potential to provide sharper size selection compared to netting meshes and thus could be used to limit the capture of undersized snow crab which is relevant for management and conservation of snow crab resources. However, a similar positive effect cannot be obtained to the same extent with elliptical and rectangular escape gaps.

1. Introduction

Snow crabs (*Chionoecetes opilio*) are distributed over cold-water areas in the Arctic, and they are considered as an important commercial species fished in the polar regions of the Northern Hemisphere such as in Norway, Canada and Greenland (Alsvåg et al., 2009). The commercial fisheries for snow crab are almost exclusively conducted using conical pots (Winger and Walsh, 2007, Burmeister 2010, 2023, Olsen et al. 2019a, Cerbule et al., 2021, 2022a). This pot type is preferred in these fisheries for being stackable which allows an effective use of deck space on the fishing vessels (Olsen et al. 2019a, Cerbule et al., 2022). The capture in this type of fishing gear consists of two processes. First, the entry process, where snow crabs are attracted to the deployed pots by bait odor and enter the gear through top entrances. The second, subsequent, process is escape by the undersized snow crab after the decay in bait odor over deployment time (soak time). The escape in these fisheries usually takes place through the netting meshes with small snow crab passing through the mesh gaps in the pot (Cerbule et al. 2023a).

In snow crab fisheries, conical pots consist of a metal frame that is covered with a diamond mesh netting with mesh sizes usually ranging from 120 to 140 mm. In Greenland, the snow crab fishery uses a minimum regulated mesh size of 140 mm (Government of Greenland 2023a). In other snow crab fisheries such as in Norway, the minimum mesh size for the pot netting is not regulated; however most vessels are using 140 mm netting to correspond the minimum landing size (MLS) of snow crab (Olsen et al. 2019a). The MLS for snow crab in Norway and Canada is set to 95 mm carapace width (CW) (Norwegian Directorate of Fisheries 2020, Fisheries and Oceans Canada 2021) while in Greenland fishery, the MLS is set to 100 mm CW (Government of Greenland 2023b). Female snow crab are smaller compared to males and do not reach the size of 95 mm CW. Therefore, the established MLS regulations in these fisheries protect female snow crab from capture. However, there is a potential for the snow crab fishery targeting only larger males to impact reproductive capacity in case of sub-optimal size selection allowing capture of undersized crabs. Specifically, in snow crab fisheries using conical pots, a large proportion of undersized crabs can be retained and thus taken

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onboard the fishing vessels (Winger and Walsh, 2011, Herrmann et al., 2021). In those instances, further size sorting takes place during catch sorting on board after pot retrieval since all undersized snow crab must be returned to sea. However, the survival rate of the released crabs can be negatively affected by such factors as release drop height and air exposure (Grant, 2003), and exposure to cold air temperatures (Van Tamelen, 2005) and windchill (Warrenchuk and Shirley, 2002). This could also potentially result in possible limb loss and delayed mortality (Warrenchuk and Shirley, 2002; Urban, 2015). Such mortality and injuries can further negatively affect stock recruitment and conservation of snow crab resources. Moreover, such size sorting of the crabs increases the workload for the fishers after the pots are retrieved (Olsen et al. 2019b).

To reduce the proportion of undersized snow crabs in the pot catches, use of a mesh size that is larger than commonly used 140 mm could be considered to potentially improve escape of more undersized snow crab during fishing. However, this at the same time increases the potential loss of target-sized individuals. Furthermore, the size selection in pots is strongly dependent not only on the mesh size but also mesh opening angle affecting how open the netting meshes are when mounted on the pot frame (Herrmann et al., 2021). Specifically, the size selectivity of the pot netting meshes is not sharp due mesh opening variation along the conical pot frame (Herrmann et al., 2021) (Fig. 1A). Furthermore, the variations in mesh opening angles can be caused by differences in pot manufacturing. Specifically, the mesh opening angle can vary due to differences between pot frames, including height and steepness, and regulations in snow crab fisheries do not specify such design details. Further, it can also depend on how the netting is mounted over the pot frame regarding its hanging ratio (i.e., how stretched the netting is over the pot frame). Therefore, although same type of conical pots are most commonly used in these fisheries, some small frame design variations are observed which can considerably affect the mesh openness of the same mesh size (Fig. 1A). Furthermore, since the mesh geometry is affected by different hanging ratio, it can also be subjected to pot frame

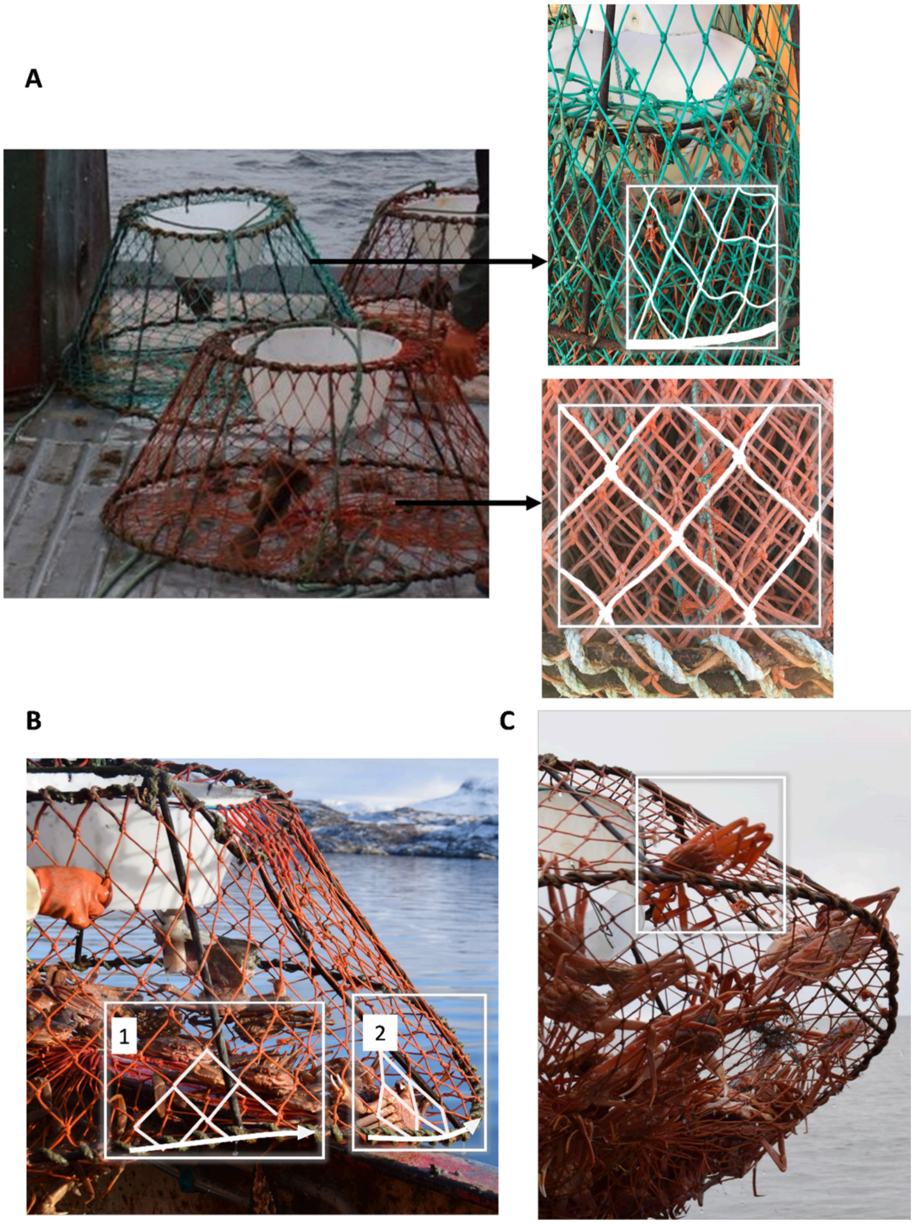


Fig. 1. Variations of mesh openings for size selection of conical snow crab pots. **A**: Variations in mesh openings for commercial snow crab pots used in the fishery. **B**: examples of pot frame deformations over time of being used in the fishery affecting the opening of the meshes on the pot frame leading to open (**1**) and closed (**2**) meshes along the lower part of the pot where the escape of undersized crabs takes place (**C**).

deformations during the fishing operations over time (see example in Fig. 1B). These deformations in pot frame can lead to mesh openings on the pots being less well-defined, increasing variation in size selectivity of snow crabs that takes place along the lower ring of the pot (Fig. 1C). Finally, the catch levels can also further affect the selectivity through meshes. Since the mesh opening angle varies along the height of the pot (Herrmann et al., 2021), pots with more crabs captured (i.e., up to the saturation level) would not allow some of the crabs escape through the lowest part of the mesh rows. Therefore, alternative designs of selective devices in snow crab pots with an increased precision are needed to improve the size selectivity (Winger and Walsh, 2007,2011).

To limit the capture of undersized snow crabs, rigid escape gaps (also called escape openings or escape vents) could be used. Such rigid escape mechanisms, often made of metal or plastics, have been identified as effective measures for releasing undersized individuals in different crab pot fisheries (i.e., Salthaug and Furevik, 2004, Winger and Walsh, 2007,2011, Boutson et al., 2009, Broadhurst et al., 2014, Zhang et al., 2022). Specifically, size selectivity can be more precise when using a rigid escape gap compared to netting meshes due to above mentioned differences in pot netting mesh opening angles along the pot frame (Herrmann et al., 2021) and possible pot frame deformations. During fishing, escape gaps aim to allow undersized individuals the possibility to escape before the pots are recovered (Miller 1990, Winger and Walsh, 2007). This reduces potential injuries and unaccounted fishing mortality after the release which can be a result of the handling when the sorting takes place after the pots are recovered on the vessel.

Escape gaps in snow crab pots are used in some fisheries on a voluntary basis, for example in Canadian snow crab fisheries (Winger and Walsh, 2011). However, there is a potential to apply a similar mechanism in other snow crab fisheries using the same type of conical pots such as Greenland and Norway (Anders et al., 2023). For such additional mechanism to be applied in commercial pot fisheries, it must demonstrate a significantly improved snow crab size selectivity compared to traditionally used gear without additional escape gaps. Specifically, the uptake of additional modifications of currently used fishing gear by the fishing industry can be slow if it requires additional labor (i.e., incorporating escape gaps in the pot netting) and maintenance between the fishing seasons or increasing expenses related to fishing gear without demonstrating improvements in the fishery such as improved selectivity.

The selectivity potential of the escape gaps for release of undersized snow crabs depends on several factors such as their size and shape. In the Canadian snow crab fishery, fishers can voluntarily use circular openings of 95 mm diameter to improve size selectivity (Winger and Walsh, 2007,2011). These gaps are designed to correspond to the 95 mm MLS in the Canadian fishery. Escape mechanisms (escape rings) are also used in Bering Sea snow crab pot fishery to reduce bycatch of undersized snow crab (NOAA Fisheries, 2024). Such designs aimed at limiting escape of snow crabs based on the carapace length size due to snow crab sideways movement (Mitchell and DeMont, 2003). In the Barents Sea snow crab fishery, Anders et al. (2023) tested stadium shaped (elongated rectangle) escape gaps made of steel bars with internal maximum height of 4 cm that was intended to prevent the passage of crab with a CW size ≥ 100 mm based on the carapace height. An optimal escape gap design has to consider the aspect that snow crabs in conical pots are able to contact the gaps from both sides while approaching and contacting escape gaps (Fig. 2). This implies a need for a symmetrical design when considering the passage through the escape gaps.

Both suggested shapes of the escape gaps (i.e., circular and stadium shaped escape gaps) are symmetrical in shape allowing snow crabs approaching the gap from either side. However, the effectiveness of such escape mechanisms are dependent on whether a snow crab of specific size is geometrically able to pass through the escape gap. Specifically, whether the specific escape gap design (shape and size) would allow escape of undersized individuals while retaining all target sized snow crabs. Therefore, the aim of this study was to determine the optimal escape gap shape i.e., elliptical and rectangular, and size in the snow crab pot fishery by investigating the size selective potential of different shapes and sizes of escape gaps to release undersized snow crabs. Such information is necessary for further designing an optimal shape and size of an escape gap that would allow release of undersized snow crabs without loss of snow crabs above the MLS, and furthermore provide an improved size selectivity potential compared to pot netting mesh selection.

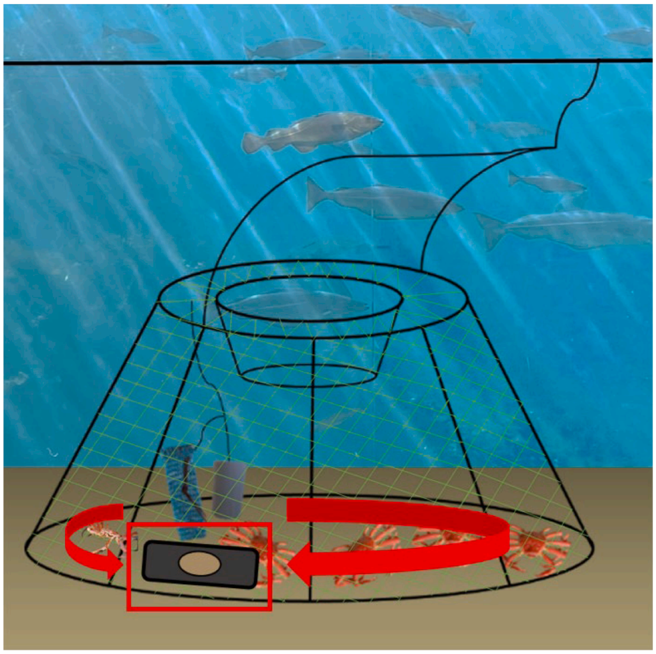


Fig. 2. Schematical drawing of a conical snow crab pot showing possible directions of snow crabs to approach escape gaps.

The aim of the present study was to address the following research questions:

- How does snow crab size selection potential depend on escape gap shape and size?
- What is the escape gap shape and size that would provide similar size selection potential to that of the pot netting meshes used in the fisheries?
- Could the use of escape gaps improve snow crab size selection potential compared to mesh selection in pots for sustainable exploitation of fishery resources?

2. Materials and methods

In this study, we conducted laboratory experiments using dead snow crabs for estimating the effect of escape gap shape and size on the pot size selection potential following the approach used in Herrmann et al. (2021) by applying a simplified version of FISHSELECT methodology (Herrmann et al., 2009; Brčić et al., 2018). This approach was used in this study for estimating snow crab selectivity for different shapes and sizes of escape gaps using the following steps:

Step 1. Collection of snow crab samples.

Step 2. Laboratory experiments with the collected specimens.

Step 3. Estimation of a predictive model for the effect of escape gap shape and size on snow crab size selection in pots based on the laboratory experiments.

Step 4. Prediction of different shape and size escape gap size selection potential in conical snow crab pots.

Step 5. Comparison of the size selection potential of escape gaps with snow crab size selection through pot netting meshes.

Step 6. Prediction of combined mesh and escape gap size selection potential in snow crab pot fisheries.

2.1. Step 1. Collection of snow crab samples

Snow crab samples were collected during a research cruise 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″). The sample collection was conducted between July 29 and August 8, 2019 (Herrmann et al., 2021). Samples were collected using conical snow crab pots. After recovering of the pots, the catch was sorted, and snow crab samples were selected to cover the widest possible range of CWs. This was done to enable predictions of size selectivity for the widest possible ranges of escape gaps (Herrmann et al., 2021).

2.2. Step 2. Laboratory experiments

Before the 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 millimeter using a caliper. The following laboratory experiments consisted of application of fall-through approach (Herrmann et al., 2021, Grimaldo et al., 2022) to test which size span of the sampled individuals can geometrically pass through escape gap templates of different shapes and sizes (Fig. 3). For the fall-through experiments, a total of 128 rigid mesh templates perforated in solid 5 mm thick nylon plates were used. The meshes consisted of rectangle ($n = 67$) and elliptic ($n = 61$) shapes with different sizes where squares and circles represented special cases for rectangles and ellipses, respectively. The size range for rectangular and elliptic escape gap templates is shown in Fig. 3.

The plates with escape gap templates were mounted horizontally in a frame and each snow crab was tested to see if it could geometrically pass through each of the templates (Herrmann et al., 2021). Each snow crab was brought towards one escape gap template at a time from above, lowering it sideways due to snow crab sideways movement pattern, and rotating it optimally to assess the potential to pass through that particular escape gap (Fig. 4A). Optimal orientation implied that each snow crab during the experiments with each escape gap template was positioned in a way that maximizes the probability of passing through the template. The only force acting on the crabs was gravity. Whether or not each individual crab passed through each of the templates was recorded as either a “yes” (crab was able to pass through the template and was considered “escaped” (Fig. 4B)) or a “no” (the crab was not able to pass through the template and was considered “retained” (Fig. 4C)) (Herrmann et al., 2021).

2.3. Step 3. Estimation of a predictive model

Successful and unsuccessful passage was recorded for each crab and each escape gap template separately. Each attempt where a crab passed through an escape gap template was considered an escape while those crabs that were not able to geometrically pass through the template were considered to be retained. Thus, according to this methodology, the acquired data were treated as covered-codend data (Wileman et al. 1996), and the following estimations of the predictive model were conducted separately for rectangular and elliptic escape gaps.

The fall-through data for each escape gap template separately was sorted into size classes that contain results for all crabs within a specific size interval of 1.0 mm CW. For each size class CW, the number of crabs that passed through the escape gap template (nP_{CW}) and those that were retained (nR_{CW}) were counted. The experimental retention probability r_{CW} at each snow crab size class CW was obtained by the following equation (Grimaldo et al., 2022):

$$r_{CW} = \frac{nR_{CW}}{nR_{CW} + nP_{CW}} \tag{1}$$

The following logit size selection model was then fitted to each fall-through dataset for each escape gap template to obtain a size selectivity curve (further in text referred to as fall-through size selection curve):

$$r(CW, CW50; SR) = \frac{\exp\left((CW - CW50) \times \frac{\ln(9)}{SR}\right)}{1 + \exp\left((CW - CW50) \times \frac{\ln(9)}{SR}\right)} \tag{2}$$

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 model parameters ($CW50$

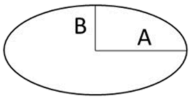
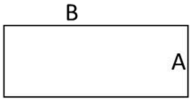
Escape gap shape	Parameter A (mm)	Parameter B (mm)
Ellipse	40	8 - 40
	45	9 - 45
	50	10 - 50
	55	11 - 55
	60	12 - 60
	65	13 - 65
	70	14 - 70
Rectangle	16 – 80	80
	18 – 90	90
	20 – 100	100
	22 – 110	110
	24 – 120	120
	26 – 130	130
	28 - 140	140

Fig. 3. Escape gap templates. **Left**: dimensions of rectangular and elliptic escape gap templates used in the fall-through experiments showing the values of the parameters A and B (in mm). Parameter B for the elliptical escape gaps and parameter A for rectangular escape gaps are shown as a corresponding size range. **Right**: photograph of an example of escape gap templates used during the laboratory experiments.

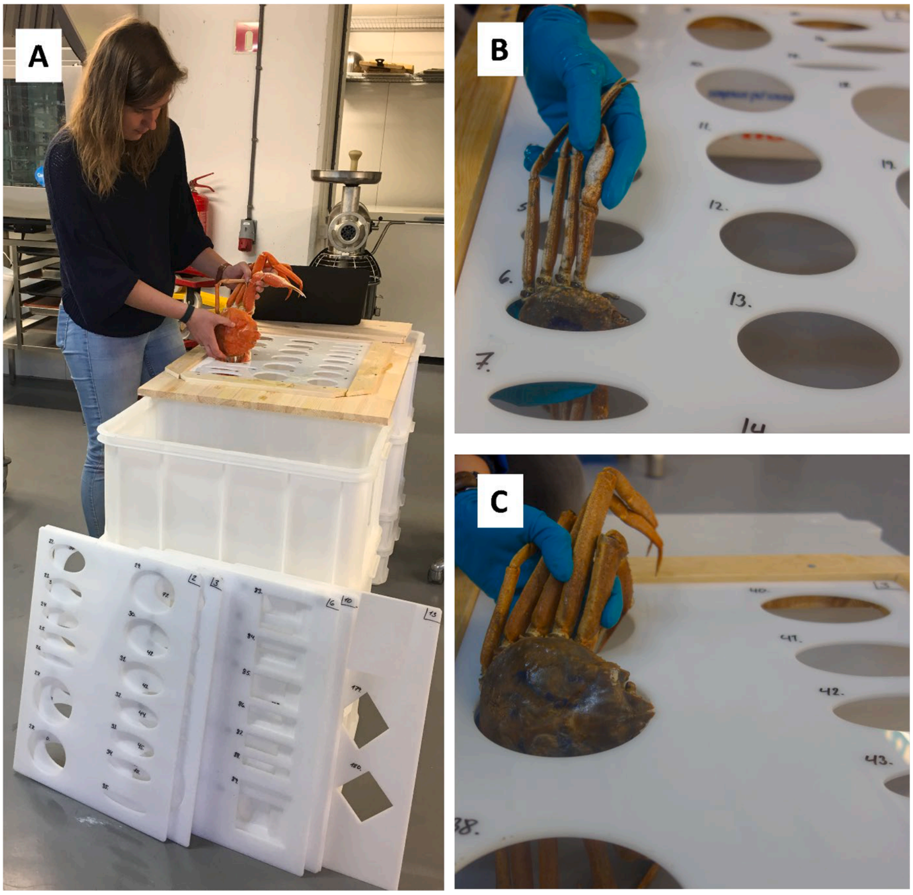


Fig. 4. Fall-through tests with a snow crab showing: (**A**) the experiment process for a specific snow crab and escape gap templates; (**B**) an example of a successful attempt with a snow crab being geometrically able to pass the specific escape gap template (recorded as "yes"), and (**C**) an example of an unsuccessful attempt with a snow crab not being geometrically able to pass through the template (recorded as "no").

and *SR*) were estimated for each escape gap template (Grimaldo et al., 2022). The estimated *CW50* and *SR* values, their covariance matrix, together with the corresponding values of size parameters *A* and *B* elliptic or rectangular escape gap templates, respectively, were used to estimate the parameters in the following predictive size selection model:

$$CW50 = \alpha_1 \times A \times B + \alpha_2 \times A^2 \times B + \alpha_3 \times A \times B^2 + \alpha_4 \times A^2 \times B^2 + \alpha_5 \times A \times B^3 + \alpha_6 \times A^2 \times B^3 + \alpha_7 \times A^3 \times B^3 + \alpha_8 \times A^3 \times B + \alpha_9 \times A^3 \times B^2$$

$$SR = \beta_1 \times A \times B + \beta_2 \times A^2 \times B + \beta_3 \times A \times B^2 + \beta_4 \times A^2 \times B^2 + \beta_5 \times A \times B^3 + \beta_6 \times A^2 \times B^3 + \beta_7 \times A^3 \times B^3 + \beta_8 \times A^3 \times B + \beta_9 \times A^3 \times B^2 \tag{3}$$

In Equation (3), $\alpha_1 \ldots \alpha_9$ and $\beta_1 \ldots \beta_9$ are the model parameters that need to be estimated (Herrmann et al., 2021). All simpler sub-models obtained by leaving out one or more terms at a time from Equation (3) were also considered for predicting *CW50* and *SR* (Brčić et al., 2018, Herrmann et al., 2021, Grimaldo et al., 2022). This process generated 262,144 models for consideration, from which the model with the lowest AICc value was selected as best for each species. AICc is the Akaike Information Criterion (AIC; Akaike 1974) with a correction for finite sample size (Burnham and Anderson, 2002).

During the fall-through trials, the snow crabs were oriented optimally to pass through elliptical and rectangular escape gap templates with size parameters *A* and *B* (Fig. 3). Interchanged parameters *A* and *B* were used for establishing the predictive model leading to same *CW50* and *SR* values. This enabled us to increase the fall-through dataset to be used for establishing the predictive model (Equation (3)).

The analysis described in this section was conducted using the statistical analysis tool SELNET (Herrmann et al., 2012,2013).

2.4. Step 4. Prediction of size selection

The prediction of size selection was performed for rectangular and elliptical escape gaps separately. To check for model self-consistency, the best model was applied to predict *CW50* and *SR* values following the procedure described in Herrmann et al. (2021) and Grimaldo et al. (2022) for each escape gap template used in the fall-through experiments. The model predictions were plotted together with their respective 95 % confidence intervals against the *CW50* and *SR* values estimated by fitting a logit size selection model (Equation (2)) to each fall-through dataset. If the predictions represented the trends of the fall-through data well, they were summarized in *iso*-curve graphs (also called isoplots or design guides) (Herrmann et al., 2021, Grimaldo et al., 2022). We displayed isoplots for different constant retention probabilities at 05, 50, and 95 %, respectively, depending on snow crab CW and escape gap shape and size (Herrmann et al., 2021, Grimaldo et al., 2022). To obtain these *iso*-curves, we first used our predictive model (based on Equation (2)) to obtain associated values for escape gap size parameters *A* and *B*, and *CW50* and *SR* for the escape gaps in the considered range (elliptic and rectangular escape gaps separately). *CW05* and *CW95* were then estimated based on corresponding *CW50* and *SR* by setting *i* to 5 and 95, respectively, in (Krag et al., 2014):

$$CWi = CW50 + \frac{SR}{ln(9)} \times ln\left(\frac{0.01 \times i}{1.0 - 0.01 \times i}\right) \tag{4}$$

The resulting design guides depict how *CW05*, *CW50* and *CW95* values vary with the change in elliptic or rectangular escape gap parameters *A* and *B*. The dataset resulting from the above procedure was processed using the statistical software tool R (version 4.3.0; (R Core Team, 2023)). All plots were produced using the ggplot2 package (Wickham, 2016).

2.5. Step 5. Comparing escape gap selection with mesh selection

In Step 5, we further predicted which combination of escape gap size parameters *A* and *B* for elliptical and rectangular escape gaps separately would provide similar size selectivity potential as the commonly applied 140 mm mesh size diamond mesh netting of different opening angles. The selectivity potential was quantified by the *CW50* values. We used the best model obtained based on Equation (3) for the elliptical and rectangular escape gaps, respectively. For the diamond meshes, we used the model established by Herrmann et al. (2021). Specifically, we compared the size selective potential of elliptic and rectangular escape gaps to the mesh selection as estimated by Herrmann et al. (2021) separately by comparing the *iso*-plot results showing estimated corresponding *CW50* results for each case.

2.6. Step 6. Prediction of mesh and escape gap size selection in snow crab pot fisheries

In this step, we aimed to illustrate whether circular, elliptic or rectangular escape gaps could have a potential for improved size selection compared to mesh selection depending on different levels of escape gap efficiency. Since the proportion of snow crabs contacting netting meshes or escape gaps, respectively, is unknown, we assumed different scenarios with escape gap effectiveness or contact with the escape gaps. In these different scenarios, 0 % escape gap efficiency implied that the crabs are not contacting the escape gaps and the size selection process takes place just through the pot netting meshes while 100 % efficiency showed a situation where all crabs contacted the escape gaps. Thus, we illustrated the predictions of escape gap size selection potential for elliptic and rectangular escape gaps as follows:

1) Diamond mesh netting of 140 mm size combined with a circular escape gap with escape gap efficiency ranging from 0 % to 100 %,
2) Diamond mesh netting of 140 mm size combined with an elliptical escape gap with escape gap efficiency ranging from 0 % to 100 %,
3) Diamond mesh netting of 140 mm size combined with an elongated rectangular escape gap limiting snow crab passage by its carapace height with escape gap efficiency ranging from 0 % to 100 %, and
4) Diamond mesh netting of 140 mm size combined with a shortened rectangular escape gap with escape gap efficiency ranging from 0 % to 100 %.

In this step, we selected one circular, one elliptic and two different rectangular escape gaps with specific parameters *A* and *B* to illustrate the size selection potential based on our predictions. For pot netting meshes, we used results from Herrmann et al. (2021) for 140 mm mesh size. We considered different mesh opening angles from 45° to 90° based on earlier observations of netting that are being used in commercial snow crab pot fisheries (see Supplementary material 5 for some examples of netting opening angle variations). For this illustrative case, we assumed uniform contributions for different mesh opening angles.

We used the data for escape gaps and meshes from FISHSELECT software and simulated a snow crab population with a uniform distribution with CW ranging from 40 to 150 mm by applying simulation facilities in the software tool SELNET (Herrmann et al., 2012). Each scenario was analyzed as covered codend data (Wileman et al. 1996) by fitting a triple Logit selection model (*TLogit*) to the data (Jacques et al., 2019):

$$\begin{aligned} & TLogit(CW, C_1, C_2, CW50_1, SR_1, CW50_2, SR_2, CW50_3, SR_3) \\ & \quad = C_1 \times Logit(CW, CW50_1, SR_1) + C_2 \\ & \qquad \times Logit(CW, CW50_2, SR_2) + (1.0 - C_1 - C_2) \times Logit(CW, CW50_3, SR_3) \end{aligned} \tag{5}$$

Compared to the simple Logit model, the triple logit model can account for gear designs where more than one selection process is being involved as would be expected when both diamond meshes and fixed-shape escape gaps are present for support of the size selection process. In Equation (5), fraction C_1 is subjected to a Logit size selection process with parameters $CW50_1$ and SR_1, fraction C_2 is subjected to another Logit size selection process with parameters $CW50_2$ and SR_2, and finally fraction $1.0\text{-}C_1\text{-}C_2$ to a Logit size process with parameters $CW50_3$ and SR_3. Based on the estimated parameter values for C_1, $CW50_1$, SR_1, C_2, $CW50_2$, SR_2 $CW50_3$ and SR_3, the combined *CW50* and *SR* values were calculated using the same numerical technique as in Sistiaga et al. (2010). The analysis was done in SELNET software (Herrmann et al., 2012). Thus, based on the level of contribution of the escape gap on the size selection potential (i.e., escape gap efficiency), we predicted size selection for snow crabs.

To further investigate the potential effects of the escape gap use in snow crab fisheries, we used exploitation pattern indicators (Herrmann et al., 2021). Specifically, indicators nP^- and nP^+ quantify the retention efficiency of snow crabs below and above the MLS of either 95 mm or 100 mm CW as a percentage, and ***nDRatio*** represents the discard ratio in numbers shown as a percentage of undersized snow crabs retained in the pots (Herrmann et al., 2021). Ideally, nP^- and ***nDRatio*** should be low (close to 0) and nP^+ should have a high value (close to 100) (Herrmann et al., 2021). For the purpose of this study, we used the simulated size selection data and expressed the values of the exploitation pattern indicators as a percentage difference when considering increasing escape gap efficiency over different scenarios. The indicators for the different scenarios were estimated by (Herrmann et al., 2021):

$$\begin{aligned} nP^- &= 100 \times \frac{\sum_{CW<MLS}\{r(CW) \times nPop_{CW}\}}{\sum_{CW<MLS}\{nPop_{CW}\}} \\ nP^+ &= 100 \times \frac{\sum_{CW>MLS}\{r(CW) \times nPop_{CW}\}}{\sum_{CW>MLS}\{nPop_{CW}\}} \\ nDRatio &= 100 \times \frac{\sum_{CW<MLS}\{r(CW) \times nPop_{CW}\}}{\sum_{CW}\{r(CW) \times nPop_{CW}\}} \end{aligned} \tag{6}$$

where $r(CW)$ is the predicted size selection curve depending on the contribution the escape gaps (0–100 %) and $nPop_{CW}$ is the population of snow crabs simulated to enter the pots.

3. Results

3.1. Fall-through results

During the experiments, we used a total of 157 snow crabs to obtain fall-through size selection data for 111 escape gap templates (57 elliptical escape gaps and 54 rectangular gaps). The CW of snow crabs varied between 46 and 149 mm. The logit size selection fitted to each of the fall-through datasets provided the *CW50* and *SR* values for escape gap templates for elliptical and rectangular gaps, respectively (Supplementary materials 1–4). These were then subsequently used to establish the predictive model for size selection of snow crabs in pots when using escape gaps. The logit size selection model (Equation (2)) was fitted to the fall-through size selection data to obtain fall-through size selection curves (Figs. 5 and 6).

We were able to obtain estimates for selection parameters *CW50* and *SR* for 111 of the 128 escape gap templates. This information was used to

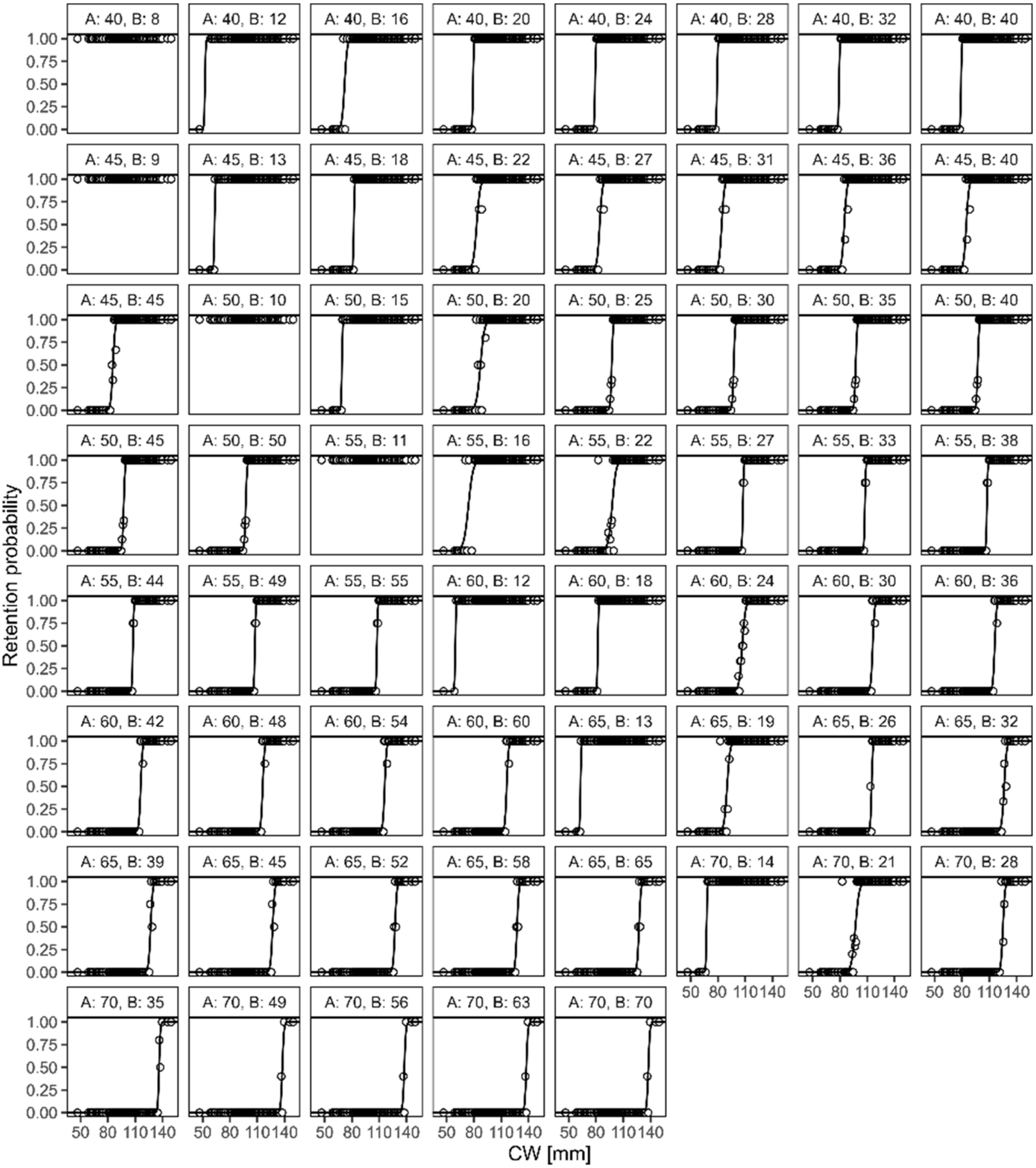


Fig. 5. Individual fall-through size selection curves for each elliptical escape gap template. The circles show the fall-through rates and the solid lines show the fitted size selection model.

establish predictive models for escape gap size selection of snow crabs depending on gap shape and size following the procedure described in Step 3 (Herrmann et al., 2021). The best model for elliptical escape gap was found to be the following (Equation (7)):

$$CW50 = \alpha_2 \times A^2 \times B + \alpha_3 \times A \times B^2 + \alpha_4 \times A^2 \times B^2 + \alpha_5 \times A \times B^3 + \alpha_6 \times A^2 \times B^3 + \alpha_7 \times A^3 \times B^3 + \alpha_8 \times A^3 \times B + \alpha_9 \times A^3 \times B^2$$

$$SR = \beta_1 \times A \times B + \beta_2 \times A^2 \times B + \beta_3 \times A \times B^2 + \beta_5 \times A \times B^3 + \beta_8 \times A^3 \times B \tag{7}$$

The results for fitting the best model to elliptical escape gap fall-through size selectivity data are shown in Table 1.

Further, the best model for rectangular escape gaps (Table 2) is shown in Equation (8) as follows:

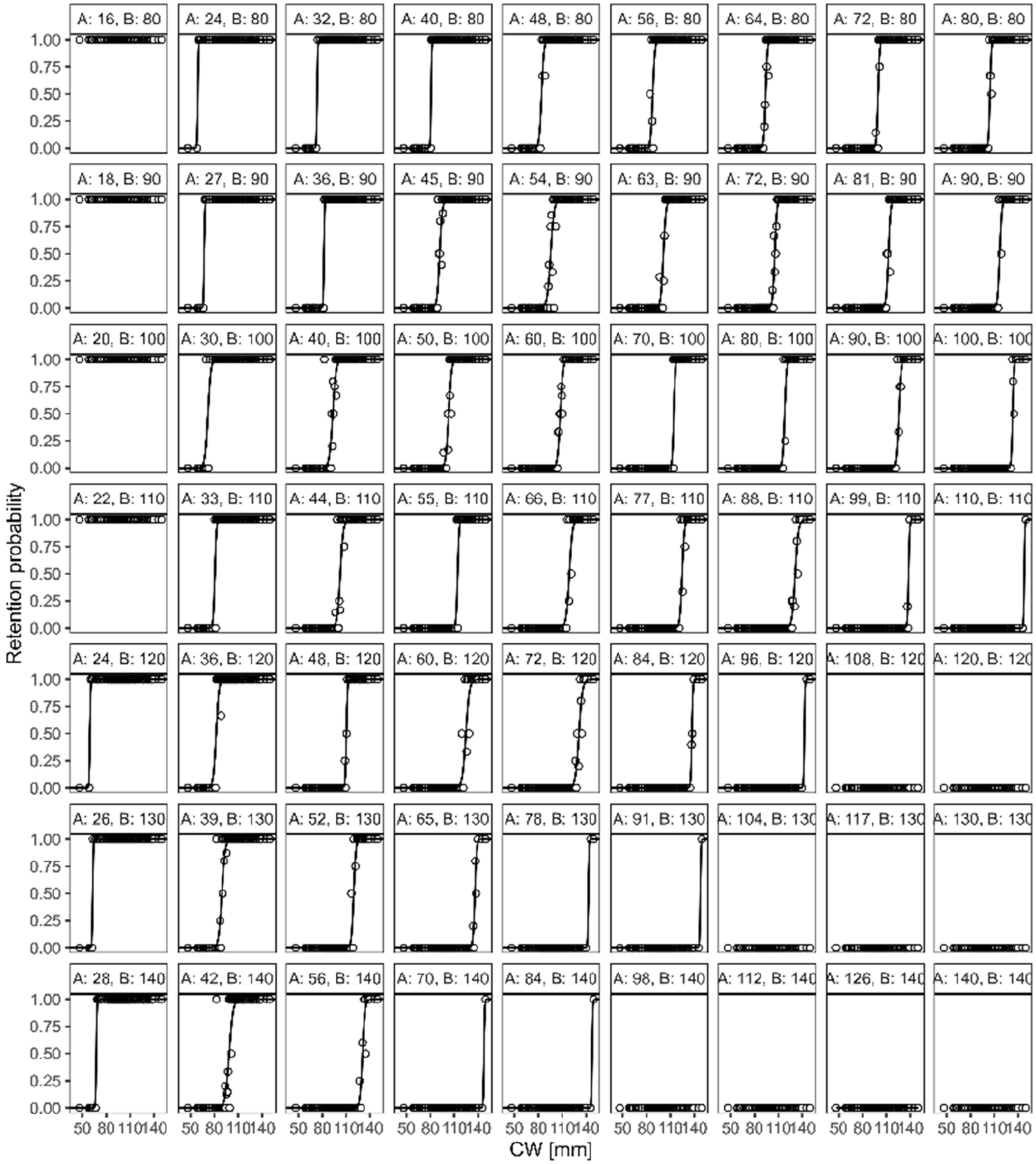


Fig. 6. Individual fall-through size selection curves for each rectangular escape gap template. The circles show the fall-through rates and the solid lines show the fitted size selection model.

$$
\begin{aligned}
CW50 &= \alpha_2 \times A^2 \times B + \alpha_3 \times A \times B^2 + \alpha_4 \times A^2 \times B^2 + \alpha_5 \times A \times B^3 + \alpha_6 \\
&\quad \times A^2 \times B^3 + \alpha_7 \times A^3 \times B^3 + \alpha_8 \times A^3 \times B + \alpha_9 \times A^3 \times B^2 \\
SR &= \beta_2 \times A^2 \times B + \beta_3 \times A \times B^2 + \beta_4 \times A^2 \times B^2 + \beta_6 \times A^2 \times B^3 + \beta_7 \times A^3 \\
&\quad \times B^3 + \beta_9 \times A^3 \times B^2
\end{aligned}
\tag{8}
$$

The results for fitting the best model to rectangular escape gap fall-through size selectivity data are shown in Table 2.

3.2. *Predicting the effect of escape gap shape and size on size selectivity of snow crab*

Fig. 7 shows the predicted *iso*-curves for 05, 50, and 95 % snow crab retention probability (*CW05*, *CW50* and *CW95*, respectively) depending

Table 1
Results for fitting the best model (Equation (7)) to the fall-through size selectivity data for elliptical escape gaps. Values in brackets represent 95% confidence intervals.

Parameter (mm)	Factor	Value	*p*-value
CW50	α_2	6.80453E-03 (6.14213E-03——7.46692E-03)	< 0.0001
	α_3	6.80453E-03 (6.14213E-03——7.46692E-03)	< 0.0001
	α_4	−4.42491E-04 (-4.84661E-04 - −4.00321E-04)	< 0.0001
	α_5	−7.70666E-05 (-8.78082E-05 - −6.63250E-05)	< 0.0001
	α_6	4.64000E-06 (4.08710E-06——5.19290E-06)	< 0.0001
	α_7	−4.94000E-08 (-5.59000E-08 - −4.29000E-08)	< 0.0001
	α_8	−7.70666E-05 (-8.78082E-05 - −6.63250E-05)	< 0.0001
	α_9	4.64000E-06 (4.08710E-06——5.19290E-06)	< 0.0001
SR	β_1	7.44883E-03 (5.76286E-03——9.13480E-03)	< 0.0001
	β_2	−1.17546E-04 (-1.66628E-04 - −6.84646E-05)	< 0.0001
	β_3	−1.17546E-04 (-1.66628E-04 - −6.84646E-05)	< 0.0001
	β_5	9.81800E-07 (4.90100E-07——1.47350E-06)	< 0.0001
	β_8	9.81800E-07 (4.90100E-07——1.47350E-06)	< 0.0001

Table 2
Results for fitting the best model (Equation (8)) to the fall-through size selectivity data for rectangular escape gaps. Values in brackets represent 95% confidence intervals.

Parameter (mm)	Factor	Value	*p*-value
CW50	α_2	8.61551E-4 (7.95276E-4——9.27826E-4)	< 0.0001
	α_3	8.61551E-4 (7.95276E-4——9.27826E-4)	< 0.0001
	α_4	−2.70400E-5 (-2.94353E-5 - −2.46446E-5)	< 0.0001
	α_5	−5.32268E-6 (-5.90281E-6 - −4.74256E-6)	< 0.0001
	α_6	1.52317E-7 (1.34579E-7——1.70055E-7)	< 0.0001
	α_7	−8.72355E-10 (-9.98091E-10 - −7.46618E-10)	< 0.0001
	α_8	−5.32268E-6 (-5.90281E-6 - −4.74256E-6)	< 0.0001
	α_9	1.52317E-7 (1.34579E-7——1.70055E-7)	< 0.0001
SR	β_2	1.24249E-5 (6.91912E-6——1.79306E-5)	< 0.0001
	β_3	1.24249E-5 (6.91912E-6——1.79306E-5)	< 0.0001
	β_4	−1.58692E-7 (-3.01396E-7 - −1.59875E-8)	< 0.0001
	β_6	−1.10344E-9 (-2.12869E-9 - −7.81850E-11)	< 0.0001
	β_7	1.51030E-11 (2.17000E-11——2.99880E-11)	< 0.0001
	β_9	−1.10344E-9 (-2.12869E-9 - −7.81850E-11)	< 0.0001

on elliptic and rectangular escape gap size parameters *A* and *B* (Fig. 3). The results displayed in Fig. 7 can be used as design guides to evaluate the effect of changing elliptical and rectangular escape gap size on the selectivity of snow crab. This, therefore, allows to estimate the optimal escape gap size for each escape gap shape with regards to MLS of the snow crab, either 95 mm CW as in Norwegian and Canadian snow crab fisheries or 100 mm MLS as established in the Greenland fishery. The results showed that, for instance, circular escape gaps with 95 mm diameter as used currently in Canadian fishery on voluntary basis would allow excluding undersized snow crabs. However, based on the carapace morphology, this escape gap size could also allow escape of some of the target sized crabs if MLS of 95 mm CW is considered. However, the same escape gap size would not be optimal in other fisheries with MLS of 100 mm CW since then the corresponding *CW50* would be under this size. Further, the predicted *iso*-curves for rectangular escape gaps for snow crabs' retention probability showed that the height of a rectangular escape gap (parameter *A*) has a large impact on the retention probability based on these results. Specifically, for snow crabs of 95 mm MLS to have a 50 % retention probability when rectangular escape gaps are used (*CW50*), the height of such escape gap should be larger than 40 mm and would need to be further increased if the MLS of 100 mm is considered.

3.3. *Comparing escape gap and mesh selection in snow crab pot fisheries*

The results of the estimated the escape gap size that could provide a similar size selection potential to that of the pot netting meshes are shown as *iso*-curves in Fig. 8. Specifically, the results in Fig. 8 show the comparison of escape gap (elliptic or rectangular, respectively) and mesh selection in snow crab pot fisheries when the most common mesh size, 140 mm, is considered with different mesh opening angles ranging from 20° to 90°. In Fig. 8, the results shown as *iso*-curves represent the diamond mesh opening angle values that have the same *CW50* values as a specific combination of parameters *A* and *B* in rectangular or elliptical escape gaps, respectively.

The results showed that the escape gaps of both shapes can match the meshes of different opening angles. For example, a circular mesh of 95 mm diameter (i.e., parameter *A* and *B* being equal to 47.5 mm) would correspond to a mesh of approximately 80° opening angle.

3.4. *Prediction of combined mesh and escape gap size selectivity of snow crab pot fisheries*

Using the results from the predictions of escape gap size selectivity of snow crab for elliptical and rectangular escape gaps separately, we were able to assess whether use of escape gaps can have a potential to improve size selection in this fishery. The potential size selection curves for snow crabs based on scenarios with different escape gap efficiency for elliptical, circular and rectangular escape gaps are shown in Fig. 9.

The results in Fig. 9 illustrate the use of escape gaps with different shapes. Specifically, we illustrated escape gap efficiency for circular, elliptical and two configurations of rectangular escape gaps with corresponding *CW50* values that allows escape of undersized snow crabs.

For the circular escape gap, the size was corresponding to escape gaps currently used on voluntary basis in Canadian snow crab fishery (95 mm diameter). This was considered a special case of elliptic escape gaps considered in this study (parameters *A* and *B* equal to 47.5 mm). The results showed that as the efficiency of this escape gap increased (in respect to 140 mm pot netting selectivity), this resulted in a sharper size selection compared to the scenario where the crabs are using meshes for escaping the gear (Fig. 9). However, the crab sizes for which full retention potential was obtained was larger compared to the 95 mm CW MLS, resulting in potential loss of some target sized individuals.

Elliptical escape gaps with size parameters *A* equaling to 47.5 mm and *B* reduced to 35 mm also resulted in reduction of undersized crabs with increasing escape gap efficiency (Fig. 9). However, the resulting retention probability was less sharp compared to what was obtained for circular escape gaps with 100 % escape gap efficiency.

Further, the use of rectangular escape gap with size parameters $A =$ 140 mm and $B = 41$ mm aiming to base the size selection on snow crab carapace height based on our predictions of escape gap size selection potential (Fig. 7). The results showed that rectangular escape gaps can have potential to exclude undersized snow crabs. However, as the rectangular escape gap efficiency increased from 0 % up to 100 %, contribution, the resulting size selection of snow crabs became less sharp due to wider *SR* of escape gaps compared to the diamond meshes (Fig. 9). The opposite was observed for circular escape gap size selection potential when the escape gap efficiency increased (Fig. 9). Specifically, the size selection potential when using circular escape gaps became sharper with increased escape gap efficiency. Further, configuring the rectangular shaped escape gap by shortening the rectangular shape (parameters *A* and *B* equal to 50 and 95 mm, respectively), did not result in a sharp size selection either when compared to circular escape gap (Fig. 9).

The illustration of results regarding escape gap efficiency for different shapes (circle, ellipse and two rectangle configurations) of escape gaps regarding exploitation pattern indicators nP^-, nP^+ and *NDRatio* is shown in Fig. 10.

The results for circular escape gaps showed that the retention of undersized crabs (nP^-) and the discard ratio (*nDRatio*) was reduced with a 100 % change when the contribution from an escape gap was increased from 0 % to 100 % (Fig. 10). However, the percentage change for individuals over MLS (nP^+) was small with increased escape gap efficiency. When considering 100 mm CW MLS with the same escape gap,

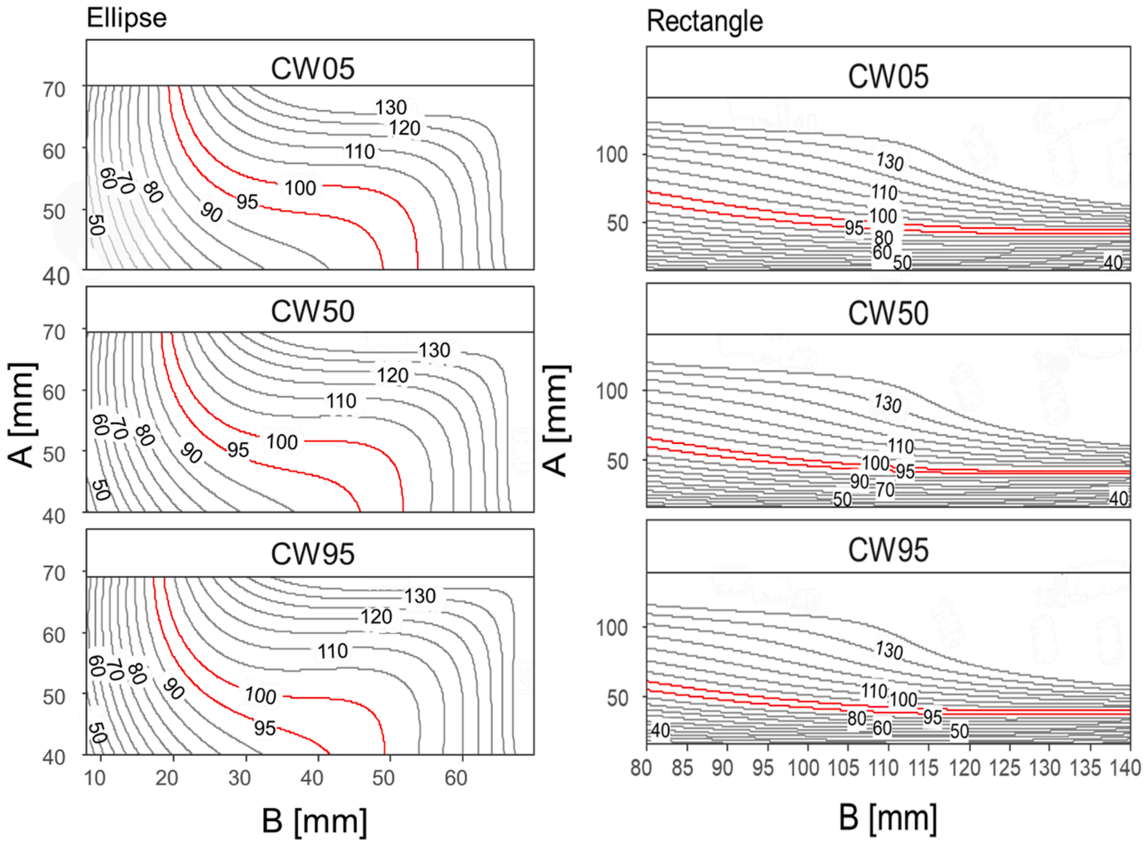


Fig. 7. Predicted *iso*-curves for snow crab carapace width (CW; mm) for 5 %, 50 % and 95 % (*CW05*, *CW50*, *CW95*) retention probability depending on escape gap size (parameter *A* and parameter *B*, respectively) of elliptic (left plots) and rectangular (right plots) escape gaps. Red *iso*-curves represent the situation where the predicted CW matches the minimum landing size (MLS) of 95 mm CW in Norwegian and Canadian snow crab fisheries, and 100 mm MLS in the Greenland snow crab fishery. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

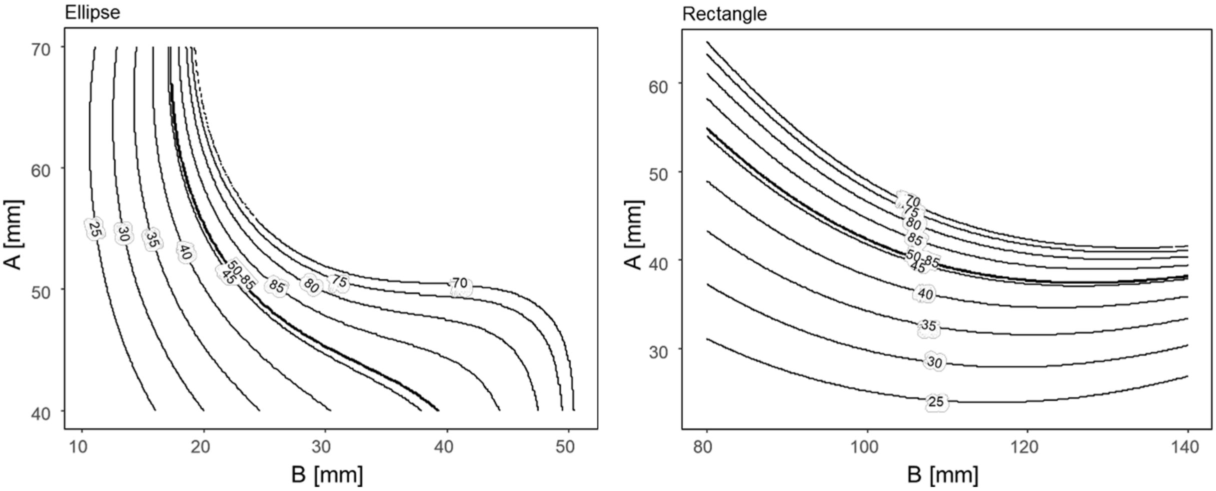


Fig. 8. Predicted escape gap and mesh selection in snow crab pot fisheries depending on netting mesh opening angles and escape gap size (parameter *A* and parameter *B*, respectively) of elliptic (left plots) and rectangular (right plots) escape gaps. The lines in the plot show different mesh opening angles ranging from 20°-90° that correspond to the specific escape gap sizes. Red lines show the most common opening angles around the lower part of the pots where the escape of the snow crab takes place.

results showed that the size of the gap would not be of sufficient size to provide full size selective potential and nP^{-} was reduced with approximately 50 % change; thus, the size of escape gap should be larger to correspond this MLS.

Use of elliptical escape gaps showed a potential to reduce undersized crab catches (nP^{-}) with up to 40 % change (Fig. 10). However, this reduction was considerably smaller compared to for example using circular escape gaps (Fig. 10). For 100 mm MLS case, the size of the escape gap was not optimal and thus it did not result in reduction in undersized crab catches due to *CW50* for this escape gap matching 95 mm MLS. The results showed no considerable effect on the catch of target sized snow crabs for either 95 or 100 mm MLS (Fig. 10).

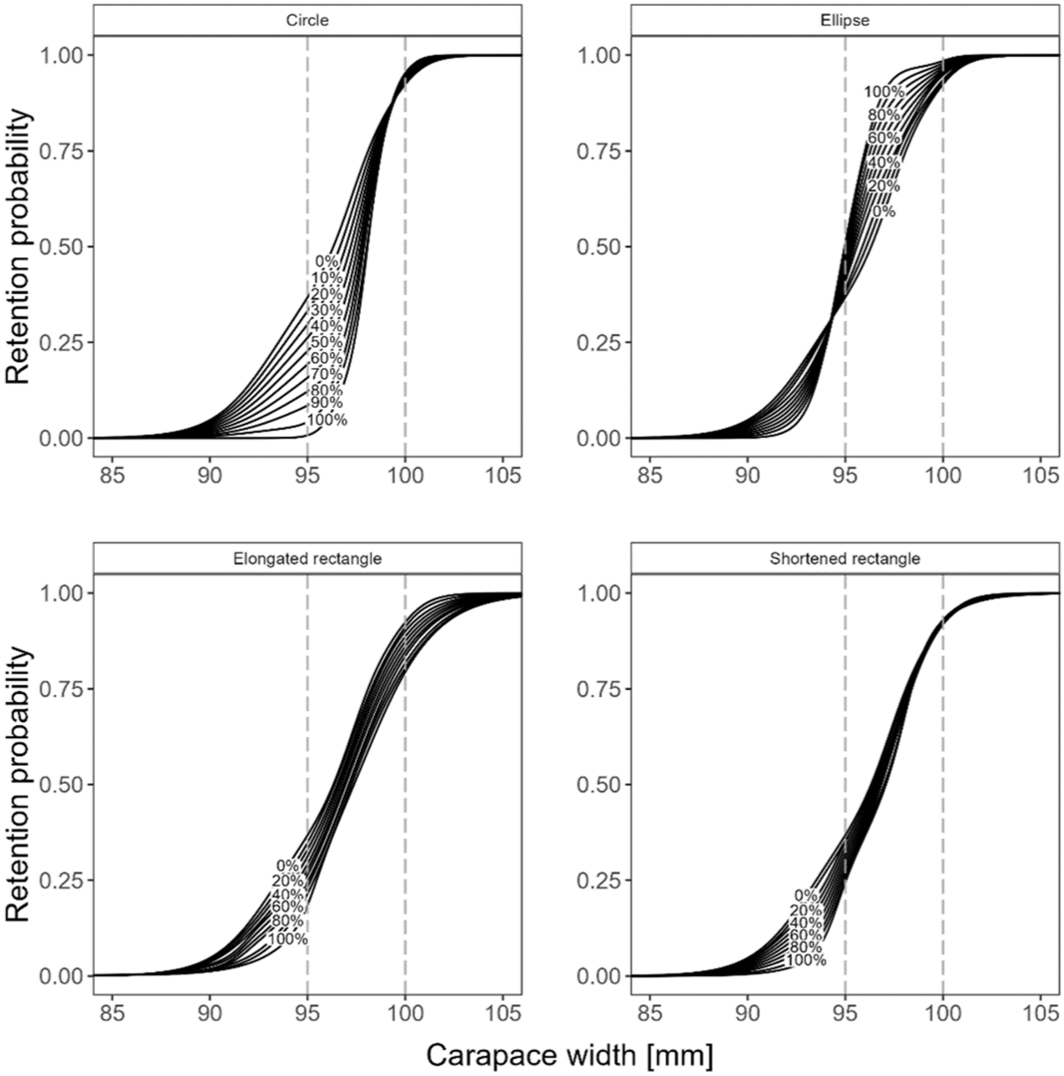


Fig. 9. Prediction of size selectivity potential for diamond mesh and escape gaps with different shapes (circular, elliptic and rectangular, respectively). The size of the circular escape gaps was 95 mm diameter (size parameters *A* and *B* equal to 47.5 mm) corresponding to the size used voluntarily in snow crab pot fisheries in Canada. Elliptical escape gaps had size parameters *A* and *B* equal to 47.5 mm and 35 mm, respectively. Two rectangular shapes were used, elongated ($A = 41$ mm, $B = 140$ mm) and shortened ($A = 50$ mm, $B = 95$ mm). Lines in the graph show retention probabilities depending on different contributions when considering escape through meshes and escape gaps ranging from 0 % to 100 % escape gap efficiency. Vertical stippled lines at 95 and 100 mm shows minimum landing sizes.

For elongated rectangular escape gaps limiting the snow crab escape by carapace height, the retention of undersized crabs (nP^{-}) and the discard ratio (*nDRatio*) was reduced with increased escape gap efficiency (Fig. 10); however, not to the same extent as observed with circular escape gaps (Fig. 10). When considering 100 mm CW MLS with the same rectangular escape gap, results showed that the size of the gap would not be optimal since the reduction of nP^{-} and *nDRatio* was considerably smaller than for 95 mm CW and also for the same 100 mm CW MLS when circular escape gaps are considered. Similar results regarding exploitation pattern indicators for target- and undersized snow crabs as well as discard ratio were shown for shortened rectangular shaped escape gap (Fig. 10).

4. Discussion

In this study, we constructed and applied models to estimate the effect of escape gap shape and size on the size selection potential of snow crabs in conical pot fisheries based on fall-through laboratory experiments. This approach has been applied in earlier trials predicting snow crab size selection when assessing the effect of pot netting mesh size and opening angle (Herrmann et al., 2021) and also used in different fisheries, including pot fishery (Brčić et al., 2018).

Our results showed that the use of escape gaps can have potential to improve size selectivity in snow crab fisheries compared to selection through pot netting meshes which is the main size selectivity mechanism in current commercial snow crab pot fisheries. Specifically, because the diamond mesh netting used in pots has changing mesh opening angles, it further affects the size of the crabs that are released (Herrmann et al., 2021). Therefore, even if the same mesh size is used in snow crab fisheries or regulated by a minimum mesh size regulation as in snow crab fishery in Greenland (Government of Greenland 2023a), the resulting size selection is still subject to variations due to these differences in mesh openings. The escape gaps can enable a more precise size selection with less variations compared to the netting meshes due to their rigid shape which, combined with the rigid exoskeleton of the crabs, can have potential to improve the selectivity in this fishery (Miller 1990, Winger and Walsh, 2007, Zhang et al. 2023) and improve conservation of snow crab. In this study, our results showed that using the escape gaps can produce the same size selective potential as the 140 mm diamond mesh selectivity (Fig. 8). Specifically, our results showed that both, rectangular and

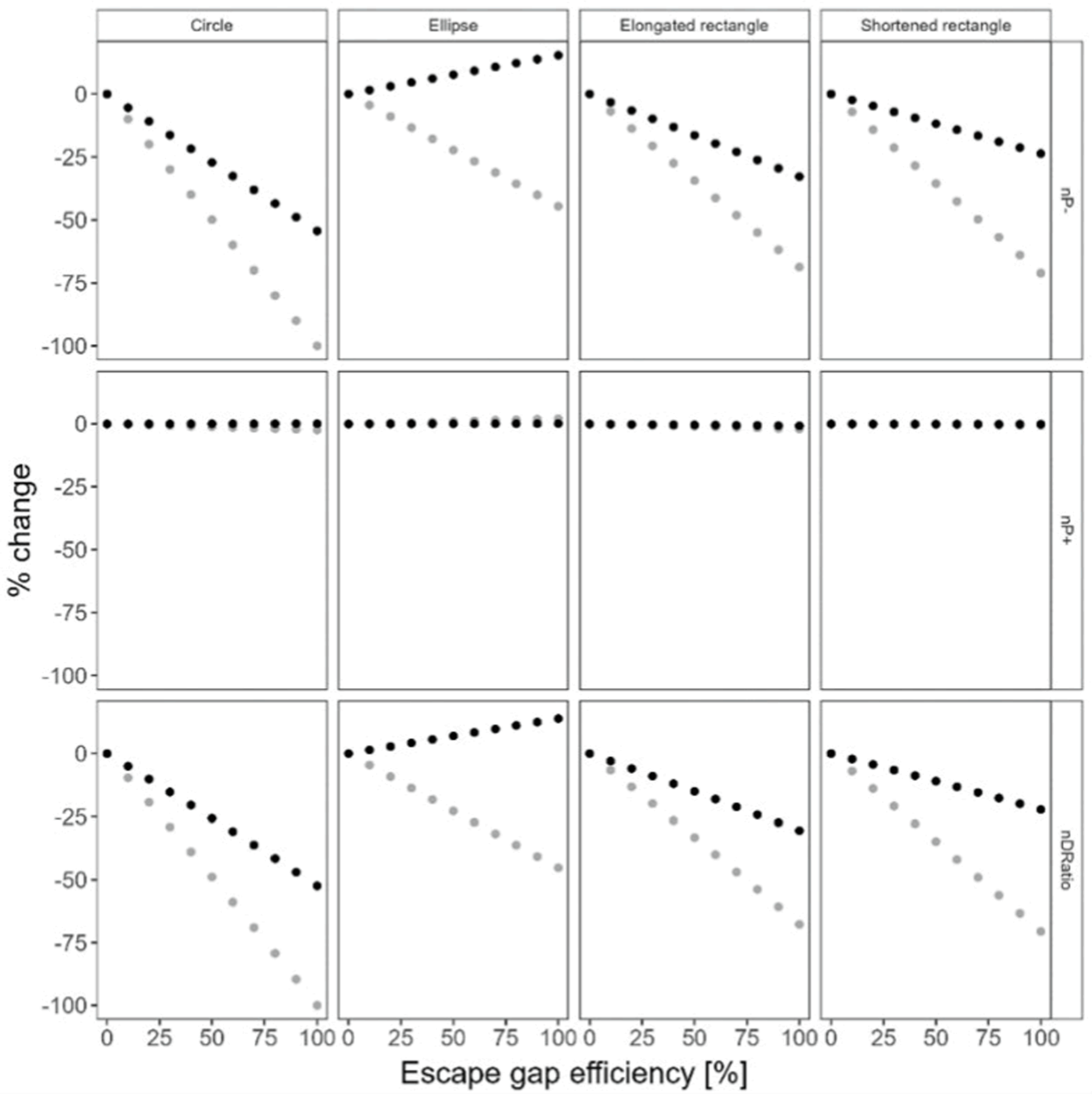


Fig. 10. Illustration of results regarding percentage change in exploitation pattern indicators for undersized (*nP*-) and target sized (nP^+) snow crabs and discard ratio (*NDRatio*) for different escape gap shapes (circular, elliptic and two rectangular escape gap configurations) depending on escape gap efficiency ranging from 0 % to 100 % efficiency when considering 95 mm (grey dots) and 100 mm (black dots) MLS.

elliptic escape gaps can match the release potential for undersized crabs in meshes of different opening angles (Herrmann et al., 2021).

Further, the results showed that escape gaps can have a potential to be used for snow crab size selection based on the results from our fall-through experiments. Specifically, escape gap size parameters can be used and adjusted to the corresponding MLS in specific snow crab fisheries. For example, the circular escape gaps in this study were considered as a special case of elliptic escape gaps. The results showed that a circular escape gap of 95 mm diameter as currently used on voluntary basis in the Canadian snow crab fishery, can exclude undersized snow crabs; however, with some potential loss of target sized individuals when MLS of 95 mm CW is considered. These results are in line with previous results testing the use of such escape gaps in Canadian snow crab fishery (Winger and Walsh, 2007) that concluded that the escape gap diameter of 95 mm would allow escape of undersized crabs. Based on the results of this study that is based on the carapace morphology, slightly smaller diameter could be considered to limit potential loss of target sized snow crabs for this specific MLS. Similarly, our results showed that the diameter of such circular escape gap should be increased if the MLS is increased to 100 mm CW as in snow crab fishery in Greenland.

For rectangular escape gaps, the height of the gap has a strong effect on the sizes of snow crabs that can be excluded from pots. Such result is in line with an earlier study testing escape gaps limiting snow crab escape on the height of the carapace. Specifically, Anders et al. (2023) tested stadium shaped escape gaps under commercial fishing conditions as means of limiting escape of snow crabs based on escape gap height similarly as rectangular escape gaps in this study. This study used an escape gap height of 4 cm resulting in estimated *CW50* of 94.6 mm, which corresponds to the results of our study which showed a *CW50* value of 95.16 mm (CI: 86.91–103.41).

Earlier studies have shown that the optimal escape gap shape and size is species dependent (i.e., Boutson et al., 2009, Zhang et al. 2023). Considering the sideways movement of snow crab (Winger and Walsh, 2007), the limiting measures of the snow crab carapace affecting the escape probability are the carapace length and height. These measures are related to the length and height of the escape gap, respectively. The fact that the escape gap selection depends more upon the body length and depth rather than carapace width has previously been acknowledged in earlier experiments testing use of escape gaps in different crab pot fisheries (i.e., Brown 1982, Boutson et al., 2009, Zhang et al. 2023). Thus, in our study, the decisive size for the elliptic escape gap was largely based on carapace length of the snow crab while for the rectangular shaped escape gap templates, the carapace height was the decisive measurement affecting passage through the escape gaps. This was also reflected in the resulting *iso*-curves for rectangular escape gaps showing that parameter *A* (escape gap height) has a large effect on the resulting retention probabilities (Fig. 7).

The predictions of combined mesh and escape gap size selection as presented in this study (Figs. 9 and 10) were used to illustrate the selection potential of conical snow crab pots equipped with different size and shape escape gaps. Specifically, the results presented herein illustrated that increasing efficiency of an appropriate shape and size escape gap can improve size selection potential. Our results showed that circular escape gaps can have potential to improve size selectivity by considerably reducing the amount of captured undersized snow crabs. Furthermore, the circular escape gaps showed a potential of providing a sharper size selection compared to the netting meshes which is preferred in the fishery. On the contrary, use of elliptical or rectangular escape gaps resulted in a less sharp size selection with increased escape gap efficiency (Fig. 9). This illustrates that use of escape mechanisms limiting snow crab passage based on carapace height, such as rectangles, would not provide an optimal size selection potential and that other shapes such as elliptical gaps limiting snow crab escape based on carapace length would be preferred due to lower *SR* values. This is the first attempt to illustrate changes in size selection potential of different escape gaps based on their efficiency in pots, and such an approach could be a useful tool to further illustrate size selectivity potential of different escape gap shapes and sizes.

The results of this study are based on laboratory experiments using dead snow crabs. However, in commercial fishing conditions, the size selectivity potential of the escape gaps can depend on several factors, including soak time. Specifically, during the time of the pot deployment, snow crabs should have sufficient time for orientating optimally for passing the escape gap during the escape process. Sufficient pot soak time would imply that the bait odor is depleted over time, allowing time for subsequent escapement of undersized crabs due to no attraction to the pots caused by bait (Olsen et al. 2019b, Cerbule et al. 2023a). However, in earlier studies by Winger and Walsh (2011) and Anders et al. (2023), the results showed that the escape gaps are showing an improved size selection already with short soak time (24 h for circular escape gaps (Winger and Walsh, 2011) and between 41 and 77 h for stadium shaped gaps (Anders et al., 2023)) compared to traditional pots. Furthermore, for escape gaps to improve the size selectivity in pots, crabs must be able to successfully locate the gaps. Therefore, use of more than one escape gap in each pot is usually recommended (Boutson et al., 2009). For example, Winger and Walsh (2011) used three escape gaps on each pot to maximize contact probability for the snow crab. Specifically, the higher the number escape gaps, the larger the probability that the crabs would fully utilize the escape gaps by having contact of close to 100 % (Figs. 9 and 10). The location of the escape gap along the pot frame (i.e., height) is also important for allowing crabs to locate such escape mechanism. The crabs move by side crawling around the bottom of the pot and due to this behaviour placement of escape gaps around the lower part of the pot could improve the possibility of locating escape gaps (Boutson et al., 2009). This has also been previously observed in snow crab pot fisheries (Winger and Walsh, 2007).

In this study, we based our results on the size selectivity parameters *CW05*, *CW50* and *CW95*. Such parameters explain the 5 %, 50 % and 95 % probability, respectively, that the snow crab of the particular size is retained in the pot. In commercial snow crab fisheries, the desirable size selection for a pot would be to limit the catches of undersized snow crabs as much as possible while avoiding loss of the target sized individuals. Therefore, when selecting the size of escape gaps, *CW95* can be applied, meaning that this parameter estimated the size of the gap that would retain 95 % of the snow crabs from the CW size of approximately 95 mm or 100 mm, respectively. Furthermore, during our experiments we assumed that the force that the snow crab can produce by moving through the different shapes is equal to the force of gravity. Whether such an assumption is realistic is unknown. However, several studies assessing crab morphology and its potential to pass through meshes based on their carapace assume that the smallest gap an animal could pass through by hand was also the smallest opening it could pass through unaided (Miller 1990, Winger and Walsh, 2007, Herrmann et al., 2021).

Finally, use of biodegradable twine to incorporate such escape mechanism in the pot netting or making escape plates fully of a biodegradable material could be considered due to the potential to reduce continuous capture of marine animals by derelict pots (so-called "ghost fishing"). Specifically, the currently pot design is largely or fully made of non-biodegradable materials (i.e., metal frame covered with polyethylene netting). Thus, such gear can continue ghost fishing for long periods when lost, abandoned or discarded at sea (Miller 1990, Humborstad et al., 2021, Cerbule et al. 2023b). Due to faster degradation of the biodegradable material, the area of the whole escape gap plate would become available for releasing also larger sized individuals in case pots are lost. Therefore, it would have potential for reducing the ghost fishing risk of lost snow crab pots.

In conclusion, the reduction of undersized snow crab catches while maintaining the catch over the MLS by installing circular escape gaps in traditionally used conical snow crab pots may have potential to improve size selectivity and thus sustainability in snow crab fisheries. Furthermore, it is a relatively inexpensive and simple measure for implementation in commercial snow crab fisheries. However, it is important to note that in this study we considered escape gap shapes based on the laboratory experiments assessing the snow crab carapace morphology and selected escape opening shapes and sizes. Such approach does not consider other parameters such as crab behaviour, movement pattern and snow crab ability to coordinate the movement of the legs optimally to pass each of the alternative escape opening shapes. Specifically, whether the crab is able to successfully pass the specific escape gap opening can be determined not only by its CW but also other parameters such as the ability to maneuver through the specific shape of a specific size. Therefore, further experiments during sea trials or laboratory observations with live snow crab could provide valuable information to supplement the results of this study.

CRediT authorship contribution statement

Kristine Cerbule: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bent Herrmann:** Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Jure Brčić:** Writing – original draft, Visualization, Validation, Investigation, Formal analysis. **Eduardo Grimaldo:** Writing – original draft, Investigation, Conceptualization. **Zita Bak-Jensen:** Writing – original draft, Visualization, Conceptualization.

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.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jnc.2024.126616.

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