Effect of gear soak time on size selection in the snow crab pot fishery

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Abstract

In the commercial pot fishery for snow crab (*Chionocetes opilio*), size selection by the pots is important for reducing catch sorting and unintended mortality. In addition to mesh size and shape, selection in the pots relies on every crab contacting the netting meshes, which makes the process complex because the odour of the bait tends to keep all sizes of crab in the pots. Thus, soak time may affect the extent of the use of the selective potential of the pots. This study was designed to assess the influence of soak time on size selectivity, and the methodology was applied to snow crab data collected in the Barents Sea. The results showed that a minimum soak time is required to reach the full size-selective potential of the pots. Specifically, a fraction of the small crabs inside a pot will not attempt to escape through the pot meshes when the pots are soaked for short periods of time (under nine days). Further, with short soak time, some of the crabs inside a pot will not make selectivity contact with the netting. Therefore, some crabs will not utilize the escape options through the pot meshes. This finding confirms the need for using a selection model that explicitly accounts for such a process when assessing snow crab size selection. Lastly, this study outlines how the concept of selectivity contact can formally be applied to model the effect of soak time on the size selectivity of the snow crab pot fishery.

1. Introduction

Snow crab (*Chionoecetes opilio*) is distributed in the polar regions of the Northern Hemisphere and for decades has formed the basis of an important commercial fishery in countries such as the USA, Canada and Russia (Alvsvåg et al., 2009; Winger and Walsh, 2007; Mathis et al., 2015). Although seines are successfully used to catch this species in countries such as South Korea (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 vary among regions, but the working principle of the gear is basically the same. Snow crabs are attracted to the pot area by the odour of the bait in the pot, and once they enter the pot they stay there until one or more mechanisms trigger their willingness to escape. 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; Broadhurst et al., 2017). However, a snow crab captured in a pot will not be able to escape unless it is able to pass through 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 will affect the size distribution of the snow crabs ultimately recovered on board the fishing vessel.

Soak time (e.g., the amount of time a pot is fished in the water) is an important factor that can affect catch performance of pot gear (Boutillier and Sloan, 1987). For a snow crab to enter a pot, it must have enough time to sense the bait, approach the pot, and finally enter it. If the pot is hauled before this process is completed, the catch performance of the pot will be suboptimal. Furthermore, if soak time is too short and the pot is hauled before the snow crab attempts to escape, the selective properties of the pot's netting will not be fully utilized.

Several researchers have used the concept of "selectivity contact" to study size selectivity of active fishing gears (e.g. Sistiaga et al., 2010; Larsen et al., 2016), but to date this concept has not been applied to pot gear. The concept of selectivity contact is that an animal must first physically contact the selectivity device (in this case the pot netting), but then be orientated in a manner to allow for a size-dependent escape to occur. For crabs, they cannot maneuver and change orientation as fast as fish and might therefore require more time to contact selectivity devices. Thus, while fish are likely to make selectivity contact with the pot netting several times in a short-time process (i.e., during haul back), the probability of crab to optimally orientate and escape through the pot meshes would be much lower. In this study, we tested whether an analytical approach that considers the probability of crab making selectivity contact with the pot netting could be used to study snow crab pot selectivity, including the effect of soak time. Off Canada, Winger and Walsh (2011) reported that increased soak time reduced the amount of undersized snow crab in pots. This suggests that selectivity contact with the netting and size selection increases over time.

Sorting crabs on deck can be a labour-intensive operation onboard a fishing vessel. If not performed with care and caution, it can result in illegal processing of undersized crabs or unnecessary 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 as the risk for their internal organs to freeze increases with decreasing temperature (Grant, 2003). Thus, size selectivity at the seabed is optimal and would decrease the sorting labour on deck and decrease unnecessary snow crab mortality.

In this study, we evaluated the size selectivity of crab pots, including the effect of soak time, in the Barents Sea snow crab fishery. This fishery is relatively new, with the species not commercially exploited in the Barents Sea until the beginning of the present decade. The total landings in the Barents Sea increased from 2.5 tonnes in 2012 to 10,430 tonnes in 2016, of which approximately 5200 tonnes were landed by Norwegian vessels (Norwegian Sales

Organization (https://www.rafisklaget.no), 2016). The fleet consists of vessels between 40 and 70 m long, and each vessel operates between 1000 and 2000 pots every day. Snow crab in the Barents Sea fishery are exclusively harvested using conical pots (ranging from 120 to 140 mm mesh sizes) deployed in strings connected to the main line (e.g., longline). The minimum legal size for snow crab in the Barents Sea is 100 mm carapace width (CW), which means that primarily only male snow crabs can be harvested as females are rarely > 90 mm CW. All undersized snow crab must be returned to the sea. The management regulations in the Svalbard Fisheries Protection Zone (ICES area SXV) and Norwegian EEZ are as follows: minimum legal size of 100 mm CW; maximum of 12,000 pots deployed per vessel; maximum soak time for pots of three weeks; mandatory use of pot gear only; the fishery is closed and all pots must be removed from the seabed from 15 June to 15 September; and a maximum of 20% post moult crab caught (Norwegian Fisheries Directorate (www.fiskeridir.no), 2018).

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

- Does soak time affect the selective performance of snow crab pots? If so, what is the minimum soak time required to exploit their full selective potential?
- Is the parameter "selectivity contact" a good indicator of the effect of soak time on the selective properties of snow crab pots?
- Are the selective properties of the conical pots used in the Norwegian snow crab fishery appropriate for the minimum legal CW regulation?

2. Materials and methods

2.1. Collection of sea trial data

Sea trials were conducted aboard the fishing vessel Northguider (55.2 m overall length and 3750 HP) in the central Barents Sea (N76°28.9–E36°36.9 and N75°56.1–E37°33.8 (ICES area

SXV)) at depths of 280–310 m. The trials took place between 01 March and 09 April of 2018. The pots used in the trials were conical, with diameters of 70 and 130 cm at the top and the bottom, respectively and a height of 60 cm. The 53 cm diameter entrance to the pot was situated on top. The pots were fished in longlines of 200 pots attached to the mainline every 30 m by a quick link system that allowed rapid attachment and release of the pots to/from the mainline (Fig. 1). During the experiments, we used size selective pots subjected to the investigation (test pots) and pots with small mesh size compared to in the test pots (control pots). All pots were identical except for the netting used to cover the frame. Test pots consisted of 140 mm (nominal) mesh size (Ø4 mm polyethylene (PE) twine), whereas 52 mm (nominal) mesh size (Ø2 mm PE twine) was used for the control pots (Fig. 1). Each third or fourth pot was a control pot. The large difference in mesh size between the test and control pots eliminated any overlap in potential size selection of snow crab between the two types of pots. Thus, this enabled an unbiased estimation of the size selectivity for the test pots based on comparing the catches in the test and control pots. Given the pots conical shape, the meshes opening angle on the netting will vary depending on their location on the pot. Therefore, both mesh size and opening angle are decisive for which sizes of crab can escape through the meshes. To get an estimation of the mesh size and opening angle on the test pots used during the sea trials, we digitized and modelled the contour of 12 meshes from a random pot used during the trials (Fig. 2). The average mesh size obtained was 136.7 mm (range 130.4–139.7 mm) and the average mesh opening angle obtained 79.2° (range 67.2–88.8°) (Fig. 2).

FIG. 1

FIG. 2

Each pot was baited with 700 g of squid (*Ilex* spp.) in a mesh bag and perforated plastic container (Fig. 3a). When the pots were hauled onboard, they were emptied separately onto a sorting board and CW of each crab was measured to the nearest mm using callipers (Fig. 3b).

FIG. 3

2.2. Analysis of sea trial data

Analyses of the sea trial data were conducted separately for each group of deployments with the same soak time. The data were analysed using the method described below, which was implemented in the software tool SELNET (Herrmann et al., 2012). Based on the experimental design, the catch data from the test and control pots were collected in pairs on the same longline and can be regarded as paired. As each longline covered a long track (approximately 6500 m for a 200 pot line), the longline was segmented into local groups (sets) for analysis purposes. In this way, it was more realistic to assume that the control and test pots from a set were fishing a population of snow crab with the same size distribution than if each set was covering the complete longline. Consequently, a set consisted of between 21 and 42 test pots and 7 and 21 control pots. The catch data from individual test and control sets with the same soak time were used to estimate the average size selectivity for the test pots for each specific soak time. The data for each soak time were pooled over sets, and the paired gear estimation method was applied (Wileman et al., 1996). Thus, the average size selectivity of the test pots was estimated based on the catch data summed over deployments by minimising the following equation, which is equivalent to maximising the likelihood for the observed experimental data:

$$-\sum_l \sum_{i=1}^{m} \left\{ nT_{li} \times ln\left(\frac{SP \times r(l,\boldsymbol{v})}{SP \times r(l,\boldsymbol{v}) + 1 - SP}\right) + nC_{li} \times ln\left(1.0 - \frac{SP \times r(l,\boldsymbol{v})}{SP \times r(l,\boldsymbol{v}) + 1 - SP}\right) \right\} \quad (1)$$

where nT_{li} and nC_{li} represent the number of snow crabs of each length class *l* retained in the *i*-th set for the test and control pots, respectively. *m* represents the total number of sets for the specific soak time group. *SP* is the split factor quantifying the sharing of the total catch between the test and the control pots (Wileman et al., 1996), and $\boldsymbol{v}$ is a vector of parameters in the size selection model $r(l,\boldsymbol{v})$. The potential for differences in entrance efficiency of snow crab between test and control pots is reflected in the value of *SP*, and therefore will not bias the estimation of the size selectivity $r(l,\boldsymbol{v})$ for the test pots. Thereby, this eliminated potential bias in estimation resulting from differences in netting twine thickness and colour between test and control pots.

Because the test pots were constructed with a single mesh size and had the entrance on the top, which prevented escape through this path, it would traditionally be assumed that the pot size selection can be described by the standard *logit* model (Wileman et al. 1996). This model has been applied by Xu and Millar (1993) and Winger and Walsh (2011) to model size selection in snow crab pot fisheries using selection parameters $\boldsymbol{v} = (W50, SR)$:

$$r(l,\boldsymbol{v}) = r_{Logit}(w,\boldsymbol{v}) = \frac{exp\left(\frac{ln(9)}{SR}\times(w-W50)\right)}{1.0+exp\left(\frac{ln(9)}{SR}\times(w-W50)\right)} \qquad (2)$$

W50 is the CW of a snow crab with 50% probability of being retained given it has entered the pot, whereas *SR* is the CW difference of a snow crab with 75% and 25% probability of being retained, conditioned they entered it. The *SR* value can explicitly reflect the intra- and between-test pot variation in mesh size and opening angle (Fig. 2) affecting the escape probability for individual crab of same size. Model (2) assumes that every crab that enters a test pot attempts to escape through the meshes before the pot is retrieved on board the fishing vessel. However, a fraction of the crabs entering a test pot may not have had sufficient time to attempt such an escape, especially for pots with short soak time. Therefore, instead of modelling the size selection in the test pot based only on the *logit* model (2), we also considered the *CLogit* model (3), which can account for the possibility that only a fraction *C* of the crabs entering the pot makes selectivity contact with the meshes and is subjected to a size selection process. This is the first time that the *CLogit* size selection model has been used to estimate size selection in a pot fishery.

$$r(w,\boldsymbol{v}) = r_{CLogit}(w,C,W50_c,SR_c) = (1-C) + C \times Logit(w,W50_c,SR_c) = 1.0 - \frac{C}{1.0+exp\left(\frac{ln(9)}{SR_C}\times(w-W50_C)\right)} \quad (3)$$

The parameter *C* holds a constant value that ranges between 0.0 (no crabs make selectivity contact with the pot meshes) and 1.0 (all crabs make selectivity contact with the pot meshes). When $C = 1.0$, the *CLogit* model simplifies to the traditional *Logit* model.

Estimation of the average test pot size selection with a *CLogit* size selection model requires finding the values for the parameters *C*, $W50_c$, SR_c, and *SP* that minimize (1) conditioned by the collected catch data. The ability of this size selection model to describe the experimental data was evaluated based on the p-value, which quantifies the probability of obtaining by coincidence at least as big a discrepancy between the experimental data and the model as observed, assuming that the model is correct. Therefore, the p-value calculated based on the model deviance and the degrees of freedom should not be < 0.05 for the selection model to describe the experimental data sufficiently well (Wileman et al. 1996). We tested the ability of both the *Logit* and the *CLogit* models to describe the experimental data based on estimation in (1). Competing size-selection models were compared using the Akaike Information Criterion (AIC) (Akaike 1974), with the lowest-value model subsequently selected.

The confidence intervals (CIs) for each size selection curve and the associated selection parameters were estimated using a double bootstrap method for paired data. This method accounted for between-set variation in the availability of snow crab and pot size selection by selecting *m* sets with replacement from the pool of sets for the specific soak time during each bootstrap repetition. Within-set uncertainty in the size structure of the catch data was accounted for by randomly selecting snow crabs with replacement from each of the selected sets separately. The number of crabs selected from each set was the same as the number of crabs caught with that longline segment. For each soak time case, we performed 1000 bootstrap repetitions and calculated the Efron 95% (Efron, 1982) CIs for the size selection curve and the associated parameters. To examine differences between the selection curves, quantified as the difference (Delta) in retention probability, we used a method based on separately obtained bootstrap files. This method is described in Larsen et al. (2018) and Lomeli et al. 2018.

2.3. Meta-analysis of the effect of soak time on size selectivity of the pots

In this section, we describe a meta-analysis that links the point estimates obtained for each specific soak time to establish models that quantify the effect of soak time (t_{soak}) on pot size selectivity for snow crab. The starting point for this modelling is the standard three-parameter logistic growth model (Gershenfeld, 1999):

$$g(t_{soak}) = \frac{c_g}{1.0 + b_g \times exp(-a_g \times t_{soak})} \qquad (4)$$

Model (4) was applied separately and independently for $g(t_{soak})$ to C, $W50_c$, and SR_c, which resulted in independent estimates for the sets of parameters (a_C, b_C, c_C), (a_{W50c}, b_{W50c}, c_{W50c}), and (a_{SRc}, b_{SRc}, c_{SRc}). The rationale for using model (4) as a starting point for the meta-analysis is that the three selection parameters (C, $W50_c$ and SR_c) are all limited in their possible value ranges, which, contrary to the scenario for simple linear models, is a priori ensured with (4). Specifically, for the selectivity contact parameter C the value range should be 0.0 to 1.0, which in (4) is ensured by fixing the parameter *c* at 1.0. In addition to model (4), we also considered the adjusted form (5). Similarly, for $W50_c$, we also considered a modified model (5). In this case, the parameter c_g in (4) is fixed to a value $W50_{cu}$ that is defined based on the maximum size of snow crab that geometrically would be able to escape through the netting meshes used in the experimental pots applied in the fishing trials. It was more complicated to establish an alternative model For SR_c. As for $W50_c$, SR_c has an upper boundary, but it is not possible to quantify this value a priori. However, it may have a lower boundary value (SR_{cl}) because individual snow crabs with the same CW are expected to differ in carapace morphology, which for a specific pot mesh size/shape will lead to between-individual variation in escape potential. The above considerations led to the following alternative model for the effect of soak time on the pot size selection of snow crab:

$$\begin{aligned} C(t_{soak}) &= \frac{1.0}{1.0 + b_C \times exp(-a_C \times t_{soak})} \\ W50_c(t_{soak}) &= \frac{W50_{cu}}{1.0 + b_{W50_c} \times exp(-a_{W50_c} \times t_{soak})} \\ SR_c(t_{soak}) &= SR_{cl} + \frac{c_{SR_c}}{1.0 + b_{SR_c} \times exp(-a_{SR_c} \times t_{soak})} \end{aligned} \qquad (5)$$

Model (5) for SR_c is in the form of the common four-parameter logistic growth model (Gershenfeld, 1999).

Besides models (4) and (5), which explicitly assume a soak time dependency for the parameters C, $W50_c$, and SR_c, we also consider the possibility that they could be soak time independent by investigating the null-hypothesis model (6) with only intercept parameters:

$$\begin{aligned} C(t_{soak}) &= a_C \\ W50_c(t_{soak}) &= a_{W50_c} \\ SR_c(t_{soak}) &= a_{SR_c} \end{aligned} \qquad (6)$$

Choice among models (4) to (6) was based on the lowest *AIC* value selecting the one with lowest *AIC* for C, $W50_c$, and SR_c individually. If model (6) results in the lowest *AIC*, we would conclude that the selection parameters do not depend on soak time. Contrary, if model (4) or (5) is the clear choice, we would interpret this as evidence that soak time affects the selection parameter values. Furthermore, to support the conclusion, we estimate (based on Wagenmakers and Farrell, 2004) the relative likelihood L_i for each of the other models i compared to the model with the lowest *AIC* value (AIC_{min}) by:

$$L_i = exp\left(-\frac{AIC_i - AIC_{min}}{2}\right) \qquad (7)$$

The *nls* function in the statistic software package R (version 3.5.0) was applied to estimate the parameter values in models (4) and (5). The estimations were made based on the data set consisting of the values for t_{soak} versus *C*, $W50_c$, and SR_c. Subsequently, the R-functions *AIC* and *Rsq* were used to obtain *AIC* and pseudo R^2 values for the model fits.

2.4. Estimation of optimal size selection

The optimal size selection curve for the 137 mm test pot was assessed using a fall-through experiment (Herrmann et al., 2009). We tested whether crab (in a sample covering a wide range of CWs) were geometrically able to pass through a typical mesh of a test pot (Fig. 4). We selected a mesh near the bottom the pot as we found it most likely that most crabs make their escape attempts here. In all tests, crab were optimally orientated with respect to the mesh. A crab that could not pass through the mesh was regarded as retained, whereas a crab that could pass through was regarded as escaped. Treating these CW-dependent escape/retention data as size selectivity data and modelling them using the traditional logistic size selection model (2) with parameters $W50_f$ and SR_f provided a fall-through size selection curve. The advantage of applying this method is that it automatically accounts for the cross-sectional shape and size of the animal when passing through partially opened meshes. Considering the cross-sectional shape of a snow crab and the shape of a partially opened mesh, simply comparing CW to the mesh size does not provide a reliable estimate of the largest sizes of snow crab that could pass through the pot meshes. Thus, the fall-through based method offers a simple and more reliable way to estimate optimal size selection. This method has previously been applied to *Nephrops norvegicus* (Frandsen et al., 2010; Brčić et al., 2018).

FIG. 4

The obtained fall-through selectivity curves were used to compare the sea trial-obtained size selection curves to the full utilization of the selection potential of the 137 mm meshes of the pot netting. Furthermore, the parameter values obtained for $W50_f$ and SR_f were used as estimates for $W50_{cu}$ and SR_{cl}, respectively, in (5).

3. Results

3.1. Optimal size selection

In the fall-through experiment, we used a total of 200 snow crab with CWs between 70 and 148 mm to estimate the optimal size selection (Table 1; Fig. 5) for the 137 mm mesh size experimental pots.

FIG. 5

TABLE 1

The fall-through results show that the 137 mm mesh size pots have a size selective potential that fits well with the minimum targeted snow crab size in the Norwegian fishery because $W50_f$ is close to 100 mm (Table 1). This is further supported by a small SR_f value (2.23 mm), which is reflected in the steepness of the size selection curve (Fig. 5).

3.2. Experimental size selection from sea trials

We fished a total of 18 sets of pots each containing between 21 and 42 test pots and between 7 and 21 control pots (Table 2). During the sea trials, the number of crabs caught in the test and control pots varied between 12 and 93 and between 20 and 573, respectively. Four sets were soaked for five days, four for six days, eight for nine days, and two for fourteen days.

TABLE 2

Based on the experimental data, the size selection in the pots was estimated for five, six, nine, and fourteen days of soak time (Fig. 6; Table 3). A comparison of the *AIC* values obtained for the *Logit* model (2) and the *CLogit* model (3) revealed that the latter better described the experimental size selectivity data when the soak time was short (five and six days). Thus, for short soak time it is necessary to use a size selection model that explicitly accounts for the fact that not all snow crabs make selectivity contact with the meshes in the pot and are not size selected by them. This finding was confirmed by the shape of the size selection curves, which show that a fraction of the crabs entering the pots is retained independent of their size (Fig. 6). When the soak time increased to fourteen days, the *AIC* value was lowest for the *Logit* model, which indicates that all snow crabs make selectivity contact with the meshes. This is also corroborated by that the estimated size selection curves reached zero retention for the smallest sizes of snow crab for these cases (Fig. 6).

As the *Logit* model is a special case of the *CLogit* model and because the sum of *AIC* values over soak time cases was lowest for the *CLogit* model, this model was applied for all cases. This choice enabled uncertainty estimation for the selectivity contact parameter *C* for nine and fourteen days of soak time, for which the average *C* was estimated to be 1.0. The p-values obtained for the *CLogit* model showed that this model could model the experimental data sufficiently well, as the estimated p-value were > 0.05 (Table 3). Therefore, we were confident about applying this model to assess snow crab size selection in this study.

FIG. 6

TABLE 3

The size selection curve obtained with each soak time with the optimal size selection obtained based on the fall-through experiment (middle column and rightmost column) are compared in Figure 6. Results show that the size selection obtained was significantly lower than optimal when soak time was short. Significant difference was nearly absent only for the longest soak time (fourteen days). These results show that conical pots reach their full size-selective potential only when they have had sufficient soak time. A positive correlation was detected between soak time and C, $W50_c$, and SR_c, as indicated by the meta-analysis that modelled the effect of soak time on these three selection parameters (Fig. 7; Table 4). After five and six days of soak time, respectively, 15% and 6% of the crabs were estimated to have not made selectivity contact with the meshes in the pot (C equal to 0.85 and 0.94). Only after nine–fourteen days of soak time were nearly 100% of the crabs in the pot been able to make selectivity contact with the meshes in the pot netting. However, Figure 7 shows that the quality of the selectivity contact with the meshes also depends on the soak time. The parameter $W50_c$ increased with soak time, and even when 100% selectivity contact was achieved, $W50_c$ was still below $W50_f$, which implies that not all crabs managed to make selectivity contact for mesh escape. The parameter SR_c also increased with soak time. The meta-analysis revealed that both the traditional model (4) and the alternative model (5) described the trends in the selection parameter values well, as the obtained pseudo R^2 values were high in all cases. The alternative model (5) performed especially well, with pseudo R^2 values > 0.96 for all parameters. This model also outperformed model (4) for AIC values, as they were always lower for model (5). Figure 7 reveals a nearly perfect fit for the trends in the experimental based point estimates versus soak time, and asymptotic values for all three parameters (1.0, $W50f$, and SR_f for C, $W50_c$, and SR_c, respectively) seem to make sense. Thus, model (5) provides a meaningful theoretical basis for understanding the effect of soak time on gear size selection in the snow crab pot fishery. Regarding the null-hypothesis (model (6)), for each of the selection parameters the *AIC* value is much higher compared to both model (4) and (5), providing clear support for that soak time affects the snow crab size selection. Specifically, the null-hypothesis model has little support with a relative likelihood of only 8.38×10^{-6}, 0.15 and 1.16 % for respectively C, $W50_c$, and SR_c compared to for the model with most support (Table 4).

FIG. 7

TABLE 4

4. Discussion

In a fishery in which the pots used have the sole purpose of trapping the target species independent of their size, soak time would only have implications for the catching performance of the pots and the time required for the target species to enter them. However, almost every pot fishery has an intended size selectivity process occurring in the pots, which can involve the netting covering the pots, an escape opening, or other devices (Krouse, 1989; Treble et al., 1998). Thus, fishing with such pots requires extra time to allow for selection to occur in addition to the time required for the catching process itself. In most cases, a species will first enter the pot; only when it attempts to leave the pot will the selection process begin.

The selectivity curves obtained for the pots tested during the trials differed significantly among the soak times tested, which clearly demonstrates that soak time can affect the selective performance of the pots (Bennett, 1974). In addition, if one considers that an inefficient selective process in the pots can lead to additional work for the crew onboard and to unnecessary mortality, one could argue that soak time directly affects the overall efficiency of crab pots as gear. The results showed that after five days at sea, on average 15% of the crabs in the pots had not achieved selectivity contact with the pot netting, and only after nine–

fourteen days of soak time was selectivity contact with the netting estimated to be 100% (Table 3). Thus, according to our results the minimum soak time required to exploit the full selective potential of the conical snow crab pots tested in this study is nine days. From an economic perspective, nine days of soak time with a corresponding 99.8 % selectivity contact is more viable than fourteen days of soak time. Moreover, replacing the bait every nine days over the course of a month of fishing would yield one more deployment with fresh bait. Despite the positive effect of soak time reported here, earlier studies on other crab species have shown that soak time can have negative effects on the damage levels of the crab harvested (Broadhurst et al., 2017). However, this potential effect was not assessed for snow crab in the present study.

Selectivity in pots has not been estimated using a model that considers the parameter "selectivity contact". We speculated that the parameter selectivity contact could be used as an indicator for the effect of soak time on the selective properties of pots, and the results in this study clearly show that this is a good approach. The fit statistics of the *CLogit* model demonstrated that this model was a good fit to the data. Furthermore, a comparison between the *AIC* values obtained with the *Logit* and *CLogit* models showed that the latter provided a better fit to the data, which demonstrated the importance of explicitly considering the parameter selectivity contact when measuring selectivity in pots. Our study outlines how the concept of selectivity contact can formally be applied to model and understand the effect of soak time on the size selectivity of snow crab pot gear. This new approach is not limited to the snow crab pot fishery, and it can be considered in future pot selectivity studies, especially in those in which soak time or other alternative variables can influence the ability of the catch/bycatch species in the pot to make selectivity contact with devices in the gear.

In the Barents Sea snow crab fishery, there is no minimum mesh size regulation for the netting used around the pots. However, the minimum CW for snow crab is 100 mm, and all crabs below this size must be returned to the sea alive and in the best possible condition. Based on experience and knowledge from other fisheries (e.g., the Canadian snow crab fishery), fishermen use 137 mm mesh size single twine netting for snow crab pots, but this is the first study designed to determine if this netting provides a satisfactory selectivity pattern for the Barents Sea snow crab fishery. For the four different soak times tested, the average $W50_c$ was between 89.9 and 94.8 mm, whereas the average SR_c was estimated to range from 3.0 to 8.8 mm. Using a slightly larger mesh size in the netting would increase $W50_c$ and consequently reduce the sorting work on deck. However, snow crab is a relatively high value species (in Norway it can exceed 16 USD per kg for fishermen) and the $W50_c$ and SR_c obtained here with 137 mm meshes were satisfactory, so the reduction of labour on deck would not make up for the loss of an important fraction of commercial crabs. Therefore, we conclude that 137 mm is an appropriate mesh size for the netting used in this fishery.

Winger and Walsh (2011) conducted a selectivity study in Canada using the same type of pots used in the present study. They compared the selectivity for 140 mm meshes and 152 mm meshes at three different fishing sites. Their average *W50*s for the 140 mm meshes ranged from 95.1 to 106.8 mm, which means that at one of the sites their *W50* was more than 10 mm bigger than the highest value in our study. Winger and Walsh (2011) noted that there are "*alternative methods for reducing incidental capture of undersized crab, including switching to larger mesh sizes and increasing soak time.*" However, the soak times tested in our study were substantially longer than that used by Winger and Walsh, and probably this discrepancy only made the differences in the estimated *W50*s between the two studies larger. The differences in the results obtained between these two studies also could be due to potential differences in mesh size/opening angle in the pots or differences in the analysis method used. Winger and Walsh (2011) also estimated *SR* values of 16.8–34.5 mm, which are much higher than the ones estimated in this study (Table 2). Sistiaga et al. (2010) demonstrated that by not considering *C*, *SR* could be significantly overestimated and *W50* could be biased. Thus, the differences in *W50* and *SR* values between the present study and that of Winger and Walsh (2011) also could be due to leaving *C* out of their model. If we compare the results obtained for six days of soak time in our study ($W50_c$ 89.9 mm; SR_c = 4.4 mm) with the results we would have obtained for the same data analyzed with the *Logit* model (without considering *C*) ($W50_c$ = 177.9 mm; SR_c = 54.6 mm), *W50* would have been overestimated by 97% and SR by 1244%. This example illustrates the importance of considering *C* in pot selectivity studies and provides a potential explanation for the difference between our results and the results from Winger and Walsh (2011).

This study presents a new framework for assessing/investigating size selectivity in pot fisheries, and it is applicable to other snow crab fisheries and pot fisheries targeting other species. Our results demonstrate that soak time and its relation to selectivity contact are important parameters to consider when investigating size selectivity in pots. Furthermore, the selective potential of the pots tested in this study were not fully utilized until the pots had soaked for nine days. Finally, our selectivity results show the 137 mm mesh size is adequate for use in conical pots in respect to the 100 mm minimum landing size of snow crab.

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TABLES

Table Legends

Table 1: Size selectivity parameters and fit statistics obtained from the fall-through experiment. Values in parentheses represent 95% confidence limits.

Table 2: For each set and its corresponding soak time, the table specifies the number of test and control pots used and the number of crabs captured in each type of pots.

Table 3: Selectivity parameters and fit statistics for each of the soak time cases presented in Fig. 5.

Table 4: Fit of models (4) and (5) to meta-data for soak time versus C, $W50_c$, and SR_c. Values in parentheses represent standard errors for the parameter estimation. *: not in model. NA: not applicable.

TABLE 1

$W50_f$ *(mm)*	98.57 (98.00–99.27)
SR_f *(mm)*	2.23 (1.37–2.67)
p-value	>0.9999
Deviance	20.83
DOF	67

TABLE 2

Set	Soak time (days)	Number of test pots	Number of control pots	Number crabs in test pots	Number of crabs in control pots
1	14	21	11	13	261
2	14	21	10	13	182
3	6	31	15	61	61
4	6	31	12	90	342
5	6	32	15	19	203
6	6	31	15	20	20
7	9	35	17	19	92
8	9	34	14	19	133
9	9	42	16	93	268
10	9	35	11	40	281
11	9	32	14	15	258
12	9	33	13	14	154
13	9	29	17	12	381
14	9	34	12	25	573
15	5	37	7	30	53
16	5	30	14	41	162
17	5	31	13	55	131
18	5	34	12	79	124

TABLE 3

Soak time (days)	*SP*	Contact	*W50$_c$* (mm)	*SR$_c$* (mm)	p-value	Deviance	DOF	*CLogit* AIC	*Logit* AIC
5	0.4906 (0.4164–0.6096)	0.8504 (0.7548–1.0000)	89.91 (85.36–99.04)	3.03 (0.10–24.94)	0.3584	96.32	92	737.71	748.59
6	0.7114 (0.4505– 0.9723)	0.9379 (0.8389–0.9988)	90.16 (68.35–102.00)	4.07 (0.10–14.25)	0.1937	102.45	91	731.1	786.3
9	0.4174 (0.3156–0.5008)	0.9978 (0.9880–1.0000)	93.05 (89.86–97.31)	8.81 (5.84–12.71)	0.8943	89.15	107	1053.58	1052.96
14	0.2813 (0.1503–0.5000)	1.0000 (0.9918–1.0000)	94.83 (85.08–103.30)	7.62 (0.10–11.98)	0.8783	60.11	74	146.61	144.61

TABLE 4

Selection parameter	Model equation	AIC	Relative likelihood (%)	Pseudo R^2	Model parameter a	Model parameter b	Model parameter c
C	(4)	-37.66	36.79	0.9998	0.9823 (0.0339)	23.9264 (4.0820)	1.0000 (0.00125)
	(5)	-39.66	100.00	0.9998	0.9829 (0.0209)	23.9893 (2.6013)	*
	(6)	-7.07	8.38×10^{-6}	NA	0.9403 (0.0350)	*	*
$W50_c$	(4)	9.40	52.25	0.9803	0.1586 (0.1257)	0.1736 (0.0496)	96.6794 (3.0761)
	(5)	8.11	100.00	0.9772	0.1079 (0.0141)	0.1688 (0.01713)	*
	(6)	21.11	0.15	NA	91.988 (1.185)	*	*
SR_c	(4)	15.71	32.14	0.9369	0.9966 (0.8491)	320.5914 (1492.2784)	8.2903 (1.0870)
	(5)	13.44	100.00	0.9647	1.702 (2.094)	5.509e+04 (6.784e+05)	6.011 (0.7293)
	(6)	22.35	1.16	NA	5.883 (1.385)	*	*

FIGURES

Figure Legends

Fig. 1: Experimental setup used during the fishing trials.

Fig. 2: Photos showing the meshes used to estimate the size and opening angle of the of the pot meshes used during the trials (a), and the digitalization (b) and modelling (c) process of the netting meshes. The mesh size, opening angle and hanging ratio for each of the meshes measured are also provided.

Fig. 3: Photos showing the emptying of the pots (a), measurement of crab with a calliper (b) and hauling operation onboard (c).

Fig. 4: Illustration of the fall-through experiments carried out to obtain optimal size selection.

Fig. 5: Optimal size selection curve (with confidence intervals) of a pot with 140 mm mesh obtained from the fall-through experiment. The grey stipple curve represents the sizes of crab used in the experiment. The vertical grey line represents the minimum legal target size for snow crab.

Fig. 6: For the different soak times, the left column shows the size distributions of the crab captured with the test (stippled grey) and control (full grey) pots together with the experimental retention data obtained (round marks) and the *CLogit* curve (black line). The plots in the middle column show the size selectivity curve (full line) with confidence intervals (stippled lines) for each of the different soak time cases (black) compared to the optimal size selectivity curve (grey). The plots in the rightmost column show the difference between the selectivity curve and the optimal selectivity curve for each of the soak time cases (delta plot).

Fig. 7: Effect of soak time on the selectivity parameters *C*, *W50* and *SR*. Model (4) and (5) are represented by respectively the black and grey curve. Circle marks represent experimental based point estimates with 95% confidence bands. For $W50_c$ the horizontal stipple line represents the upper band asymptotic value $W50_{cu} = W50_f$. For SR_c the horizontal stippled line represents the lower band asymptotic value $SR_{cl} = SR_f$.

FIGURE 1

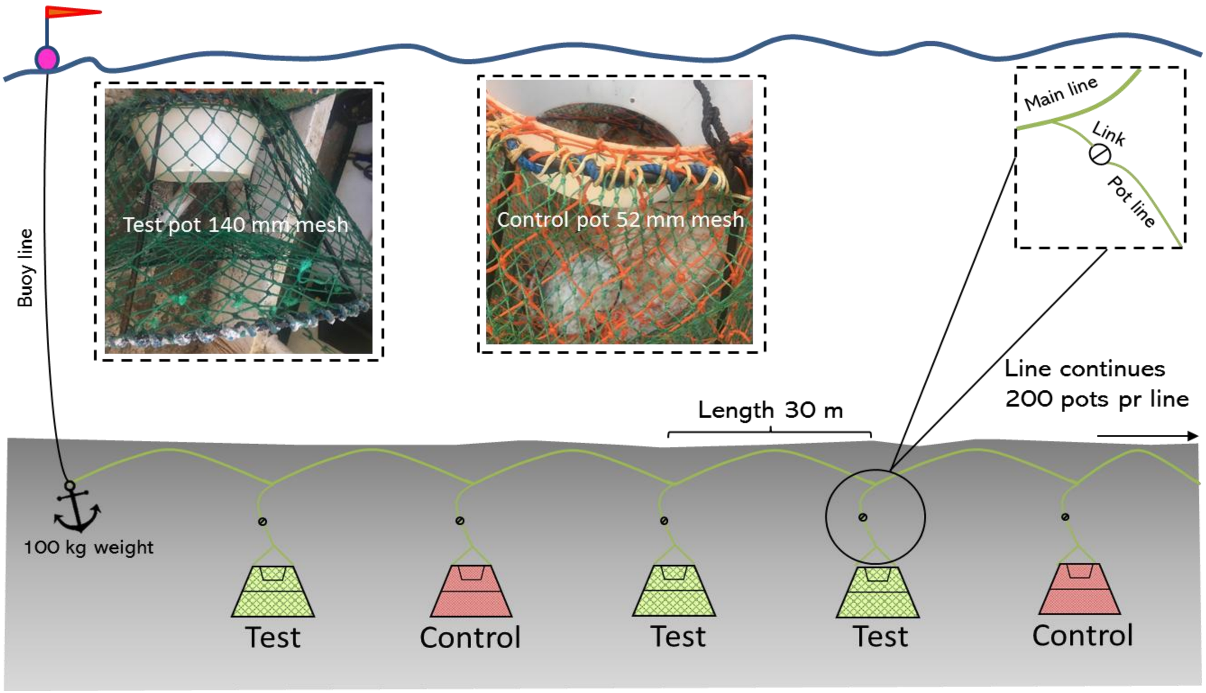
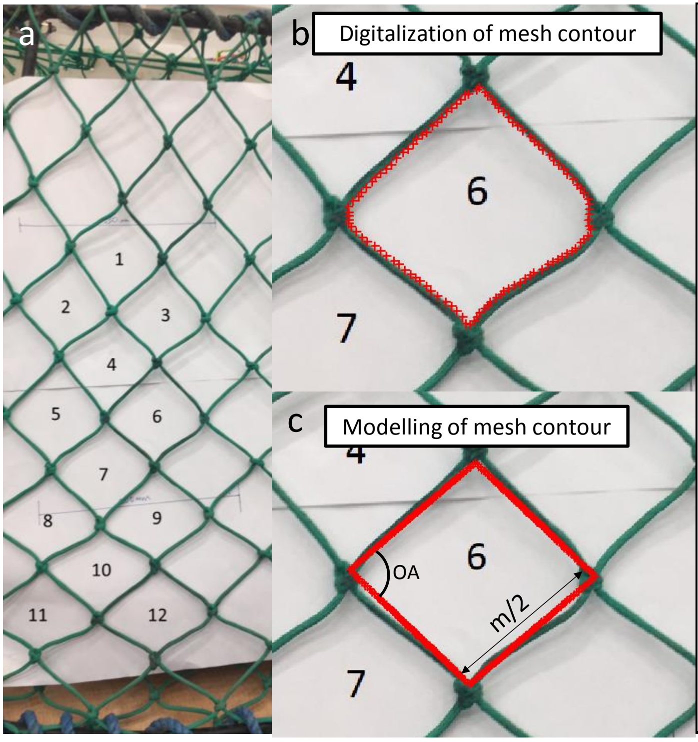

Buoy line
Test pot 140 mm mesh
Control pot 52 mm mesh
Main line
Link
Pot line
Line continues
200 pots pr line
Length 30 m
100 kg weight
Test
Control
Test
Test
Control

FIGURE 2



Mesh #	Mesh size (mm)	Opening angle OA (Degrees)	Hanging ratio
1	137.50	87.29	0.72
2	134.28	88.89	0.71
3	130.42	86.31	0.73
4	134.85	87.07	0.72
5	139.73	88.61	0.72
6	135.32	83.96	0.74
7	136.84	81.57	0.76
8	139.17	72.76	0.81
9	138.47	73.48	0.80
10	137.07	69.37	0.82
11	137.71	64.30	0.85
12	139.63	67.21	0.83

FIGURE 3

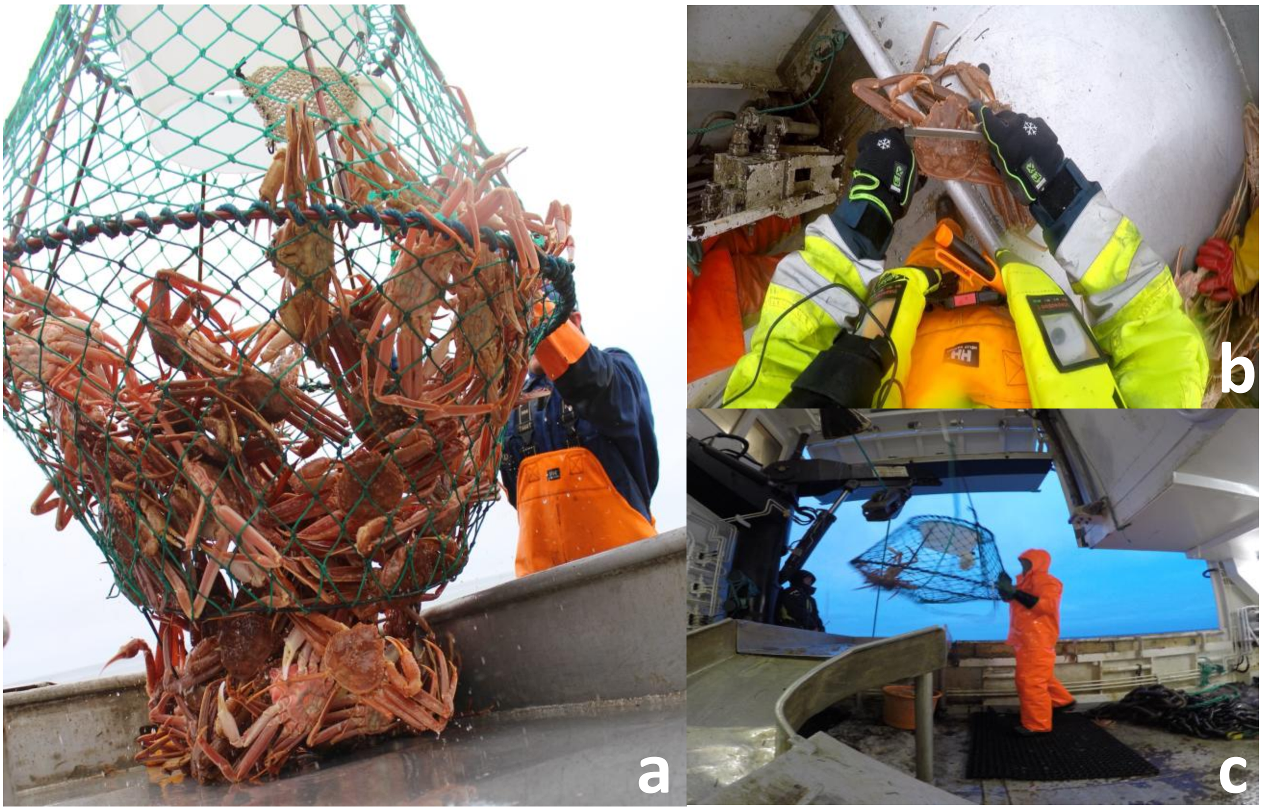
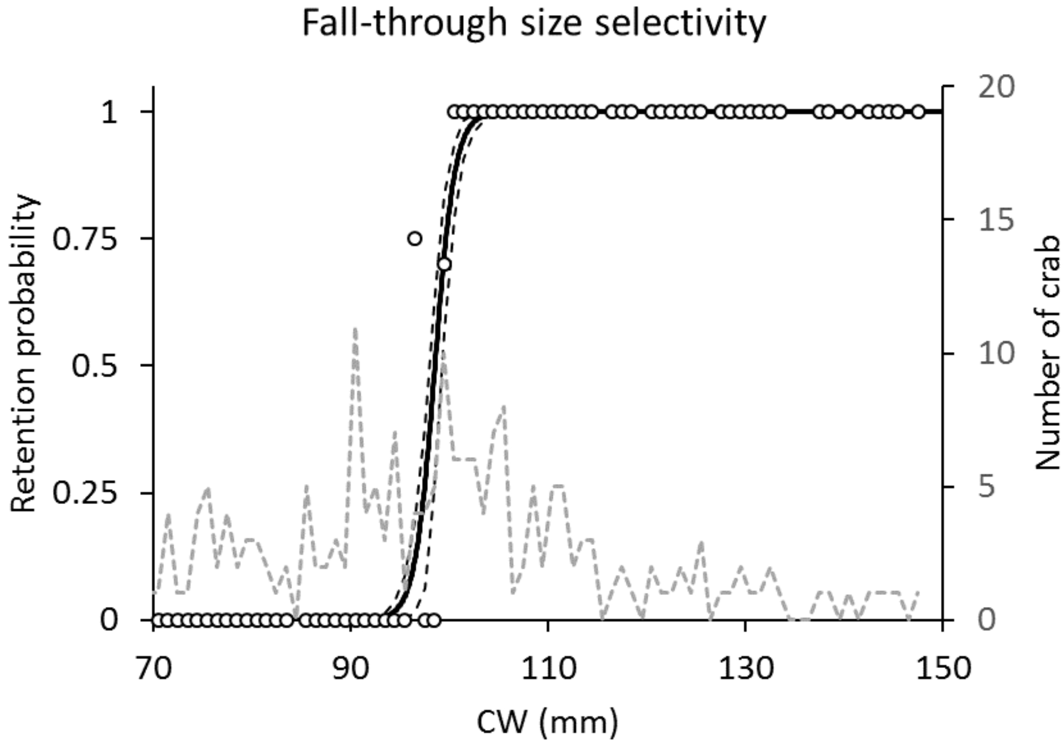


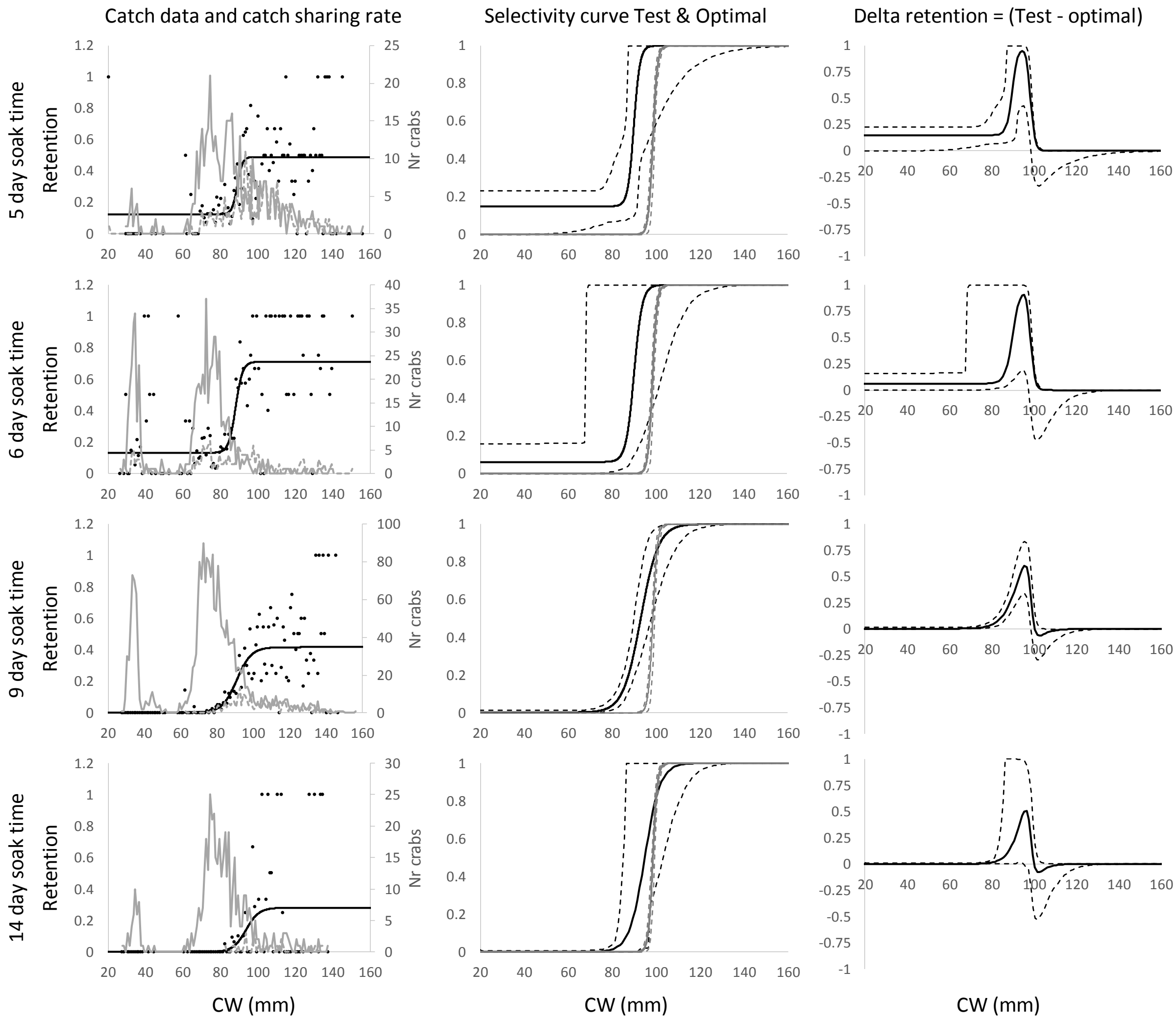
FIGURE 4

FIGURE 5



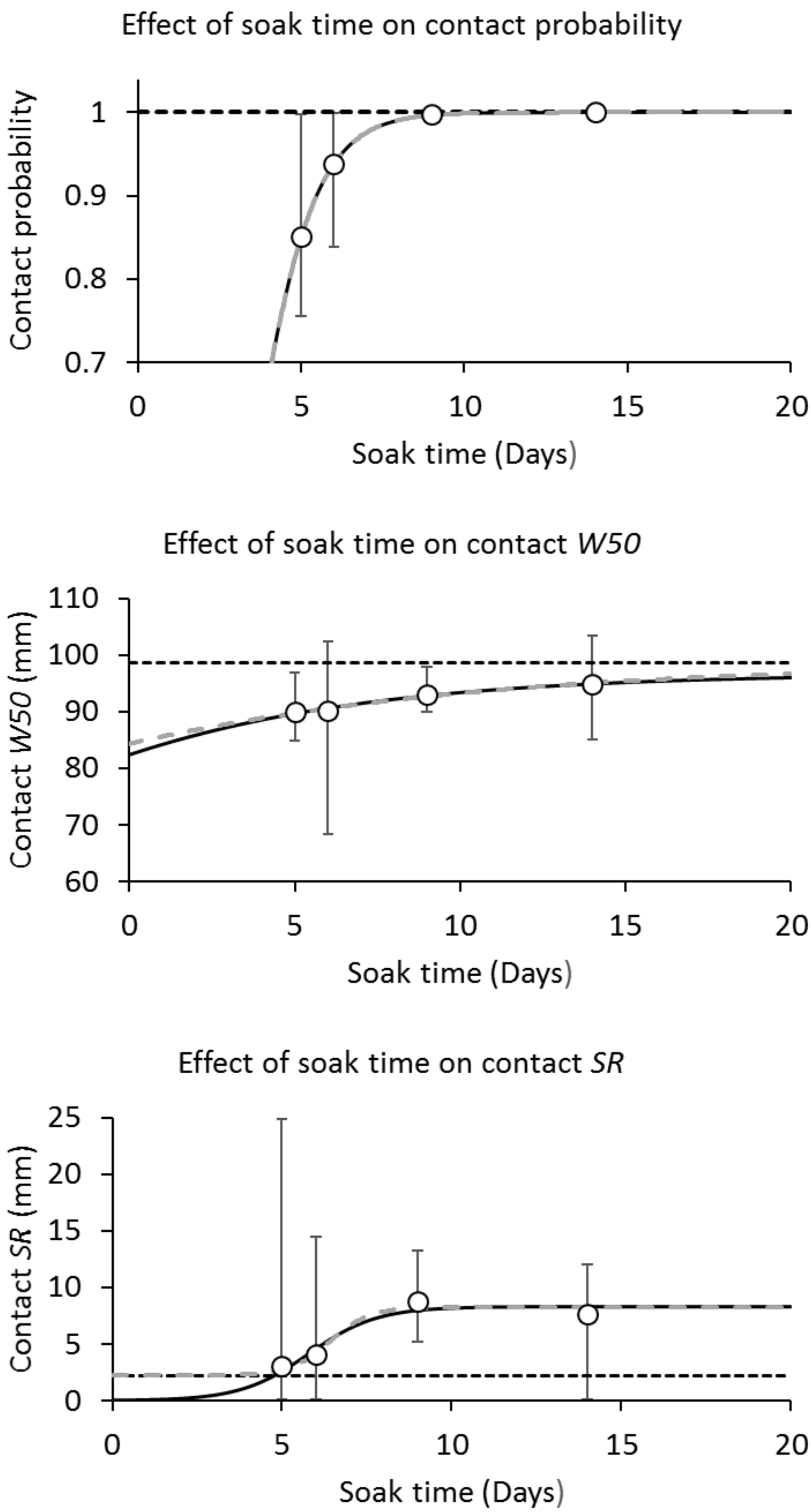
Fall-through size selectivity
Retention probability
1
0.75
0.5
0.25
0
70
90
110
130
150
CW (mm)
Number of crab
20
15
10
5
0

FIGURE 6



Catch data and catch sharing rate
Selectivity curve Test & Optimal
Delta retention = (Test - optimal)
5 day soak time
6 day soak time
9 day soak time
14 day soak time
Retention
Nr crabs
CW (mm)

FIGURE 7



Effect of soak time on contact probability
Contact probability
1
0.9
0.8
0.7
0
5
10
15
20
Soak time (Days)
Effect of soak time on contact W50
Contact W50 (mm)
110
100
90
80
70
60
0
5
10
15
20
Soak time (Days)
Effect of soak time on contact SR
Contact SR (mm)
25
20
15
10
5
0
0
5
10
15
20
Soak time (Days)