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Improving size selection in the Norwegian red king crab (*Paralithodes camtschaticus*) fishery through modification to pot design and soak time.

Neil Anders [a], Kenneth Arnesen [b], Anette Hustad [c], Terje Jørgensen [a], Svein Løkkeborg [a], Sten Siikavuopio [d], Tina Thesslund [d], Anne Christine Utne-Palm [a]

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Highlights

- Size selective properties of two new red king crab pot designs investigated.
- Size selection of a standard commercial pot determined for 1- and 4-day soak times.
- New designs not better than the commercial pot at reducing sub-legal sized crab.
- Laboratory observations suggest crab have flexible behaviour dependent on pot type.

- Size selection optimized best by increasing the soak time of the commercial pot.

Abstract

Red king crab (*Paralithodes camtschaticus*) represent a valuable inshore fisheries resource for communities in northern Norway. The fishery is regulated east of the 26th meridian by vessel quotas and a minimum landing size of 130 mm carapace length. It is executed using baited pots that must be fitted with circular escape openings. Despite this, pot catches typically contain a large proportion of sub-legal sized crab. This implies increased labor-intensive sorting which can lead to crab becoming injured, loosing limbs or delayed mortality. Such consequences negatively impact the sustainability of the fishery. In this study, we examined the potential of two new pot designs and longer soak times to reduce undersized crab catches in comparative field trials. A design consisting of a tarpaulin panel on the pot entrance (intended to prevent undersized individuals from gaining traction and entering) was found to be no better at reducing undersized catches than the currently used commercial design fitted with escape openings. A second design with a baited lower chamber (which could be accessed through the pot floor via escape openings) was intended to motivate undersized crab to escape more readily. If fished commercially, any crab in the bottomless lower chamber would be left behind on the seabed upon hauling. This design was found to have minimal effects on sublegal catches. However, increasing the soak time of the currently used commercial design from 1 day to 4 days reduced undersized crab catches substantially. This effect is likely related to bait becoming exhausted over time, thereby increasing the opportunity and motivation of sublegal crab to find and exit the pot through the mandatory escape openings. Laboratory-based behavioural observations using the panel design indicated that entry was dependent on crab orientation and that crab were less successful at entering than for the commercial design. However, all sizes of crab used an unintentional fold in the panel to increase their entrance probability. This may explain the lack of success of this design during the field trials. We conclude that ensuring bait is exhausted by employing longer soak times than is typically used by fishers would reduce catches of undersized crab in the fishery.

Data availability statement

The data underlying this article will be shared on reasonable request to the corresponding author.

Key words

Red king crab; *Paralithodes camtschaticus*; Fishing; Pot; Size selectivity; Catch efficiency; Escape openings; Soak time

1. Introduction

The Norwegian red king crab (RKC) (*Paralithodes camtschaticus*) fishery was established as a research fishery in 1994 and opened for commercial harvest in 2002 (Hjelset, 2014). There is quota regulation east of 26°E and south of 71° 30' N, and free fishing to the west (Lovdata, 2022). The goal of the regulated area is to maintain a sustainable long-term RKC fishery, while the intention of the free fishing area is to minimise the westward expansion of the population (Sundet et al., 2019). To ensure recruitment in the regulated area, there is a minimum landing size (MLS) of 130 mm carapace length for both male and female RKC. All crab caught outside the regulated area, regardless of size, must be landed. In 2021, the set quotas were 1629 tonnes (t) male, 120 t female and 181 t injured male (Lovdata, 2022). Though not large in terms of quantity, RKC's high individual value means this species has great economic significance for coastal communities where regulated fishing takes place. Norwegian fishers primarily target RKC with collapsible, single-chamber baited pots. The maximum number of pots per vessel is 30 (Lovdata, 2022).

Escape openings are rigid structures incorporated into pots to allow the escape of non-target species (Saunders, 2009). They are known to reduce the amount of undersized RKC caught in pots (Salthaug and Furevik, 2004, Jørgensen et al., 2017) and it is mandatory to have a minimum of four circular escape rings (Ø: ≥ 150 mm) fitted into the pot walls when fishing within the regulated area. Despite this, catches with up to 80% sub-legal sized crab are common (Siikavuopio et al., 2018). The MLS legislation means that such crab must be sorted out onboard and released back to sea. This can be labour-intensive and time-consuming for fishers. Furthermore, RKC can lose limbs or be damaged by crushing injuries during capture and sorting. In recent years, ~20% of RKC are missing legs or claws in the regulated area (A. M. Hjelset, Institute of Marine Research, personal communication). The proportion is >40% in the Russian area of the Barents Sea, with fishery interactions thought to be the major contributing factor (Dvoretsky and Dvoretsky, 2009). Regeneration of lost limbs takes at least 7 years (Morado et al., 2014), and damaged crabs have lower growth, lower meat content, lower fecundity, and higher natural mortality (Dvoretsky and Dvoretsky, 2009, Stevens, 2014). Experiments in Alaska have shown that as much as 20% of handled and released crab may ultimately die (Stevens, 2014). Given the potential animal welfare, sustainability and profitability impacts of this, there is a desire from numerous stakeholders to reduce the catch of undersized RKC in the Norwegian fishery. As capture related stressors are cumulative (Breen et al., 2020), the optimal solution would be to avoid the capture of undersized RKC as early into the process as possible, ideally at the fishing depth.

To obtain a high catching efficiency, fishers typically use a large amount of bait and haul their pots daily. The attractiveness of bait reduces over time, as odour is washed out and as it is consumed by captive animals (Løkkeborg, 1990, Løkkeborg et al., 2014, Siikavuopio et al., 2017). The selective properties of baited pots may therefore not be fully released until they are soaked for long enough to exhaust the bait, so that captured animals become motivated to attempt to escape. In Alaska, increased soak times reduced the ratio between sub-legal and legal RKC caught in baited pots (Pengilly and Tracy, 1998). The potential for reducing undersized catches in RKC pots in Norway through increased soak time therefore exists. An alternative approach to reduce undersized catches would be to try and prevent such individuals from entering the pot in the first place. This could be achieved by altering pot design. In Canada, the introduction of a "panel" that was difficult for small individuals to pass reduced catches of undersized snow crab (*Chionoecetes opilio*) (Chiasson et al., 1993).

In this study, we developed two new pot designs intended to reduce catches of undersized RKC and tested their size-selective properties through a series of comparative fishing trials in northern Norway. The designs were based on the principle that sub-legal catches could be reduced by either preventing such individuals from entering, or by motivating them to exit once inside. We also investigated whether the size selective properties of the pot design in current commercial use could be improved by using longer soak times. As the capture efficiency of baited passive fishing gear such as pots is largely determined by the behavioural response of the target species (Johannessen et al., 1993, Anders et al., 2017), behavioural studies can help explain the performance of different gear designs during fishing trials and thereby suggest ways they can be improved (Fernö, 1993). We therefore also conducted laboratory observations of RKC behaviour whilst interacting with our new designs.

The overall objective of our study was to determine which pot design or fishing strategy (i.e. increased soak time) optimised the size selective properties of RKC pots in comparison to the design currently used commercially. The selective properties of fishing gear are optimal when catches of sub-legal sized individuals are avoided whilst maintaining or improving the catch rate of target individuals. Specifically, we aimed to address the following research questions:

(i) Can RKC pot catches be optimised by a design that includes a "panel" around the entrance to restrict their entrance?

(ii) Can RKC pot catches be optimised by a design that includes a baited "escape chamber" to enhance their rate of escape?

(iii) Can observations of RKC behaviour in the laboratory explain the size-selective properties of the new designs?

(iv) Can RKC pot catches be optimised by using an extended soak time?

2. Material and methods

2.1. Field trials

Comparative fishing trials were conducted onboard the 15 m fishing vessel "Fangst" on commercial fishing grounds in the Porsanger Fjord (70°N, 25°E) in northern Norway in September and October 2020 and 2021. Strings consisting of pots spaced at 30 m intervals were fished in mid-fjord areas over muddy substrates at a mean depth of 147 m (range: 125 – 179 m). Pots were either non-size selective ("control") or selective ("test") (see below for detail of selective devices in the various pot designs). On all pots, the mesh size on all outer surfaces was 80 mm (nominal stretched mesh length). The mesh was square mounted, resulting in a widest opening of ~56 mm. This mesh size was considered to be non-selective for the size of crab found on the fishing grounds. One wall on all pots could be opened by a string to release the catch. Control and test pots were positioned in alternating positions along the string. Upon retrieval, catches from individual pots were sexed and then carapace length (CL) (distance from the right or left eye orbit to the medial-posterior margin of the carapace, Salthaug and Furevik, 2004) was measured to the nearest mm using digital callipers.

2.1.1. Trial 1 – "escape opening" design

To determine the selective properties of the pot design in current commercial use (also known as the “Leif Henriksen” pot, Fig. 1A), we successfully set and retrieved a total of 10 strings between 9th and 19th September 2021 (Supplementary Material 1). All strings consisted of 5 test and 5 control pots. Test pots were of the same design as those in the commercial fishery and included the mandatory minimum four escape opening rings set into the pot wall ~8 cm above the bottom frame. We use rings of 160 mm Ø; the size commonly used by fishers. Test pots measured 150×150 cm with a maximum height of 90 cm when fully extended by the floats (14 total, each with 550 g lift). Two opposite facing, upwards sloping “funnels” (75 cm long, constructed from 50 mm [floor] and 46 mm [walls, roof] nominal stretched mesh length, mounted in diamond configuration) formed the entrances. Funnels terminated in a 60×27 cm opening situated ~40 cm from the pot base. Control pots (Fig. 1D) were identical except the escape rings were removed and replaced with 80 mm mesh. All pots were baited with two defrosted and cut Atlantic herring (*Clupea harengus*) placed in a mesh bait bag hung in the centre. Strings in Trial 1 were soaked for 1 day.

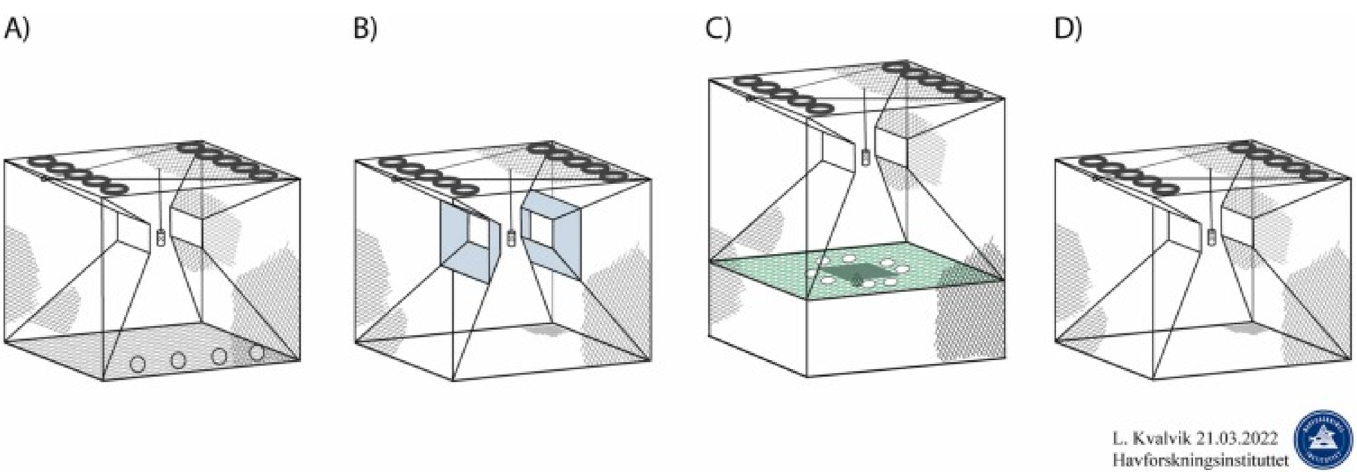

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Fig. 1. Schematics of the various red king crab (*Paralithodes camtschaticus*) pot designs used in comparative fishing trials to determine selectivity. A: the “commercial” design, including 4 circular escape rings of 160 mm diameter on the wall; B: the “panel entrance” design, with the 50 cm wide tarpaulin panels highlighted in blue; C: the “two-chamber” design, with 8 circular escape rings leading to a lower chamber containing an additional bait bag. and D: the non-selective “control” design, identical to the “commercial” design but without the escape rings. All pots were baited with herring (*Clupea harengus*). Pots were fished in strings consisting of alternate test and control pots.

2.1.2. Trial 2 – "escape opening" design with longer soak time

To determine the potential of soak time manipulation to influence selection in the "escape opening" design, we used the same setup and bait as described for Trial 1 but with a soak time of 4 days. A total of seven strings were fished between 9th and 16th September 2021 (Supplementary Material 1).

2.1.3. Trial 3 – "panel entrance" design

Sub-legal sized snow crab can be prevented from entering pots by introducing a "panel" of smooth material around the entrance (Chiasson et al., 1993). The lack of traction on the panel prevents crab from walking directly into the pot, requiring them to gain leverage from elsewhere. As a result, only crab of sufficient size to extend an appendage over the panel can gain access. By manipulating the size of the panel and through knowledge of the relationship between carapace and appendage length, the size of crab entering the pot can be regulated. We determined this relationship for RKC (see Section 2.2 for further detail) and tested various panel widths in preliminary laboratory experiments (results not reported here). Consequently, for the fishing trial, we modified the "escape opening" design to: (i) remove the escape rings; and (ii) cover the terminal end of the entrance funnels with a 50 cm wide tarpaulin panel (Fig. 1B). Removing the escape rings was motivated by anecdotal reports from fishers that claim that undersized RKC may enter pots via escape rings. We wanted to remove this possibility in the "panel entrance" design. We fished 8 strings consisting of 5 "panel entrance" pots (test) and 5 control pots (as described for Trial 1), and a further string consisting of 3 test and 3 control pots, between 29th September and 6th October 2020 (Supplementary Material 1). All strings were soaked for 1 day and were baited as for Trial 1.

2.1.4. Trial 4 – "two-chamber" design

Undersized catches may be reduced if a way can be found to motivate crab to exit before hauling. For this trial, we created a "two-chamber" pot (Fig. 1 C) by modifying the "escape opening" design. For this, we: (i) doubled the number of 160 mm escape rings to eight and moved them from the pot wall to the pot floor; (ii) fitted the pot with a "lower escape chamber" of the same length and width as the "escape opening" pot but with 37 cm height; (iii) hung an additional bait bag in the centre of this lower chamber; (iv) added four additional floats to compensate for the additional weight of the lower chamber; and (v) installed a fine mesh panel (680 ×680 mm, with a 5 mm bar length) on the floor of the "upper chamber" to prevent crabs accessing the lower bait bag by reaching through. In this way, we intended small crab to exit the upper chamber via the escape rings, motivated by the presence of the additional bait in the lower chamber. By placing the escape openings inside the pot rather than on the pot walls, we hoped to prevent undersized crabs from entering the pot through the escape openings. As the floor of the "lower chamber" is open to the seabed, any crab in this chamber would remain on the seabed upon hauling. However, for the field trial, the floor of the lower chamber was fitted with mesh to retain all crabs. We fished 7 strings consisting of 5 two-chamber pots (test) and 5 control pots (as described for Trial 1) and a further 2 strings containing 2 test and 2 control pots between 28th September and 6th October 2020 (Supplementary Material 1). All strings were soaked for 1 day and both bait bags were baited with two defrosted and cut Atlantic herring.

2.2. Behavioural observations

Laboratory studies were conducted at the Aquaculture Station in Kårvika, Tromsø, concurrently with the field trials. We used wild-caught male crabs from Bals Fjord and Porsanger Fjord, Troms, Norway with a mean (± SD) CL of 118.3 mm (± 19) (range: 80–170 mm). CL, carapace width (CW, measured across the widest part of carapace) and the second walking leg length (LL, measured from the carapace join to the tip of the leg) was measured. CL was a statistically significant predictor of LL + CW (ANOVA, $F = 2541$, $df = 134$, $p < 0.001$, n = 136), and the relationship ($R^2 = 0.95$) was described by simple linear regression in the following terms: $CW + LL = (CL \times 39.4) - 237.9$. This relationship was used as the justification for setting the width of the panel in the "panel entrance" design to 50 cm for the laboratory and field trials, to correspond to the morphometrics of crab with the minimum landing size of 130 mm CL.

For behavioural observations, crabs were randomly divided into six groups of 15 individuals each and numbered on their carapace with waterproof varnish. Three groups consisted mostly of crab with a CL < 125 mm (fished in September), while crab in the other groups were mostly > 125 mm (fished in October). Each group were housed in separate compartments (100 ×74 cm) within holding tanks for at least 3 days before any experiments. Holding tanks had a constant flow (15 l/min) of natural sea water at 9.7 °C (± 0.5) pumped from the nearby fjord. Crabs were not fed for at least 1 week before beginning experiments.

2.2.1. "Panel entrance" design

Observations were conducted in a large circular tank (5 m Ø and ca. 1.5 m water depth), with the same water circulation system as the holding tanks but with a water exchange rate of 200 l/min. The tank was continually lit from above by a centrally positioned white LED light (45–80 LUX at the water surface). A pot was placed in the tank, then a group of crab was introduced and left to interact over the next 18 h. Pots were placed alongside the tank wall, as preliminary observations indicated that more entrance attempts occurred here than when the pot was in the tank middle. Bait was one cut Atlantic herring, placed in a bait bag and hung centrally. All groups of crab were exposed to a total of two pot designs, the "panel entrance" design and the control (designs as described for the field trials). Half of the groups were exposed to the "panel entrance" first followed by the control pot, and *vica versa* for the remaining groups. Two GoPro HERO 5 cameras video recorded the pot entrances.

We were interested in determining how the panel influenced the entrance probability of crab of different sizes and their associated behavioural response. Hence, from the collected footage, we used BORIS event logging software (Friard and Gamba, 2016) to quantify: (i) the duration; (ii) the frequency; and (ii) the outcome (i.e. successful or not) of entrance attempts by individuals. An entrance attempt was considered to start when the entire carapace was within the entrance funnel, and end when either: (i) the entire carapace entered the pot (successful entrance attempt); or (ii) the entire carapace was no longer in the funnel (unsuccessful entrance). Upon successful entry, we noted carapace orientation (either: "forward" [corresponding to the sector of the carapace between the two claws], "obliquely" [between claws and first walking legs], "sideways" [between first and third walking legs] or "backwards" [between the third walking legs]) relative to the opening at the terminal end of the funnel. Contrary to intentions, a fold in the tarpaulin on the panel entrance funnel was noticed to provide traction for entering crab. We therefore recorded the frequency of crab using this fold during entrance attempts. As a measure of intra-observer reliability, ten randomly selected entry attempts were re-sampled. A Cohen's kappa coefficient (Cohen, 1960) of 0.68 was achieved ("substantial" agreement, according to Landis and Koch, 1977).

2.2.2. "Two-chamber" design

Observations of crab responding to the two-chamber design were undertaken in a 1.6 × 1.6 × 1.05 m tank, with the same water circulation system as described above but with water exchange at 60 l/min. The tank was lit in the same way as for the "panel entrance" design observations during night-time but followed the outdoor lighting regime during the day as the laboratory facilities had a transparent roof. The pot was baited as for the "panel entrance" design but placed in the lower chamber only. This baiting was different from our field trials but was deemed acceptable because: (i) an additional bait in the upper chamber was not feasible because of the tank water depth (ca. 0.9 m, meaning the top 40 cm of the pot was out of the water); and (ii) we were primarily interested in whether crab could physically locate and use escape openings to enter the lower chamber, rather than attempting to invoke real capture scenario behavioural responses. We used five of the same crab groups as for the "panel entrance" design observations. One group at a time was placed into the upper chamber of the pot and left to interact for 15 – 18 h. A GoPro HERO 4 camera was placed inside the pot and recorded the escape openings. We used behavioural observations to quantify: (i) the number of crab successfully entering the lower chamber; and (ii) the number of crab returning from the lower to the upper chamber.

2.3. Analytical methods

All statistical analysis was conducted in R software (version 4.1.1).

2.3.1. Field trails

Carapace lengths were rounded to nearest 5 mm. Catches in individual pots were relatively low (Supplementary Material 1). Consequently, we summed catches by length class from each pot type (categorical: either "control" or "test") over the whole string. In the case of the "two-chamber" design, we considered just those crabs remaining in the upper chamber. The resulting datasets were modelled as catch comparisons (Holst and Revill, 2009). For this, the proportional retention in the test pot (in comparison to the total catch from both the test and control pot) was calculated for each length class. A proportional retention of 0.5 indicates the probability of retaining a crab of a given length is the same for the test and control. Values < 0.5 and > 0.5 indicate a lower and higher probability of retention of a given length in the test pot, respectively.

We modelled retention probability using a Generalised Additive Mixed Model (GAMM) approach, with binomial error structures and logit link functions. A mixed model approach was deemed appropriate to account for random variance between different pot strings and offered an improvement in model fit compared to models without random effects (as indicated by Akaike information criterion [AIC]). We fit separate random intercept (for each string) and random intercept + slope (carapace length) models. As fixed effects, we considered two separate models; a main and an interactive effect model, with "carapace length" (continuous) and "sex" (categorical: either "male" or "female") as predictor variables. AIC and significance testing were used to select the most parsimonious model between these candidates. Carapace length was fit as a cubic regression b-spline function with the optimal degrees of freedom selected by AIC. Significance of predictor terms was determined through Wald chi-squared testing. Adequacy of model fit was checked using deviance residuals (plotted against predictor variables) with consideration of the dispersion parameter (Wileman et al., 1996).

The data collected from some pots were deemed unreliable. This occurred due to sex/length recording errors or due to the pot opening string not being tied correctly prior to setting. Removing such pots from the datasets effectively resulted in a difference in relative "fishing effort" between test and control pots within the same string. To correct this bias, we included an offset term in models (*c.f.* Xu and Millar, 1993).

To quantify uncertainty around catch comparison models, we first removed any random effects from models and employed the "double bootstrap" method (Millar, 1993). This approach first resamples (with replacement) the same number of pot strings, then resamples (also with replacement) crab from within each resampled string. The most parsimonious model was then re-fit to the resulting dataset. In this way, inter- and intra-string variability is encapsulated in the resulting Efron 95% confidence intervals. 1000 bootstrap replicates were performed. The selfisher R package was used to fit catch comparison models and run bootstrap replicates (Brooks et al., 2020).

2.3.2. Behavioural observations

Generalised linear mixed models (GLMM) were used to determine the importance of crab size (categorical: "sub-legal" [< 130 mm CL] or "legal" [≥ 130 mm CL]), pot design (categorical: "control" or "panel"), carapace orientation (categorical: "forward", "obliquely", "sideways" or "backwards") and the use of the tarpaulin fold (Bernoulli: "fold used" or "fold not used") on the entrance behaviour of RKC. Crab often made multiple entrance attempts. To account for this pseudo-replication and potential heterogeneity between crab groups, all models included either a random intercept term of individual crab nested within crab group, or a random intercept term for crab group alone. Entrance probability / proportions were modelled with binomial error structures (logit link), entrance duration with gaussian errors (identity link) and the number of entrance attempts required before success with Poisson errors (log link). The significance of terms in GLMM's was determined by Wald chi-squared testing. Maximal models (considering all possible interactions) were first fit and then reduced according to significance testing and AIC. GLMM's were fit using the glmmTMB R package (Brooks et al., 2017), and model assumptions checked using the DHARMa package (Hartig and Lohse, 2022). Confidence intervals were constructed from model estimated standard errors.

3. Results

3.1. Field trials

The data from most pots on most strings were deemed reliable and most strings fished with 5 control and 5 test pots (Supplementary Material 1). The amount of crab retained in control pots varied considerably between strings (Supplementary Material 1). Mean total catch (± 95% confidence intervals) for strings that fished with 5 control pots was 341 ± 134, 541 ± 142, 509 ± 76 and 419 ± 196 crab for the "escape opening (1-day soak)", "escape opening (4-day soak)", "panel entrance" and "two-chamber" trials respectively. For test pots, mean catches were lower at 126 ± 40, 83 ± 62, 233 ± 58 and 208 ± 135 respectively. The majority of catches in all trials in both test and control pots were male (Supplementary Material 1).

The mean percentage of catch in individual test pots that were of sub-legal size was 81 ± 3.8%, 54 ± 8.8%, 74 ± 2.2% and 80 ± 35% for the "escape opening (1-day soak)", "escape opening (4-day soak)", "panel entrance" and "two-chamber" trials respectively. In absolute terms, this equates to an average of 24 ± 8, 12 ± 7, 37 ± 5 and 40 ± 11 individuals below landing size per test pot, respectively.

The optimal degree of freedom for the "carapace length" spline function was 5, 4, 4 and 3 for Trials 1–4 respectively. The GAMM results (Table 1) demonstrate that carapace length significantly affected the probability of retention in all trials, either as a main effect or interactively with sex. The effect of sex was, overall, less important but did significantly influence retention in all trials apart from the "escape opening (1-day soak)" experiment (Table 1). Females tended to have marginally lower retention probability for a given size than males, but the confidence intervals for both sexes overlapped in all cases (Fig. 2).

Table 1. Wald chi-squared (χ2 with associated degrees of freedom, df) results to determine the statistical significance of red king crab (*Paralithodes camtschaticus*) carapace length and sex to proportional retention during comparative pot fishing trials. Different pot designs were fished in strings consisting of test and control pots in the Porsanger Fjord, northern Norway, in autumn 2020 and 2021. Associated model fit statistics for the underlying generalised linear mixed models are also presented.

	Main effects models										**Interactive models**			
	X_1 ("Carapace Length")			**X_2 ("Sex")**			**Fit statistics**				**X_1 ("Carapace Length") × X_2 ("Sex")**			**Fit stati**
Trial	**df**	**χ2**	***p***	**df**	**χ2**	***p***	**Deviance**	**df**	**Dispersion parameter**	**AIC**	**df**	**χ2**	***p***	**Devianc**

	Main effects models										Interactive models			
	X_1 (“Carapace Length”)			X_2 (“Sex”)			Fit statistics				X_1 (“Carapace Length”) × X_2 (“Sex”)			Fit stati
Escape opening (1-day soak)	5	39	< 0.001	1	1.09	0.3	336	293	1.03	1069	5	7.71	0.17	329
Escape opening (4-day soak)	4	55.4	< 0.001	1	10.4	0.001	244	217	1.05	675	4	12.7	0.01	232
Panel	4	147	< 0.001	1	20.9	< 0.001	375	311	1.23	1226	4	6.29	0.18	368
Two-chamber	3	15.9	0.001	1	5.4	0.02	379	322	1.02	1183	3	6.99	0.072	372

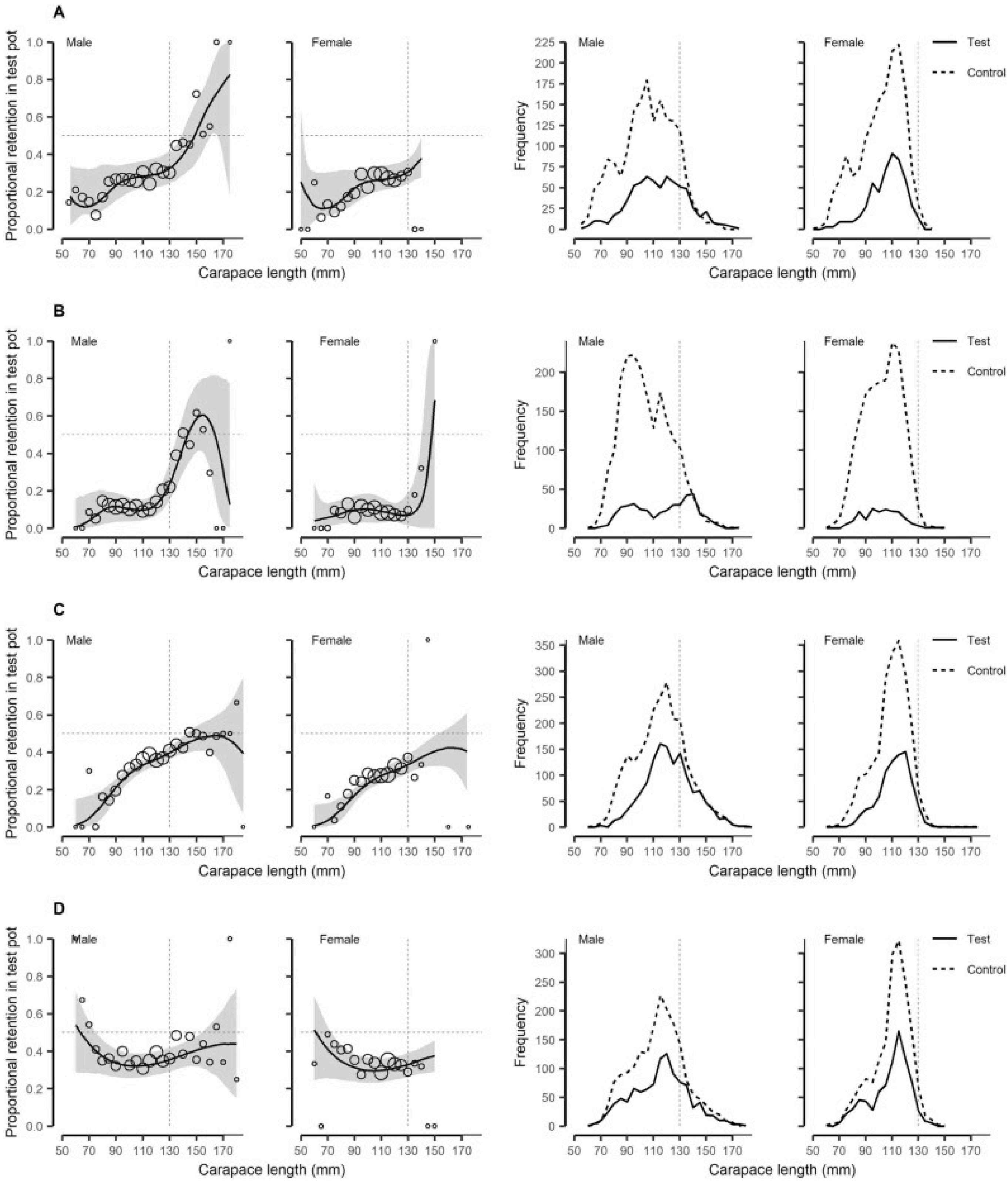

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Fig. 2. Sex dependent proportional retention (left panels) of red king crab (*Paralithodes camtschaticus*) in test pots during comparative fishing trials to determine the selective properties of different pot designs. Pots were fished in strings consisting of test and control

gears in the Porsanger Fjord, northern Norway, in autumn 2020 and 2021. The various trials are displayed in rows: A: “commercial” pot design (1-day soak); B: “commercial” design (4-day soak); C: “panel entrance” design and D: “two-chamber” design. The most parsimonious length dependent curves (black lines) were fit as spines with Efron 95% confidence intervals (grey shaded areas) determined by bootstrapping. Circles represent the underlying datasets and are scaled in diameter to indicate sample size. The horizontal dashed lines at 0.5 indicate equal retention probability between test and control pots. The vertical dashed lines indicate minimum landing size of crab in the Norwegian fishery. Right hand panels display the length frequency distribution of catches from test and control pots.

Based on AIC and significance testing, the main effect models were selected as the most parsimonious for all experiments apart from “escape opening (4-day soak)”, for which the interactive model was a marginally better fit (Table 1). The catch comparison curves from these models are presented in Fig. 2. The curves were a good fit to the data but with increasing variability outside the range of typical crab sizes (~80–140 mm). This was particularly true for female crab, where few individuals above the minimum landing size of 130 mm were encountered. Consequently, drawing inferences beyond this size range is speculative.

This notwithstanding, there was a significant (as evidenced by the confidence intervals not overlapping 0.5 retention probability) length dependent reduction in undersized crab catches in all trials (Fig. 2). However, the strength of the reduction differed between trials. For the “two-chamber” design, retention probability for sub-legal male and female crabs was relatively flat at ~0.4 (Fig. 2d). For the “escape opening (1-day soak)” and “panel entrance” trials, the probability of retention decreased with decreasing crab size. Despite this, the probability of retaining an undersized individual for these designs was still considerable. For instance, the models predicted that a crab of 110 mm would have around a 30 – 40% chance of being retained in these two designs (Fig. 2A and C). The reduction in retention probability for sub-legal sized individuals was notably steeper for the “escape opening (4-day soak)” trial (Fig. 2b), resulting in a much lower probability of retaining undersized crab. For example, for the “escape opening (1-day soak)” and “panel entrance” trials, the confidence bounds encompassed 0.2 retention probability at ~80 mm carapace length for male crab. For the “escape opening (4-day soak)” trial, this point was only reached at ~120 mm (Fig. 2b).

With regards to catches of legal sized crab, all trials exhibited some reduction in catches relative to control pots (because the confidence intervals did not entirely overlap 0.5 retention probability above 130 mm). Where there is sufficient data, the curves indicate that test pots fished equally to controls for individuals above ~135 – 140 mm in all experiments apart from the "two chamber" one. For this, a reduction in catches up to ~155 mm was observed (Fig. 2).

3.2. Behavioural observations

3.2.1. "Panel entrance" design

Crab making entrance attempts were rare during the behavioural observations (Table 2); on average (± SD) 0.43 ± 0.37 and 0.96 ± 0.99 entrance attempts occurred per hour for the "control" and "panel entrance" designs respectively.

Table 2. The number of successful and unsuccessful entrance attempts made by red king crab (*Paralithodes camtschaticus*) of different sizes into two different pot designs. Observations were undertaken in laboratory tanks with replicate groups of crab consisting of 15 individuals. Sub-legal and legal size refers to the minimum landing size of carapace length (CL) of 130 mm in the Norwegian fishery.

		Sub-legal (CL < 130 mm)		Legal (CL ≥ 130 mm)	
Pot design	**Crab group**	**Unsuccessful entrance attempts**	**Successful entrance attempts**	**Unsuccessful entrance attempts**	**Successful entrance attempts**
Control	G1	3	11	2	1
	G2	1	8	0	1
	G3	1	7	0	1
	G4	1	1	2	9
	G5	0	2	13	10
	G6	6	7	3	5
Panelentrance	G1	44	2	1	2
	G2	49	1	0	1
	G3	33	4	7	1
	G4	2	0	20	4
	G5	1	1	9	5

Pot design	Crab group	Sub-legal (CL < 130 mm) Unsuccessful entrance attempts	Sub-legal (CL < 130 mm) Successful entrance attempts	Legal (CL ≥ 130 mm) Unsuccessful entrance attempts	Legal (CL ≥ 130 mm) Successful entrance attempts
	G6	3	6	10	1

The probability that a crab would enter a pot was determined by its size and the pot design (pot × size interaction term: $\chi^2 = 8.04$, df = 1, $p < 0.01$). Crab were significantly less likely to enter the "panel entrance" design; for each legal and sub-legal crab that entered the panel pot, 2.7 and 7.8 crab respectively entered the "control" design (Fig. 3A). The probability of entrance into the "panel entrance" design for crab of legal size was 2.3 times higher than for sub-legal crab (Fig. 3A).

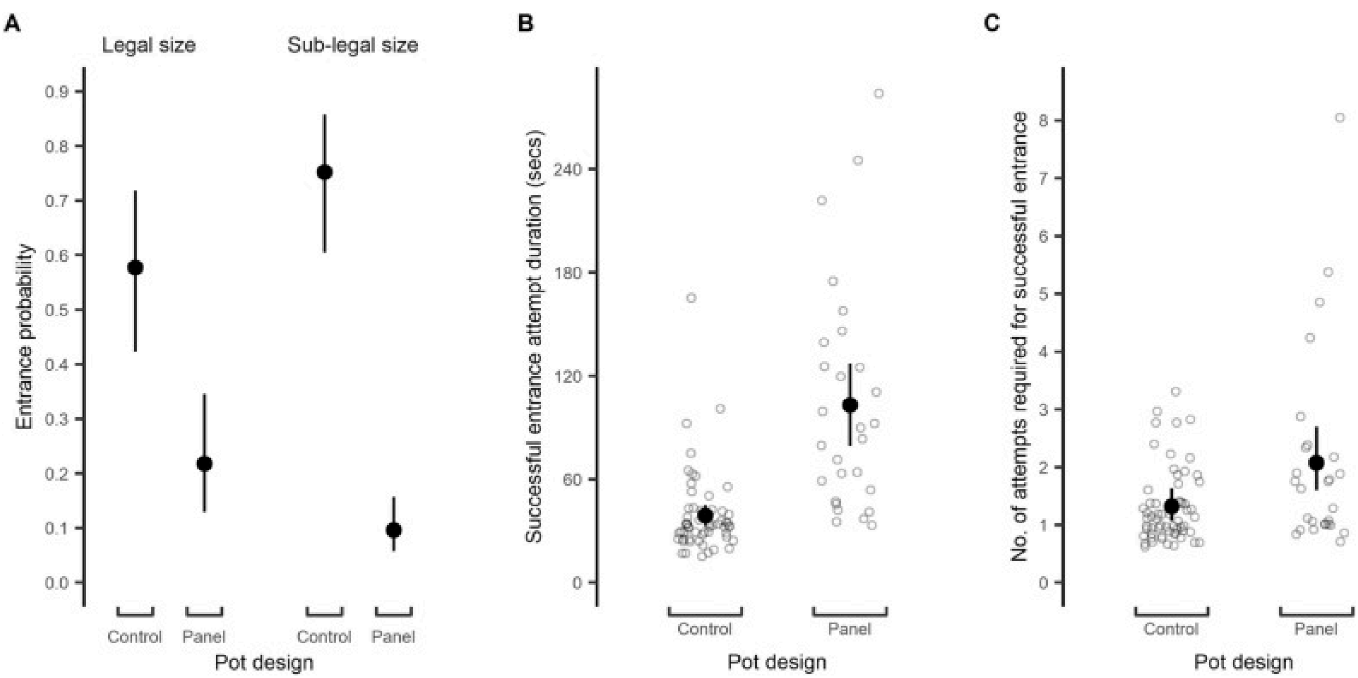

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Fig. 3. Entrance behaviour of individual red king crab (*Paralithodes camtschaticus*) into two different pot designs: A: entrance probability for legal (carapace length ≥ 130 mm) and sub-legal (< 130 mm) sized crab; B: the duration of successful entrance attempts; and C: the number of attempts required for successful entrance. Observations were undertaken in laboratory tanks with six replicate groups of crab consisting of 15 individuals. The "panel" design included 50 cm wide tarpaulin panels in the entrance funnels, intended to regulate the size of crab able to enter. The "control" pot was identical but did not include panels.

Black points represent generalised linear mixed model derived mean estimates, with whiskers indicating 95% confidence intervals.

On average, crab required ~3 times longer (Figs. 3B) and 1.5 times more attempts (Fig. 3C) to successfully enter the "panel entrance" design compared to the control. These differences between designs were statistically significant (duration: $\chi^2 = 6.64$, df = 1, $p = 0.01$; attempts: $\chi^2 = 20$, df = 1, $p < 0.001$). There was no evidence that the number of attempts or their duration differed between crab of different sizes ($p > 0.05$ in both cases).

No crab oriented themselves backwards when they entered pots; consequently, this level was excluded from modelling procedures. Otherwise, successful entrance depended on the orientation of crab in the funnel (pot × orientation interaction term: $\chi^2 = 9.10$, df = 2, $p = 0.01$). The proportion of crab entering the control pot was similar between the observed orientations (Fig. 4). However, for the "panel entrance" design, a significant majority of successful entrances (~75%) occurred for crab whose carapace was sideways orientated (Fig. 4). The orientation of crab of different sizes was not statistically different (size term: $\chi^2 = 0.09$, df = 1, $p = 0.771$).

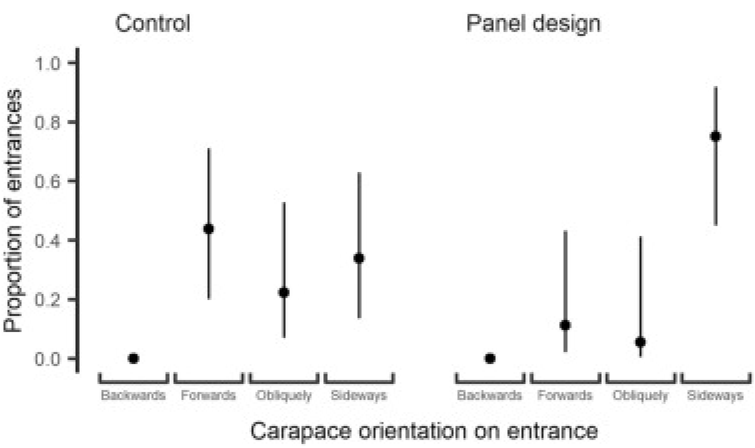

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Fig. 4. The carapace orientation of red king crab (*Paralithodes camtschaticus*) during successful entrances into two different pot designs. Observations were undertaken in laboratory tanks with six replicate groups of crab consisting of 15 individuals. Orientation was judged relative to the pot entrance funnel as either: "forward" (the sector of the carapace between the two claws), "obliquely" (between claws and first walking legs), "sideways" (between first and third walking legs) or "backwards" (between the third walking legs). The "panel" design included 50 cm wide tarpaulin panels in the entrance funnels, intended to regulate the size of crab able to enter. The "control" design was identical but did not include panels. Black points represent generalised linear mixed model

derived mean estimates, with whiskers indicating 95% confidence intervals. Due to no entrances occurring in backwards orientation, this level was excluded from modelling procedures.

For both sub-legal and legal crab, use of the (unintentional) fold in the tarpaulin in funnel of the "panel entrance" design significantly influenced their probability of entering (size term: $\chi^2 = 5.83$, df = 1, $p < 0.05$; use of fold term: $\chi^2 = 24.55$, df = 1, $p < 0.001$). When the fold was used, entrance probability increased by 5.2 and 23.5 times for sub-legal and legal sized crab respectively (Fig. 5).

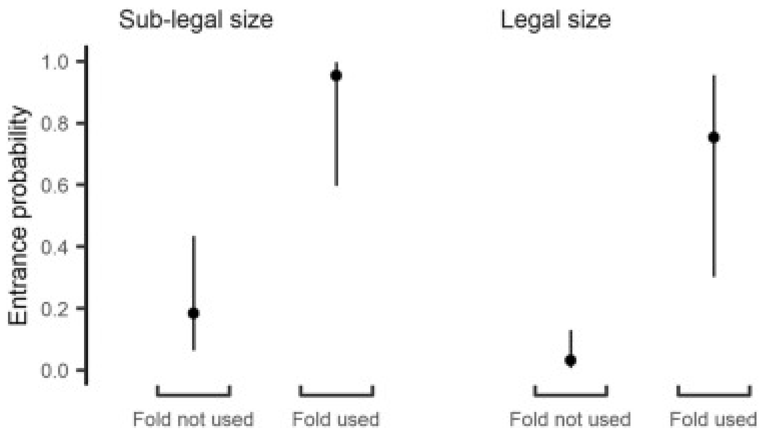

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Fig. 5. The effect of using an area of traction (a "fold") on the entrance probability of legal (carapace length ≥ 130 mm) and sub-legal (< 130 mm) sized red king crab (*Paralithodes camtschaticus*) for into a new pot design. Observations were undertaken in laboratory tanks with six replicate groups of crab consisting of 15 individuals. The pot design ("panel entrance") included 50 cm wide tarpaulin panels in the entrance funnels, intended to regulate the size of crab able to enter. Contrary to intentions, the panels contained a fold in the tarpaulin that provided an area of traction for crab attempting to enter. Black points represent generalised linear mixed model derived mean estimates, with whiskers indicating 95% confidence intervals.

3.2.2. "Two-chamber" design

Sub-legal sized crab placed in the upper chamber were adept at entering the lower chamber. 85 ± 11% (mean ± 95% CI) sub-legal sized crab ultimately entered the lower chamber. No legal sized crab entered the lower chamber, and no crab were observed to re-enter the upper chamber after descending.

4. Discussion

The results of the field trials support reports from fishers and the literature (Siikavuopio et al., 2018) that the pot design currently used during commercial RKC fishing in Norway retains considerable amounts of undersized crab if fished for one day. This was because although the presence of escape rings significantly reduced the relative retention probability, the absolute numbers of sub-legal crab retained was still high. In Alaska, sub-legal sized RKC were found to remain in pots over 2 days despite having the opportunity to escape (Zhou and Kruse, 2000). RKC have been observed to enter pots through escape rings (Siikavuopio et al., 2018) and rings can become unavailable for extended periods of time as others attempt to leave (Jørgensen et al., 2017). Fishers anecdotally report that sub-legal RKC may use escape openings as entrances. Such effects may have contributed to the high numbers of undersized crab we observed in the commercial pot with escape openings soaked for one day. However, the reaction of RKC to baited pots is primarily a chemically mediated, food search response (Zhou and Shirley, 1997, Stiansen et al., 2010). As such, if bait is present within the pot, the motivation for captured crab to attempt to exit would likely be low. As the bait is washed out or consumed, it loses its attractive potential (Løkkeborg, 1990). We therefore hypothesise that the attractive potential of the bait was not exhausted during the one-day soak time trial, and that this primarily accounts for the relatively large proportion of sub-legal sized crab we observed. This supposition is supported by the findings of the 4-day soak trial, for which the catch of undersized crab was significantly reduced. In this scenario, the attractive potential of the bait is exhausted and the motivation to exit the pot is increased. Longer soak times also give crab more time to find and successfully use the escape openings. These finding are similar to results obtained during selective pot fishing for both RKC (Pengilly and Tracy, 1998) and other crab species (Rumble et al., 2008, Winger and Walsh, 2011, Olsen et al., 2019) in that longer soak times can result in better size selection or a lower ratio of sub-legal individuals. They are also consistent with observations that RKC readily exit pots without bait (High and Worlund, 1979, Marshall and Mundy, 1985).

One day is the typical soak time currently used by fishers. The rate at which bait attractiveness is lost is a function of the type and amount used, the type of holder used to contain the bait, the local water current and temperature conditions and how rapidly it is consumed by crab or other scavengers (Løkkeborg, 1990, Løkkeborg et al., 2014). These factors are not standardised throughout the fishery. Consequently, it is difficult to prescribe an exact soak time that would guarantee optimal selection, and our finding of improved selection with a four-day soak time should be considered as a demonstration of the importance of bait exhaustion rather than a recommendation as to the optimal soak time.

As RKC are cannibalistic (Borisov et al., 2007), extended soak times may negatively impact animal welfare and the economic value of catches. There is therefore a theoretical upper limit of how long pots should be soaked for. Current legalisation requires pots to be hauled at least once per week (Lovdata, 2022).

The “two-chamber” design did not substantially reduce the catch of under-sized crab relative to the currently used design with escape openings. The results also demonstrate a considerable reduction in legal sized catches. In the laboratory studies, the majority of undersized crab entered the lower escape chamber, while all legal sized individuals were prevented from doing so. This suggests that problems related to the escape rings dimensions were not to blame for the poor selectivity of this design in the field trial. Rather, we hypothesize that the presence of the bait bag in the upper chamber meant that crab lacked sufficient motivation to assess the bait bag in the lower chamber. The reduction in catches relative to the control pot (including commercial sizes) can be perhaps explained by the additional lower chamber raising the pot entrances further from the seabed. As result, crab had to climb further from the seabed to assess the entrances. Furthermore, the climb may have required crab to exit the odour plume produced by the lower bait before encountering the odour plume of the upper bait or the pot entrances. Pot designs which require such behaviour have been demonstrated to have lower capture efficiency, as the search strategy for chemically stimulated RKC is primarily restricted to the odour plume (Zhou and Shirley, 1997, Stiansen et al., 2010). Combined with our experience that the two-chamber pot was considerably more difficult to handle onboard, this design is not a viable option for the fishery.

The laboratory behavioural observations of the “panel entrance” pot help to explain the findings of the field trial. In the laboratory, crab required more effort (in terms of entrance attempt duration and frequency) and a particular orientation to enter the “panel entrance” design compared to the control. Legal sized crab were more than twice as likely as sub-legal crab to be successful in entering the “panel entrance”. Considering that the “panel entrance” design did not include escape rings, these observations help to explain the reduced sub-legal sized catches in the field trial; that is, the panel functioned as intended and prevented some crab from entering. Despite this, catches of under-sized crab still occurred in the “panel entrance” trial and the design likely does not offer improved selection compared to the currently used commercial design with escape openings. The laboratory observation of entrance probability being significantly increased when crab used the unintentional tarpaulin fold suggests an explanation for this. Over the course of the field trials, the seams of the panel entrances became increasingly damaged as they were hauled, emptied and re-set. This gave many potential traction areas which crab could utilise to gain entrance. Future development should therefore focus on creating the entrance panel from a more robust material and/or a design that better accounts the behavioural abilities we observed in the laboratory. Our behavioural studies showed that RKC can exhibit flexible behaviour in that: (i) entrance behaviour shifted to sideways orientation for the panel design so that their reach could extend across the tarpaulin; and (ii) they were able to take advantage of available traction (the unintentional fold in the panel) as an aid to entering. It may also be fruitful to combine the panel entrance with escape holes to help reduce the catch of any undersized individuals that do manage to enter. However, fishers anecdotally report that sub-legal sized crab enter pots through escape openings. If so, adding openings to the panel design would only be successful if entrance rates through the escape openings were lower than exit rates.

A lack of large individuals (particularly for females, who achieve smaller maximum sizes than males Nilssen and Sundet, [, 2006]), limited the confidence in the fitted retention curves for these sizes. This is likely due to our trials taking place after the main RKC fishing season, meaning that larger individuals may have been removed from the grounds during commercial fishing. Conducting future trials in areas with larger crab would help to overcome this. Furthermore, it is questionable how reflective the observations we made in the laboratory match the behaviour of RKC in the field. For instance, the circular laboratory tanks likely caused the bait plume to become highly dispersed, whereas at sea it would be more directional because of the current. Consequently, in the wild, RKC typically approach pots from downstream (Zhou and Shirley, 1997, Stiansen et al., 2010). RKC are gregarious and respond to stimuli from conspecifics (Tolstoganova, 2002). Due to logistical constraints, our laboratory observations used relatively small groups of crab and only males. It may have been that capture dynamics are changed when larger number of individuals interact with the pot at the same time, or where different social and/or sexual hierarchies are present (Lord et al., 2021). Physical assistance and/or hinderance from other individuals may also change entrance and exit rates when large numbers of RKC are present. We therefore suggest that future research in this area employ behavioural observations in the field.

Although sex was important in determining the overall shape of the retention curves in most trials, the curves for male and female were generally similar and the confidence intervals overlapped. The findings of previous studies on the importance of sex to retention for RKC pot catches are inconsistent. For catches in Norway, females have been found to escape less readily than males (Salthaug and Furevik, 2004, Stiansen et al., 2008). In Alaskan laboratory trials, an apparent lower escape rate for males was explained by individuals in that group moulting; otherwise there were no differences in escape behaviour between the sexes (Zhou and Shirley, 1997). We were unable to investigate the effect of sex during our laboratory behavioural observations due to a lack of female crab availability. However, quotas for RKC in Norway are sex based and the permitted catch for females is relatively small (Lovdata, 2022). We therefore suggest that future behavioural observations of RKC during capture investigate possible behavioural differences between the sexes, as such differences could form the basis of sex-based selection devices in future pot designs (Fernö, 1993).

4.1. Conclusion

Relative to the currently used commercial design with escape openings, we conclude that the alternative designs we tested were not as successful at optimising RKC pot catches. This is because they either offered no substantive improvement in selectivity (the "panel entrance" design), or had a higher probability of retaining undersized catches and reducing catches of legal crab (the "two-chamber" design). The use of behaviour observations in the laboratory explained the relatively poor performance of the "panel entrance" design in the field trials, in that areas of traction on the panel are readily used by sub-legal sized crab to gain entry. Laboratory observations also indicated how the selectivity of "panel entrance" functions, in that this design requires increased effort (in terms of attempts and time) and particular behaviour (in terms of carapace orientation) for crab to enter. Undersized RKC catches were reduced the most by soaking the "escape opening" design for four days, with no appreciable effect on legal sized catches. We hypothesise that this occurs primarily because of bait exhaustion, as well as the longer soak giving more time for undersized crab to locate and use the escape openings.

If bait exhaustion does improve selection, then there are two, non-mutually exclusive, possible solutions to reducing sub-legal RKC catches. The first would be to reduce the amount of bait used so that it is exhausted more rapidly. Using less bait would reduce operating costs for fishers. However, successful management based on bait amount would require a standardisation of the type of bait, and anecdotal reports from fishers indicate that a variety are currently in use. Alterations to the amount or type of bait may alter also crab capture efficiency. As such, effective legislation based on this recommendation may be difficult to achieve. A second solution would be to require pots to be soaked long enough so that the bait is exhausted. In our trials, we tested a 4-day soak time but it may be that bait is well exhausted before this point. The time required for typical RKC pot baits to exhaust should therefore be subject to further study. Introducing a mandatory minimum soak time beyond the currently typical 1-day would imply a longer crab fishing season, as there are restrictions on the maximum number of pots allowed per vessel. Additional knowledge regarding the acceptability of this with commercial fishers is therefore also required before the results presented in this study can be practically implemented.

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CRediT authorship contribution statement

Contributions listed according to CRediT guidelines. **Neil Anders**: Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Kenneth Arnesen**: Investigation, Data curation, Writing – original draft, Writing – review & editing. **Anette Hustad**: Methodology, Investigation, Writing – review & editing. **Terje Jørgensen**: Conceptualization, Methodology, Investigation, Supervision, Funding acquisition. **Svein Løkkeborg**: Conceptualization, Resources, Writing – review & editing. **Sten Siikavuopio**: Conceptualization, Writing – review & editing. **Tina Thesslund**: Methodology, Investigation, Writing – review & editing. **Anne Christine Utne-Palm**: Conceptualization, Methodology, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Anne Christine Utne Palm reports financial support was provided by Norwegian Seafood Research Fund.

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Appendix A. Supplementary material

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Supplementary material

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Recommended articles

Data availability

Data will be made available on request.

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In different trap fisheries worldwide, escape openings are often used to improve size and species selectivity by reducing bycatch. The selectivity efficiency of escape openings depends on their shape and size designed according to the target species morphology. However, the efficiency also depends on the number of trapped animals contacting such escape openings. In pot fisheries, the escape process of bycatch individuals is often dependent on how long the gear is deployed (soak time). In this study, we conducted experimental fishing trials to evaluate size selectivity and catch patterns of pots configured with two types of escape openings among three different soak times (2, 5, 7 days) in the swimming crab (*Portunus trituberculatus*) fishery of the Yellow Sea, China. Increasing soak time significantly decreased the retention probability of undersized crabs. Longer soak times enhanced crab contact probability with escape openings, with over 90% achieving selectivity contact after 7 days soak time. Additionally, use of escape openings reduced capture of bycatch species and significantly affected catch composition. There were no significant differences in size selectivity between circular and rectangular escape openings. These findings contribute to understand the importance of soak time on the size selection processes of *P. trituberculatus* pots. Further, they provide insights for the development of more sustainable fishing practices.