Regional Studies in Marine Science 52 (2022) 102237

Contents lists available at ScienceDirect

Regional Studies in Marine Science

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

Understanding and predicting the effect of entrance cone diameters on the catch efficiency of snow crabs (*Chionoecetes opilio*) in conical pots

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ARTICLE INFO

Article history:
Received 29 November 2021
Received in revised form 7 January 2022
Accepted 7 February 2022
Available online 11 February 2022

Keywords:
Snow crab
Pot entrance
Morphology
Catch efficiency
Pot fishery

ABSTRACT

Conical pots with a plastic entrance cone on the top are a type of fishing gear used to harvest snow crabs (*Chionoecetes opilio*) in Arctic regions. In this study, we assessed the effect of pot entrance diameter on the catch efficiency of snow crabs. We used catch data collected during sea trials of pots with different entrance cone diameters, and we conducted laboratory experiments where morphological characteristics of snow crabs were investigated to estimate the extent of the different body parts of the animal that are decisive for the catch efficiency of the pot entrance. The results show that body parts larger than the carapace affected pot entrance efficiency. We predicted that entrance diameter is a key factor determining catch efficiency and that the experimental pots used in this study would experience significant reductions in the catch of marketable size crab, compared to pots currently used in the fishery.

1. Introduction

The snow crab (*Chionoecetes opilio*) is a cold-water species inhabiting Arctic regions of the ocean. Commercial fishing for this species is conducted on fishing grounds in Norway, Canada, the USA, and Russia (Alsvåg et al., 2009). In snow crab fisheries, crabs are harvested using pots. In the Barents Sea and in Newfoundland and Labrador in Canada, conical pots are most commonly used in the snow crab fisheries (Winger and Walsh, 2007; Olsen et al., 2019a). This type of pot is light, stackable, and effectively uses available deck space on the fishing vessel, which makes it convenient, especially when pots need to be transported over large distances to the fishing grounds. The pots consist of a metal frame covered with a diamond mesh netting with mesh sizes of 120 to 140 mm, and they target snow crabs of minimum target size (MTS) of 95 mm carapace width (CW) (Norwegian Directorate of Fisheries, 2020a; Fisheries and Oceans Canada, 2021).

The commercial fishery for snow crabs in the Barents Sea is relatively new (Huse and Bakketeig, 2018). It takes place far off the coast at depths of 200–300 m. Therefore, the fleet consists of large factory vessels that process the crabs onboard. During the period between 2012 and 2016, the fishery developed rapidly, with Norwegian landings increasing from 2.5 to 5406 tonnes (Norwegian Directorate of Fisheries, 2020a). However, issues such as low capture efficiency (e.g., 2.5 kg of snow crabs per pot Olsen et al., 2019a) and the closure of the snow crab-dense Russian part of the Barents Sea to international fishing vessels have reduced the landings substantially in recent years (Norwegian Directorate of Fisheries, 2020b). This reduction in the landings and evidence suggesting that the resource is spreading westwards in the Barents Sea to areas that are again accessible to fishermen (Prozorkevich et al., 2018; Hjelset et al., 2019) have prompted the exploration of new methods to improve the catch efficiency of conical pots. The focus on catch efficiency has become even more important because new regulations limit the number of pots used by each vessel to 9000 units (Norwegian Directorate of Fisheries, 2020b).

Several earlier experiments have investigated the effect of snow crab pot design. For example, Vienneau et al. (1993) investigated the importance of the number of entrances while Hébert et al. (2001) investigated the effect of plastic barriers in the pot design. The greatest potential for increasing the catch efficiency of crab pots is to ease entrance and increase entry probability (Miller, 1990; Li et al., 2006). Thus, the entrance size and design are elements critical to the catch efficiency of conical pots. To

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https://doi.org/10.1016/j.rsma.2022.102237
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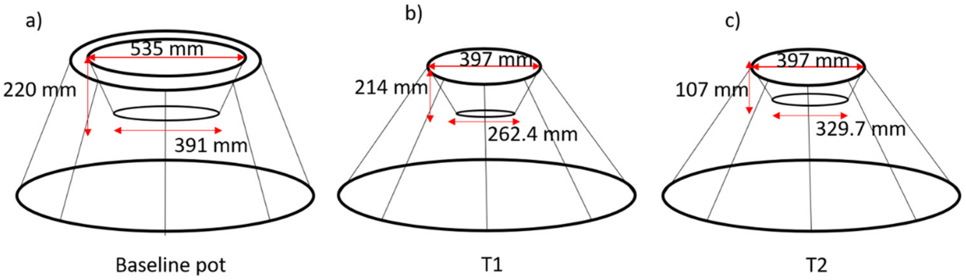

Fig. 1. Schematic drawing (not in scale) specifying entrance cone dimensions of the baseline (a) and test pots T1 (b) and T2 (c).

enter the pot, each crab must climb to the top entrance and pass through the plastic entrance cone, which is placed there to prevent crabs from escaping and reduce the risk of loss of the catch during pot retrieval (Miller, 1980). An optimal entrance cone design should allow efficient entrance of snow crabs with CW > 95 mm (i.e., over MTS), particularly the largest and more valuable individuals, while reducing the risk of catch loss during retrieval. However, the optimal diameter of this entrance cone is unknown. Furthermore, the size of the entrance can affect the pot design, including the height and the steepness of the pot inclination angle. A steeper angle might negatively affect catch efficiency because it would require additional effort to climb the pot (Olsen et al., 2019a). Additionally, it is unknown whether the carapace is the only part of the snow crab body that limits its passage through the entrance cone or if other body parts, such as the walking legs and claws, should also be considered when evaluating the catch efficiency of conical pots. This knowledge is critical for optimizing the design of snow crab pots, ensuring high catch efficiency of the largest and most valuable snow crabs, and minimizing loss of snow crabs above MTS.

In this study, we compared the catch efficiency of standard conical pots as used in the Barents Sea and Eastern Canadian waters with that of pots with a reduced entrance cone diameter. We also investigated whether body parts other than the carapace can explain the entry probability of snow crabs in conical pots when different entrance cone diameters are considered. Specifically, the goal of this study was to answer the following research questions:

- How does reducing the diameter of the entrance cone in conical pots affect the size-dependent catch probability of snow crabs?
- Which of the snow crab body parts explain the size-dependent catch probabilities observed for the different types of pots tested?

2. Materials and methods

2.1. Assessing the effect of entrance diameter on catch efficiency

2.1.1. Pot designs and data collection

The sea trials for the pot entrance experiments were conducted on board the commercial fishing vessel “Northeastern” (55.2 m length overall and 2250 HP) between 1 and 24 May, 2020, in the central Barents Sea (N75°34.19 E33°43.27 and N75°34.19 E33°43.27) at depths that varied between 250 and 280 m. The vessel operates 9000 pots and has the capacity of deploying and retrieving 2000 pots per day.

During the sea trials, we used the standard commercial conical pots employed by the commercial fishing fleet as the baseline, against which we tested two modified conical pot designs. The standard pots have a bottom ring diameter of 1300 mm, a top diameter ring of 700 mm, and a height of 600 mm, and the inclination angle on the side of the pots is approximately 63 degrees (Fig. 1a). The plastic entrance cone has a top diameter of 535 mm, a bottom diameter of 391 mm, and a height of 220 mm. The pot frame (including the upper ring) and the lower ring are made of 12 mm and 14 mm steel bars, respectively, and the total weight of each pot is approximately 12.5 kg. These pots are covered with a diamond mesh netting built of Ø4 mm single braided polyethylene twine with 140 mm mesh size.

We used two modified pot designs, hereafter called test 1 (T1) and test 2 (T2), which had a reduced entrance cone diameter. These pots had a bottom ring diameter of 1470 mm, a top diameter ring of 400 mm, and a height of 470 mm, and the inclination angle was reduced to 40.6 degrees. The top diameter of the entrance cone for both test pots was 397 mm. The entrance cone height of T1 was 214 mm, resulting in a lower cone diameter of 262 mm (Fig. 1b). The entrance cone height for T2 was 107 mm, resulting in a larger cone diameter of 329 mm compared to T1 (Fig. 1c). The netting of the test pots was identical to that used in the standard commercial pots.

The pots were deployed in fleets with pots attached to the main line every 30 m with a quick link system. Experiments with T1 and T2 pots were carried out separately by deploying them in separate fleets with 174 and 103 pots, respectively. Each fleet alternated between a test pot (either T1 or T2 pot) followed by one baseline pot. All pots were baited with approximately 800 g of squid (*Illex* spp.). Half of the bait was placed in a bait container and the other half in a bait bag, which were mounted under the entrance of the pot. The soak time in both experiments was 11 days.

When the pots were hauled on board, the CW (the largest distance across the carapace of the snow crab, including spines) of all snow crabs in each pot was measured to the nearest millimetre below using a calliper according to Jadamec et al. (1999).

2.1.2. Estimation of the effect of pot entrance diameter on the snow crab catch efficiency

To quantify the effect of decreasing the diameter of the pot entrance cone on catch efficiency, we evaluated the relative size-dependent catch efficiency (often referred to as catch ratio) between the test pots and the baseline pots (Herrmann et al., 2017; Olsen et al., 2019a; Grimaldo et al., 2020). We used the catch information (numbers and CW sizes of snow crabs caught in each pot) to determine whether there was a significant difference in the catch efficiency between test (either T1 or T2) and baseline pots.

The relative size-dependent catch efficiency between test and baseline pots was independently estimated for each of the two experiments. To assess the relative size-dependent catch efficiency, we used unpaired catch comparison ($CC(w, v)$) and catch ratio ($CR(w, v)$) analyses (Herrmann et al., 2017). The size-integrated average catch ratio value for snow crabs under ($CR_{average-}$) and above ($CR_{average+}$) MTS was estimated directly from the catch data. Two catch pattern indicators quantifying the ratio of snow crabs below and above the MTS captured in test

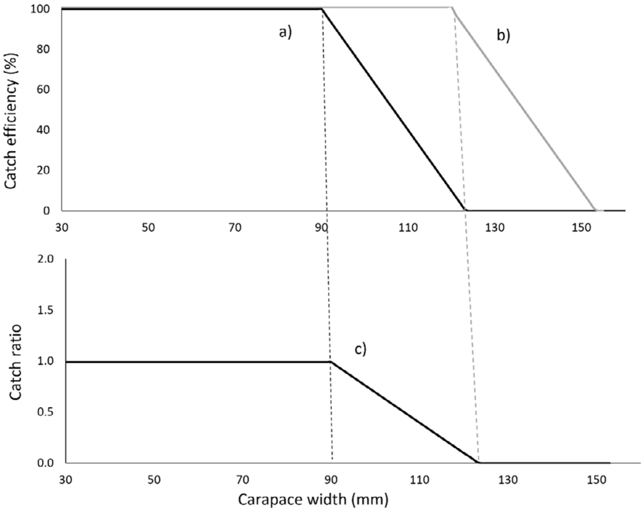

Fig. 2. Hypothetical illustration of catch efficiency. The upper plot shows the catch efficiency of test (a. black line) and baseline (b. grey line) pots and the lower plot displays the corresponding catch ratio (c) for the hypothetical size-dependent catch efficiency.

($Discard\ Ratio_{Test}$) and baseline ($Discard\ Ratio_{Baseline}$) pots were estimated to quantify the ratio between undersized and target sized snow crabs captured. Finally, the size frequency distribution and cumulative size frequency (CDn_w) distribution were estimated to compare the catch patterns between test and baseline pots.

We used the statistical software SELNET to conduct size-dependent catch comparison and catch ratio analyses (Herrmann et al., 2012). Details about the estimation of $CC(w, v)$, $CR(w, v)$, $CR_{average}$, $DiscardRatio$, and CDn_w are provided in the supplementary material (S1).

2.2. Snow crab morphology in relation to catch efficiency

We conducted laboratory experiments to investigate whether the morphology of snow crabs could explain the size-dependent catch ratios observed for the pots differing in entrance cone diameter. We assume that the estimated size dependent catch efficiency for the smaller sized snow crabs (snow crab <91 mm) is not affected by the particular entrance cone diameter in the test and baseline pots. Therefore, the catch efficiency for the smallest size snow crabs in the test pots (Fig. 2a) and baseline pots (Fig. 2b) should display a similar pattern. If the entrance diameter for both test and control pots is large enough not to reduce entrance efficiency, then the catch ratio (test/baseline) should be at least 1.0, as the reduced steepness of the test pots would provide an entrance opportunity that is at least as good as that for the steeper baseline pot (Fig. 2c). The catch ratio is estimated as the ratio between the efficiency in the test pots and the baseline pots. However, with increasing crab size the entrance diameter might begin to reduce entrance efficiency. Because the test pots have a smaller entrance diameter than the baseline pots, the test pots could affect the entrance efficiency at a smaller crab size than the baseline pots. Consequently, this would cause the catch ratio (test/baseline) to decrease with increasing crab size. The reduction in catch efficiency could depend on the size of the entrance diameter. When the entrance diameter is too small for a given snow crab size, the efficiency could reach 0 (Fig. 2a, b), meaning that the entry diameter is too small for a particular size of snow crab to pass through. Fig. 2 presents a hypothetical case in which the test pots could start to lose catch efficiency for snow crabs with CW > 90 mm (Fig. 2a), whereas the baseline pots could theoretically start to lose catch efficiency for a larger size snow crabs (CW > 120 mm) due to their larger entrance diameter.

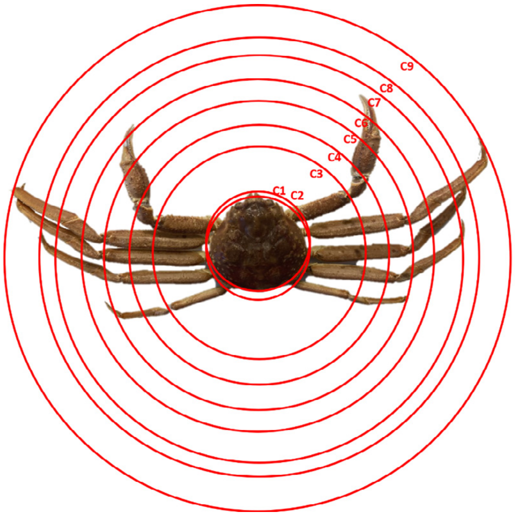

Fig. 3. Morphology measurements of the snow crabs (C1 to C9) that were considered with respect to entrance cone diameters.

The purpose of the morphology experiments was to estimate the point at which the test pots start to lose catch efficiency and ultimately exclude snow crabs from entering the pots. This estimation was conducted by applying the following steps as detailed below:

2.2.1. Step 1: Collection of snow crab samples

The snow crabs for the laboratory experiments were collected during a research cruise conducted between 29 July and 8 August, 2019, on board the research vessel “Lance” (LOA 60.7 m, GT 1380) in the central Barents Sea (from N76°10.06 to N76°40.70 and from E32°20.58 to E37°55.865) using conical pots with standard entrance cone diameters (Herrmann et al., 2021). Snow crabs were selected to cover as wide a size interval as possible to be able to make predictions about catch efficiency of a wide size range. Before image analysis was conducted, the CW of each snow crab was measured to the nearest millimetre below using a calliper.

2.2.2. Step 2: Measurement of different snow crab body parts

We selected the following snow crab body measurements (Jadamec et al., 1999) to determine the entrance cone diameter that would be necessary for entry when considering that particular body part for each size of the snow crab (Fig. 3). Diameters were given as twice the distance from the centre of the snow crab carapace to the specific body part.

1. Carapace length (CL) (to the rostral horn) (C1);
2. Carapace width (CW) (C2);
3. Cheliped (pereiopod 1) (C3);
4. Carpus of cheliped (pereiopod 1) (C4);
5. Dactyl of 4th walking leg (pereiopod 5) (C5);
6. End of merus of 1st walking leg (pereiopod 2) (C6);
7. End of carpus of 1st walking leg (pereiopod 2) (C7);
8. Dactyl of 2nd walking leg (pereiopod 3) (C8);
9. Dactyl of 1st walking leg (pereiopod 2) (C9).

We obtained the measurements by using images of each snow crab ($n = 59$) combined with circles corresponding to the measurements C1 to C9 (Fig. 2). The diameter of each circle for each snow crab was measured using ImageJ software (Schneider et al., 2012).

Table 1
Details from the two deployed fleets: T1 and T2 showing start position of the lines, depth, number of test and baseline pots, number of retained snow crabs, and pot soak time.

	T1	T2
Start position of deployment	N75°34.19 E33°43.27	N75°34.19 E33°43.27
Depth (m)	220	220
Number of test pots (tq)	88	55
Number of baseline pots (bq)	86	48
Crabs in test pots (nt)	314	587
Crabs in baseline pots (nb)	250	472
Pot soak time (days)	11	11

2.2.3. Step 3: Estimation of optimal pot entrance diameters considering various body parts for a range of snow crab sizes

The effect of the snow crab size and body parts (C1 to C9) on the pot entrance diameter derived from the laboratory measurements was investigated applying the linear model function (lm) in the statistical package R (version 4.0.5.;www.r-project.org) We combined these results with the diameter sizes of the entrance cones used during the experimental trials (T1 and T2; both top and bottom diameters) to estimate the CW for each morphology measurement that would correspond to the point where the snow crab catch efficiency starts to be limited.

2.2.4. Step 4: Examination of whether the predictive model can explain catch efficiency results obtained at sea

We examined whether the results from the linear regression analysis of snow crab morphology measurements would be able to explain the catch ratio results obtained during the sea trials. This was based on the hypothesis that snow crab pots with a reduced entrance diameter would start to limit the catch efficiency for the largest sizes of snow crabs by decreasing catch efficiency with increasing crab size. Therefore, we examined which morphology measurements (body parts) would explain the limitations in catch efficiency in the CR curve for T1 and T2 pots for a given size (CW) of snow crab.

2.2.5. Step 5: Prediction of the effect of entrance diameters on the snow crab catch efficiency

If the results of step 4 were able to explain the experimental catch ratio results between test and baseline pots, we predicted the effect of entrance cone diameters that would limit snow crab of a particular CW entering the pots when the top and bottom diameters of the entrance cones were considered for T1, T2, and baseline pots. We predicted the maximum size of snow crabs that would be able to enter a pot with a given entrance diameter without any reduction in entry efficiency and we predicted which sizes would be able to enter with reduced efficiency.

3. Results

3.1. Catch efficiency estimation from the sea trials

During the sea trials we used 55 and 88 test pots and 48 and 86 baseline pots for the T1 and T2 experiments, respectively (Table 1). We measured 1623 snow crabs, 314 in the T1 pots, 587 in the T2 pots, and 250 and 472 in the baseline pots of the two experiments, respectively (Table 1).

The fit statistics of the catch comparison analysis for the T1 fleet showed that the deviation between the experimental data and the modelled data fitted well ($p > 0.05$) (Table 2). For the T2 fleet, the p-value was <0.05 (Table 2). However, examination of the deviations between the experimental catch comparison points and the fitted curve (Fig. 4) showed that the low p-value was due to overdispersion (Wileman et al., 1996).

Table 2
Fit statistics of the catch comparison analysis obtained for T1 and T2. DOF = degrees of freedom.

	T1	T2
p-value	0.4237	0.0373
Deviance	75.69	84.40
DOF	74	63

Table 3
Catch ratio ($CR(w)$) (%). Values in parentheses represent 95% confidence intervals. *: values >1000.

w (m)	CR (w) (%) to baseline pot	
	T1	T2
50	145.28 (0.00–*)	* (264.79–*)
55	140.88 (0.01–*)	* (297.24–*)
60	137.34 (1.32–825.51)	* (312.64–*)
65	133.10 (17.37–590.85)	* (247.56–*)
70	126.06 (58.84–397.00)	* (190.92–*)
75	116.70 (75.42–307.18)	357.79 (124.59–*)
80	105.95 (74.89–255.95)	155.36 (75.48–*)
85	94.68 (68.12–174.29)	84.70 (44.48–195.01)
90	82.79 (61.12–119.56)	56.57 (30.26–76.60)
95	71.32 (51.33–92.71)	44.76 (26.63–56.92)
100	60.36 (42.28–75.43)	40.46 (29.00–52.80)
105	50.10 (36.06–63.47)	40.22 (31.68–59.04)
110	40.69 (30.41–54.84)	42.19 (33.08–67.16)
115	32.24 (22.83–50.08)	44.72 (31.86–73.18)
120	24.82 (15.96–45.39)	45.73 (26.37–71.58)
125	18.50 (9.10–36.33)	43.00 (17.42–62.10)
130	13.29 (4.20–24.80)	35.32 (8.01–54.65)
135	9.22 (0.74–17.59)	24.06 (1.74–52.92)
140	6.24 (0.04–13.00)	12.91 (0.16–7.00)
145	4.15 (0.00–10.43)	5.27 (0.06–136.62)
150	2.71 (0.00–8.75)	1.74 (0.00–*)
155	1.75 (0.00–7.82)	0.70 (0.00–*)
$CRaverage-$	87.72 (61.23–127.15)	66.21 (42.87–97.29)
$CRaverage+$	42.40 (33.59–53.01)	41.71 (32.61–53.00)
$DiscardRatio_{test}$	36.31 (29.77–43.45)	26.40 (19.03–33.91)
$DiscardRatio_{baseline}$	21.60 (17.02–26.71)	18.43 (13.95–23.25)

In both experiments, the catch efficiency of T1 and T2 was size dependent. At the MTS, the catch efficiency was significantly lower in the test pots compared to the baseline pots. T1 pots retained significantly (29.68%) fewer snow crabs of 95 mm CW ($CR = 71.32\%$ (confidence interval (CI): 51.33–92.71%) compared to baseline pots. For T2 pots, the retention of crabs of this size was 44.76% of what the baseline pots retained (CI: 26.62–56.92%) (Table 3). The catch efficiency of both T1 and T2 pots continued to decrease with increasing snow crab size. Compared to the baseline pots, the T1 pots retained significantly fewer snow crabs starting at 95 mm CW, whereas the significant loss began at 90 mm CW for the T2 pots (Table 3).

The average size-dependent catch efficiency ($CR_{average+}$) of T1 and T2 pots for snow crabs above the MTS was 42.40% (CI: 33.59–53.01%) and 41.71% (CI: 32.61–53.00%), respectively. The results indicate that T1 pots retained more undersized snow crabs compared to the baseline pots; however, this was not statistically significant (Fig. 4). The discard ratio for T1 was significantly higher than for the corresponding baseline pots ($Discard\ Ratio_{Baseline}$), while the discard ratio for T2 ($Discard\ Ratio_{Test}$) showed an indication to contain more snow crabs under the MTS compared to the baseline pots. The percentage of individuals below MTS was estimated to be 31.31% (CI: 29.77–43.45%) for T1 and 26.40% (CI: 19.03–33.91%) for T2, whereas for the baseline pots it was estimated to be 21.60% (17.02–26.71%) and 18.43% (13.95–23.25%), respectively (Table 3).

The cumulative density plots showed that most of the catch of the T1 and T2 pots consisted of snow crabs above the MTS (Fig. 5). However, these pots also contained a large proportion of

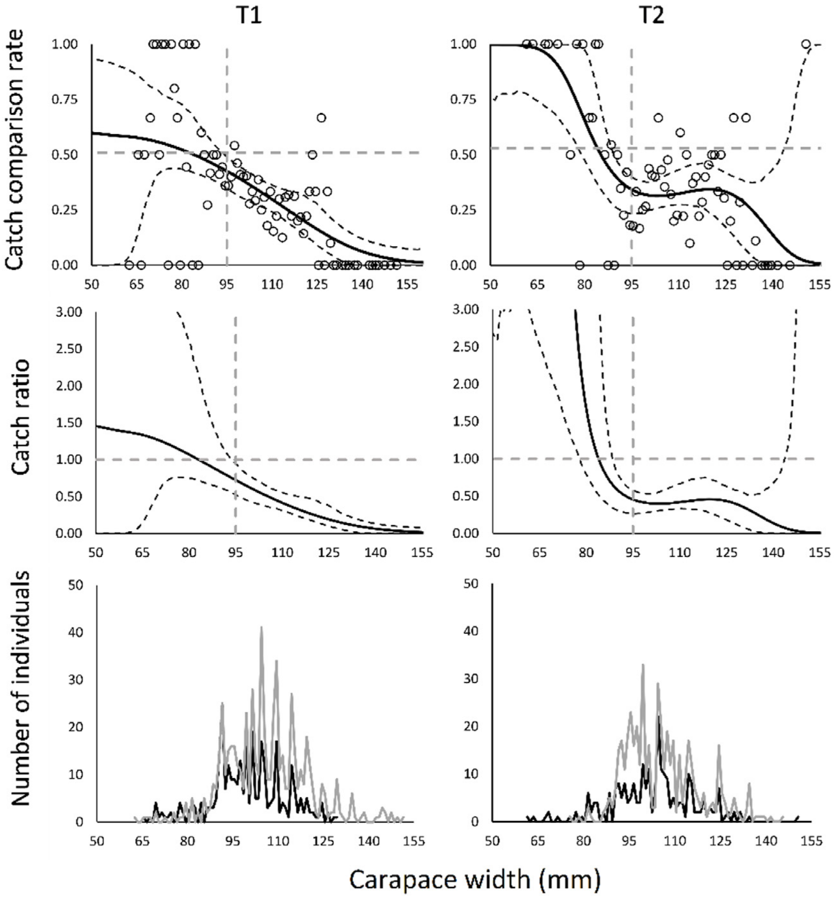

Fig. 4. Catch comparison rates (upper row) and catch ratios (middle row) with 95% CIs (stippled curves) and population caught in test (T1 and T2; black line) and baseline (grey line) pots. Circle marks represent experimental catch comparison rates. The stippled vertical lines represent the MTS of the snow crab (95 mm CW). Horizontal stippled lines represent the rate at which there is no significant difference between test and baseline pots.

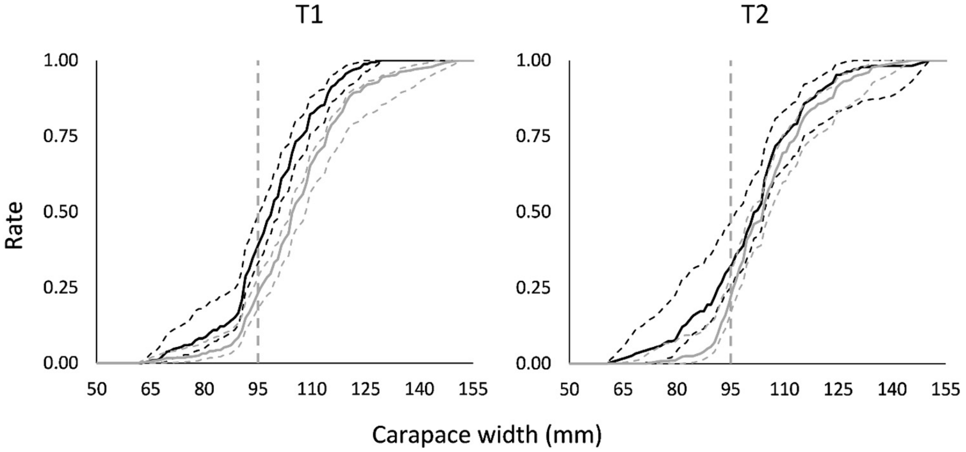

Fig. 5. Cumulative density plots for baseline pots (grey line) and test pots (black line) for T1 (left) and T2 (right) experiments. The stippled curves are the 95% CIs. The grey stippled vertical line represents the MTS of the snow crab (95 mm CW).

snow crabs under the MTS. The proportion of snow crabs under the MTS was similar for the baseline and both T1 and T2 pots.

3.2. *Explaining catch efficiency by snow crab morphology*

3.2.1. *Effect of snow crab morphology on pot entrance*

We took morphological measurements of snow crabs with CW sizes ranging from 46.7 to 141.6 mm. In cases when a measurement was not possible (e.g., when a pereiopod was missing), we used only the other possible measurements of that particular snow crab. In total, we performed 443 morphology measurements. Based on the linear regression fitted to each of the nine morphology measurements for each crab (C1 to C9) (Table 4), we estimated the effect of snow crab size based on morphology measurements on pot entrance.

The regression lines show how big the diameter of the top entrance cone (Fig. 6) and bottom entrance cone (Fig. 7) would have to be to allow the larger snow crabs to enter the pot when

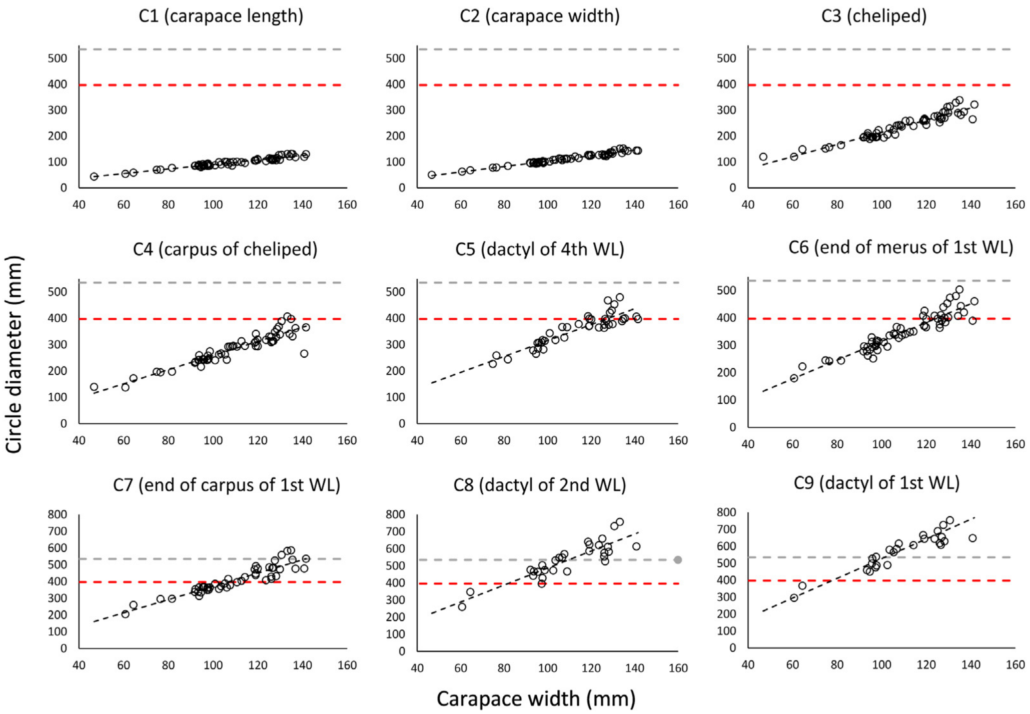

Fig. 6. Correlation between the top entrance cone diameters and the snow crab morphology measurements. Red stippled line: entrance diameter of T1 and T2 pots (397 mm); grey stippled line: entrance diameter of baseline pots (535 mm); and linear regression (black stippled line) for measurements of crab morphology. WL: walking leg. C1 to C9 are morphology measurements (Fig. 3). The *y*-axis in the bottom row is scaled up to 800 to fit the regression line values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Linear regression results. α = the effect of snow crab size based on morphology measurements (C1 to C9) on the pot entrance. Intercept terms in all cases were found to be non-significant.

Measurement	α	R^2	Standard error	Significance (*p*-value)
C1	0.899727	0.9974	0.005989	<0.0001
C2	1.036270	0.9988	0.004732	<0.0001
C3	2.16893	0.9957	0.01865	<0.0001
C4	2.59775	0.9940	0.02643	<0.0001
C5	3.13701	0.9946	0.03709	<0.0001
C6	3.17764	0.9950	0.02994	<0.0001
C7	3.74222	0.9945	0.03967	<0.0001
C8	4.88681	0.9916	0.084676	<0.0001
C9	5.34166	0.9909	0.09696	<0.0001

Table 5
Estimated snow crab CW sizes that would allow snow crabs to pass through the entrance cone diameters unimpeded when measurements C1 to C9 were considered (B: baseline pot).

Measurement	Top diameter		Bottom diameter		
	T1 and T2	B	T1	T2	B
C1	453.9	610.8	300.9	377.4	447.1
C2	378.9	510.0	251.0	314.9	373.2
C3	177.7	236.5	120.4	49.0	175.2
C4	151.6	203.1	101.4	26.5	149.3
C5	135.5	81.1	91.1	13.3	133.6
C6	124.1	64.4	84.8	04.4	122.3
C7	106.5	41.3	72.5	89.5	104.9
C8	81.8	09.5	54.8	68.3	80.6
C9	77.6	01.3	54.4	65.9	76.5

different body part measurements (C1–C9) were considered. In Figs. 6 and 7, horizontal lines represent entrance cone diameters for each of the pots in our experiments (T1, T2, and baseline). The regression line crossing any of the horizontal lines shows that snow crabs larger than the particular corresponding CW size would not be able to pass through unimpeded that particular entrance. For example, a snow crab with a CW of 80 mm would not be able to pass through the entrance cone top diameter of a T1 pot if measurements C8 or C9 (dactyl of first or second walking leg, respectively) are important for capture (Fig. 6), while the pot's bottom diameter would limit the entry if measurement C7 (end of carpus of the first walking leg) is important for capture (Fig. 7). For snow crabs of the MTS (95 mm CW), the limiting measurement of the upper entrance cone for both test pots is C8 (dactyl of first walking leg). The entrance cone upper diameter in the baseline pot does not limit entrance of crabs with 95 mm CW (Fig. 6). However, the bottom diameter of the baseline pot impedes entry of crabs of 95 mm CW when the C8 measurement is considered (Fig. 7).

Table 5 shows the theoretical estimated snow crab CW sizes that would be able to pass through the top and bottom diameters of the entrance cone of the T1, T2, and baseline pots. Some of the theoretical CW estimates (>150 mm CW) do not make biological sense because the maximum size of snow crabs is seldom larger than 150 mm CW (Nguyen et al., 2019). However, because we used the CW as the reference of snow crab size, these estimates imply that the legs are the factors limiting the entrance of snow crabs. Table 5 shows that the cheliped (C3) would start to limit the entry of crabs of 120.4 mm CW into the T1 pots.

3.2.2. Estimating catch ratio in relation to morphology measurements

Combining the catch ratio curves (Fig. 4) with results from the linear regression (Table 5) enabled us to estimate pot entry limitations related to different morphology measurements (Figs. 8–11). Considering the top entrances of T1 (Fig. 8) and T2 (Fig. 9), measurements C4 to C5 (carpus of cheliped and dactyl of fourth walking leg) explain the point at which snow crab are excluded from entry into the T1 and T2 pots. Measurement C8 (dactyl of the second walking leg) would limit entry into the T1

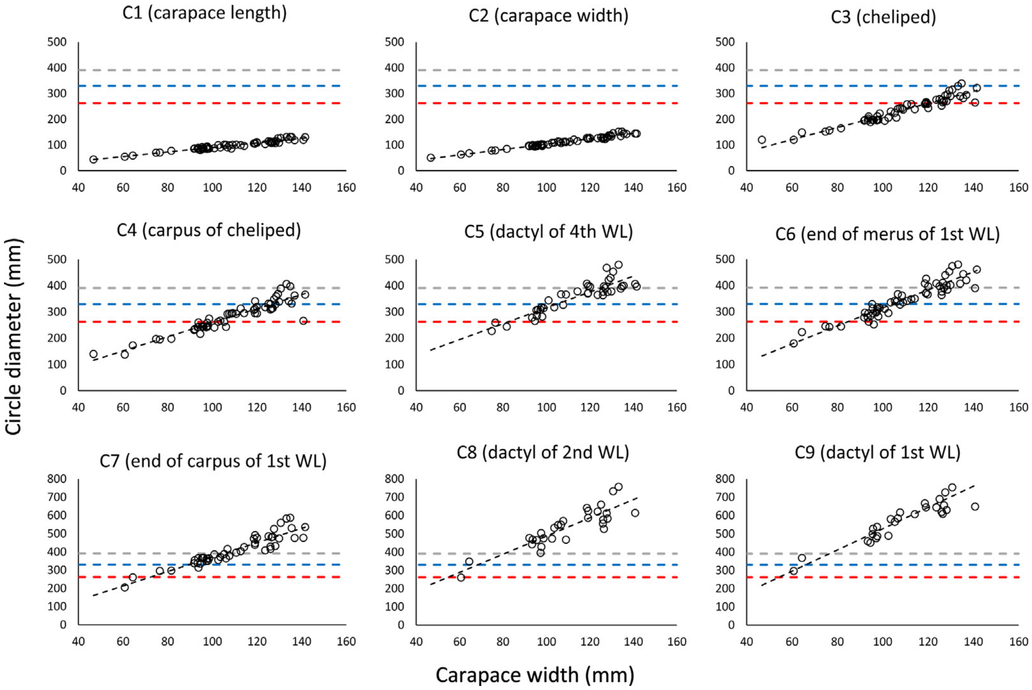

Fig. 7. Correlation between the bottom entrance cone diameters and the snow crab morphology measurements. Red stippled line: entrance diameter of T1 (262.4 mm); blue stippled line: entrance diameter of T2 (329.7 mm); grey stippled line: entrance diameter of baseline pots (391 mm); and linear regression (black stippled line) for measurements of crab external anatomy. WL: walking leg. C1 to C9 are morphology measurements (Fig. 3). The *y*-axis in the bottom row is scaled up to 800 to fit the regression line values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

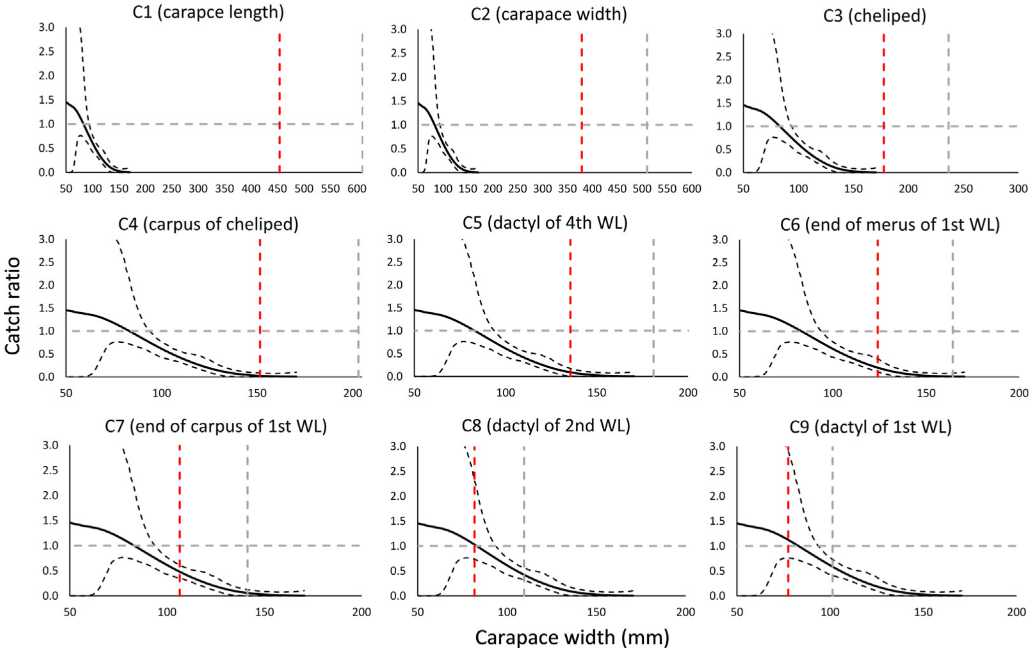

Fig. 8. T1 catch ratio curves combined with estimated CW measurements of C1 to C9 for entrance cone top diameters. Vertical stippled lines show the corresponding CW of the snow crabs for each of the morphology measurements that limit snow crab entry through the top diameter (data from Table 5). Red stippled line: test pots; vertical stippled grey line: baseline pots. WL: walking leg. The *x*-axes in the plots are scaled to fit the regression values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and T2 pots, as this is the point at which the catch ratio curve crosses the horizontal stippled line representing the point where both test and baseline pots capture the crabs equally.

For the entrance cone bottom diameters for the T1 pots (Fig. 10) and T2 pots (Fig. 11), the measurements C3 to C4 (cheliped and carpus of cheliped) would ultimately exclude snow crabs from entering the pots, whereas measurement C7 (end of carpus of first walking leg) would limit the entry probability.

3.2.3. Predicting the effect of entrance diameters on the snow crab catch efficiency

By applying the results from Table 5 and Figs. 8–11, we predicted how the entrance cone diameters of the test and baseline

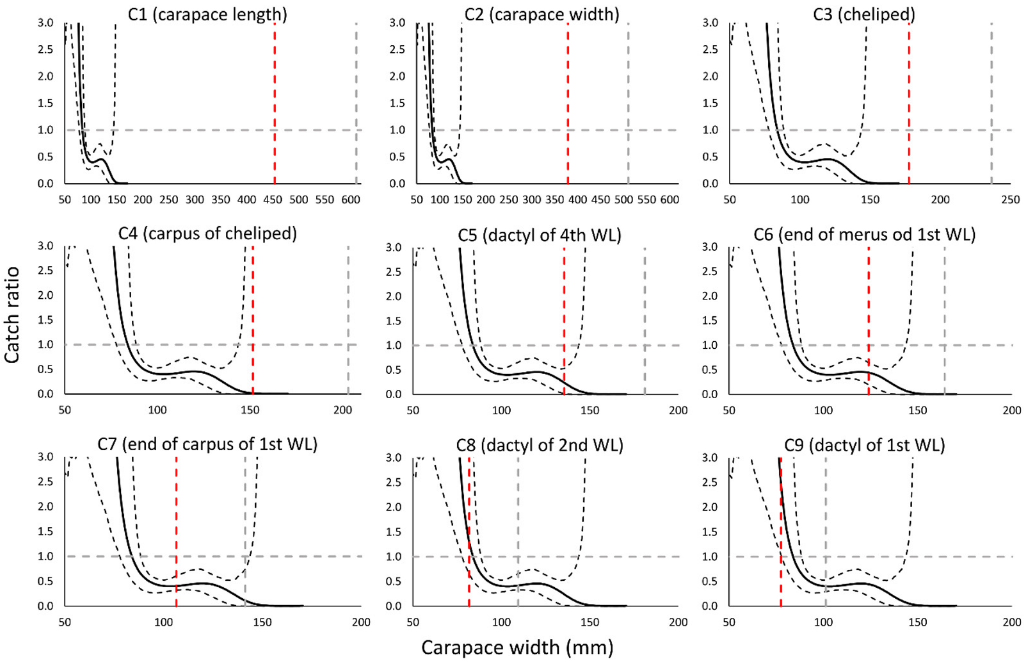

Fig. 9. T2 catch ratio curves combined with estimated CW measurements of C1 to C9 for entrance cone top diameters. The red and grey vertical lines for test and baseline pots, respectively, show the corresponding CW of the snow crabs for each of the morphology measurements that limit snow crab entry through the top diameter of either the test or baseline pot (data from Table 5). WL: walking leg. The *x*-axes in the plots are scaled to fit the regression values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

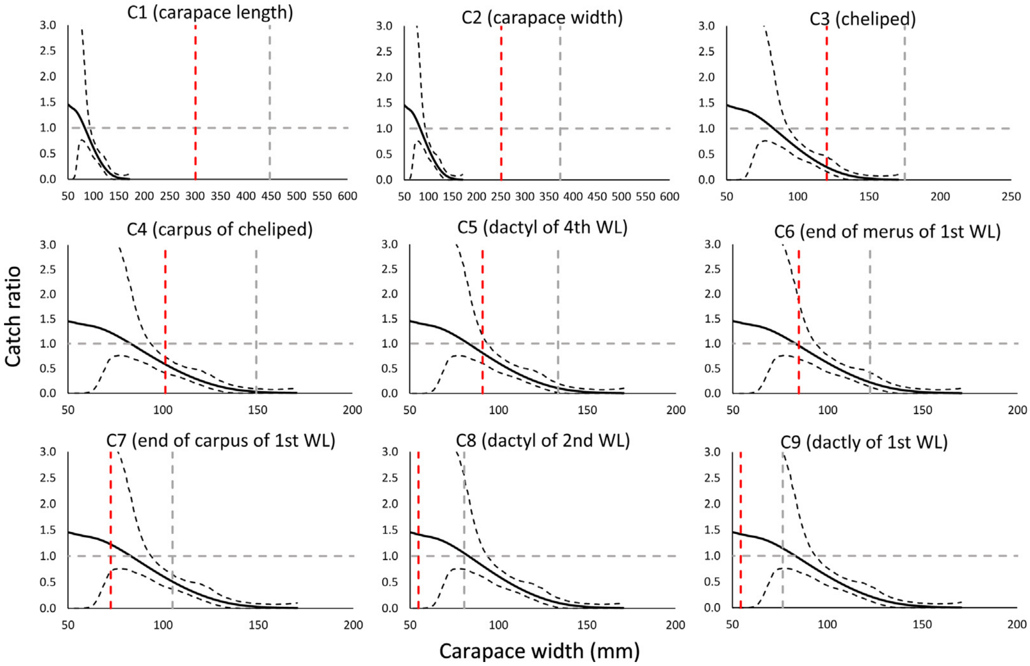

Fig. 10. T1 catch ratio curves combined with estimated CW measurements of C1 to C9 for entrance cone bottom diameters. Vertical stippled lines show the corresponding CW of the snow crabs for each of the morphology measurements that limit snow crab entry through the bottom diameter (data from Table 5). Red stippled line: test pots; vertical stippled grey line: baseline pots. WL: walking leg. The *x*-axes in the plots are scaled to fit the regression values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pots would hypothetically limit and exclude snow crabs of a given size from entering the pots considering the top (Fig. 12) and bottom (Fig. 13) entrances. The results show that the entrance diameter of the baseline pots (535 mm) begins to reduce catch efficiency for crabs above 110 mm CW. The test pots with narrowed entrance diameters (T1 and T2) begin to reduce the catch efficiency of smaller sizes of snow crab: over 85 mm CW when the top diameter of the test pot entrance cones are considered

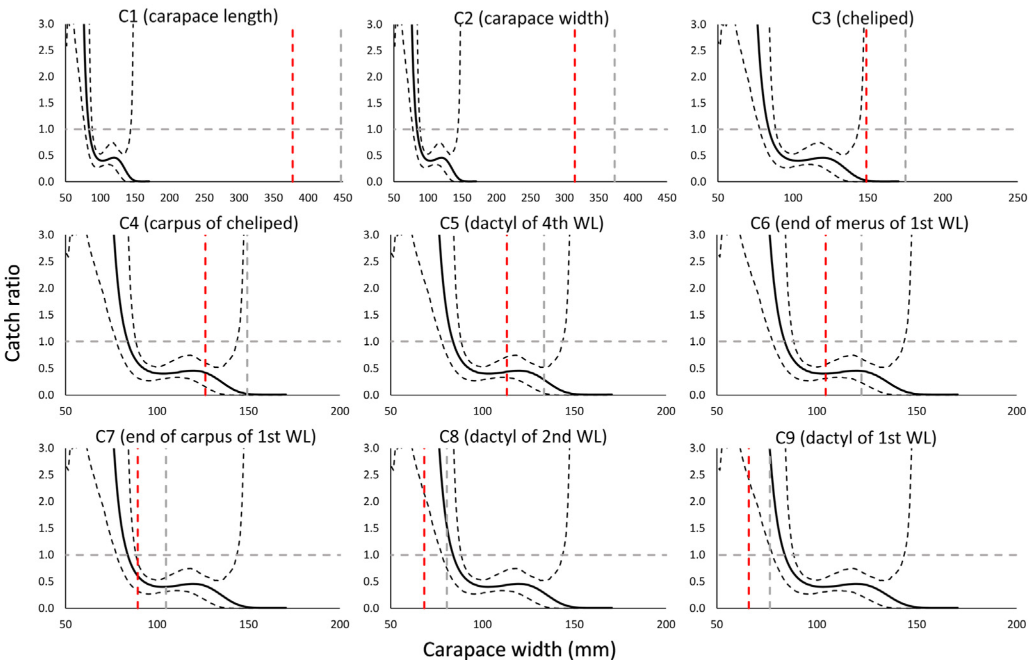

Fig. 11. T2 catch ratio curves combined with estimated CW measurements of C1 to C9 for entrance cone bottom diameters. The red and grey vertical lines for test and baseline pots, respectively, show the corresponding CW of the snow crabs for each of the morphology measurements that limit snow crab entry through the bottom diameter of either the test or baseline pot (data from Table 5). WL: walking leg. The x-axes in the plots are scaled to fit the regression values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

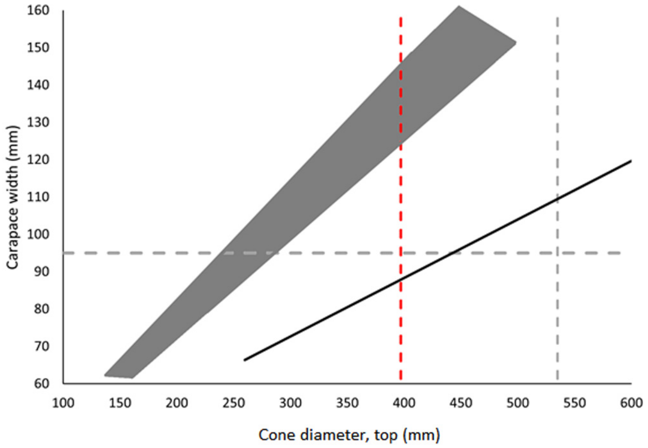

Fig. 12. Predicted limiting (black line) and excluding (grey area) measurements for snow crabs when top entrance diameters are considered. The grey horizontal line represents the MTS of snow crabs (95 mm CW), the red vertical line shows the size of the top entrance cone for the test pots, and the grey dashed line shows the size of the top entrance cone for the baseline pot. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

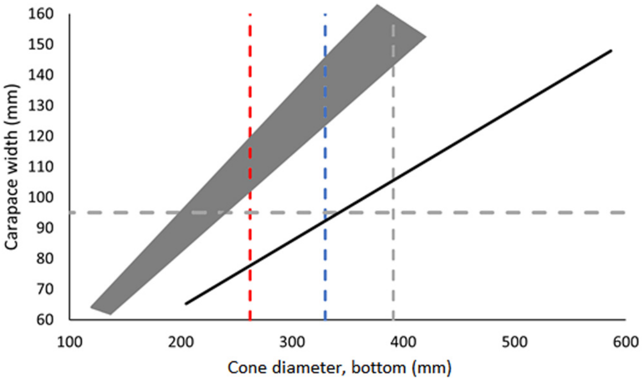

Fig. 13. Predicted limiting (black line) and excluding (grey area) measurements for snow crabs when bottom diameters of the entrance cone are considered. The grey horizontal line represents the MTS of snow crabs (95 mm CW). The red vertical line shows the size of the bottom part of the entrance cone for the test pots with a narrow entrance (T1), the blue vertical line represents test pots with a narrowed entrance and reduced entrance cone length (T2), and the grey dashed line shows the size of the bottom part of the entrance cone for the baseline pots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 12), and over 75 mm and 90 mm CW for bottom diameters of the T1 and T2 pots, respectively (Fig. 13).

4. Discussion

In this study, we investigated the catch efficiency of modified snow crab pots with different entrance cone diameters and compared them to that of standard conical pots. The size of the entrance must be of sufficient diameter to allow snow crabs, especially the largest and more valuable individuals, to pass through the pot entrance and be retained (Miller, 1990). Thus, determining the optimal size of the entrance cone is crucial to optimizing catch efficiency.

Our results from the sea trials showed that the catch efficiency differed significantly between the test and baseline pots and that it was size dependent. Specifically, the entrance diameters of the test pots resulted in reduced catch efficiency for snow crabs above the MTS, thus the test pots did not retain any of the largest sizes compared to the baseline pots. Our results are in agreement with what was previously found by Vienneau et al. (1993) that compared the pots with single larger entrance with pots with multiple smaller top entrances. The results of the study by Vienneau et al. (1993) showed that the most efficient pot was the one having conical single large entrance. The entrance cone diameters of the test pots were of sufficient size to allow the snow crabs to pass through the entrance if only the CW of the snow crabs was considered, but passage of individuals with CW > 95 mm was limited. However, the sea trial data did not provide information about when snow crabs of certain sizes begin to show decreased probability of being caught in T1 and T2 pots. These data also did not enable inference of the optimal pot entrance diameter or whether it is the CW or other body parts of snow crabs that are responsible for the reduction in catch efficiency.

The laboratory experiments showed that the chelipeds and walking legs can explain the differences in the catch efficiency of the pots observed in our sea trials. Specifically, for both the T1 and T2 pots, the carpus of the cheliped and the dactyl of the fourth walking leg explained the point in the catch ratio at which snow crabs were excluded from entering the pot, whereas the dactyl of the second walking leg limited entry when the top entrance cone diameter was considered. However, for the entrance cone bottom diameters, the cheliped and carpus of the cheliped led to snow crabs being excluded from pot entry, whereas the end of the carpus of the first walking leg limited the entry probability. These results have potential applicability to the baseline pots. When we considered the chelipeds and walking legs of the largest individuals, we predicted a reduction of pot catch efficiency for the largest individuals in the fishery when standard conical pots are used. However, the largest snow crabs have the highest market value and, therefore, capture of those crabs is important for the fishery.

To optimize catch efficiency of a conical pot, it is required that crabs can easily climb the pot to reach the top entrance and then that the entrance is big enough to allow commercial size crabs to pass through the entrance cone. In order to increase the diameter of the pot entrance cone while maintaining the same steepness of the pot frame, the diameter of the pot's lower ring must be increased, resulting in larger and heavier pots that may be more complicated to handle on deck. Standard snow crab pots weigh approximately 12.5 kg each, and the crew operates between 1500 and 2000 pots every day. Thus, having larger and heavier pots may not be an attractive option for the industry. The risk of work-related accidents and fatalities are generally high in fishing operations, compared to other industries, and this is especially true for pot fisheries (Aasjord et al., 2012; McGuinness et al., 2013). However, larger snow crab pots are used in Nova Scotia snow crab fishery without reported problems (Fisheries and Oceans Canada, 2020). Further, larger pots might reduce the risk of pot saturation (Miller, 1990; Nguyen et al., 2020) which could be an issue in snow crab fisheries with high catch rates. Current low snow crab catch rates in the Barents Sea do not create this issue (Nguyen et al., 2019).

Another way to increase the entrance cone diameter while keeping low pot steepness is to scale up the design of the T1 pot to match the entrance cone size to that of the baseline pot. In this way, the diameter of the lower ring of the pot frame would increase from 1300 mm to approximately 1650 mm, with the inclination angle close to 40 degrees. Pots with less steep walls make the climb easier and increase the probability of crabs reaching the pot entrance (Olsen et al., 2019a). With this design, the entrance cone diameter would be of similar size to the currently used pots while potentially increasing the probability of crabs climbing a low-angle pot wall. Olsen et al. (2019a) documented a 30% catch efficiency reduction when the inclination angle of the pot was increased from 60 to 80 degrees. Thus, reducing the angle to 40 degrees could possibly increase the chances of crabs climbing the pot and coming into contact with the pot entrance cone. However, this design could affect the snow crab catches. Specifically, the reduced distance for crab to escape out of the top once catch accumulates in the pot could have had a negative effect on pot saturation (Miller, 1990) and can greatly reduce number of crab entering the pot.

The results of this study are applicable to the entry of snow crab into conical snow crab pots with the entrance at the top because the mode of contact is different for pots with side entrances. Furthermore, different morphological measurements would have to be considered in future studies for escape process. During escape, crabs can orient their carapace to pass through the pot netting meshes provided that the carapace size is sufficiently small to pass through the mesh opening (Winger and Walsh, 2007; Olsen et al., 2019b). During the fishing, crabs have enough time for several attempts to orientate their carapace and legs optimally for escape. The same applies to escape openings that are mounted in the pot to allow crabs of certain size to escape (Winger and Walsh, 2007). Therefore, chelipeds and pereiopods cannot be considered limiting factor during the escape process to the same extent as they are during the entry through the top entrance.

The authors recognize some limitations of this study. We wish to note that, in addition to entrance diameter, other features of the pots also varied. This included pot height, diameter of the pots, steepness, and volume (see Fig. 1). Each of these parameters may have affected the catch efficiency of the pots. However, we assume that lowering the pot steepness may have contributed to increasing the chance that snow crabs could climb the pots and reach the pot entrance more easily compared to the steeper baseline pots (Olsen et al., 2019a). Therefore, we assume that the lower steepness cannot be the cause of the lower catch efficiency observed for the T1 and T2 pots. Further, our predictions were based on image analysis of snow crab external morphology, and any effect of crab behaviour was not considered. Therefore, an experiment using direct observations through laboratory experiments with live specimens or via underwater video recording would provide valuable information about the entry pattern and snow crab behaviour during the fishing process. Future studies should consider snow crab pot entrance cone diameters that are larger than those used in current commercial pots.

CRediT authorship contribution statement

Kristine Cerbule: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Bent Herrmann:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Eduardo Grimaldo:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Manu Sistiaga:** Writing – original draft, Visualization. **Jesse Brinkhof:** Writing – original draft. **Jørgen Vollstad:** Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We are grateful to the academic editor and reviewer for their valuable comments, which we feel have improved our manuscript. We would like to thank the company Opilio AS and the crew of their vessel MS "Northeastern" for their invaluable help during this experiment and Egersund Trawl AS for providing the pots for this experiment. We are grateful to the crew of the research vessel "Lance" for their valuable help collecting the snow crabs used in our laboratory experiments. The cruise on board the R/V "Lance" was financed by the project "Ecology and management of the invasive snow crab: Predicting expansion, impacts and sustainability in the Arctic under climate change, Norway" (Grant no. 294464).

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.rsma.2022.102237.

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