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Published in:
Fisheries Research

Link to article, DOI:
10.1016/j.fishres.2023.106609

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Fisheries Research 261 (2023) 106609

Contents lists available at ScienceDirect

Fisheries Research

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

Avoiding grey seal depredation in the Baltic Sea while increasing catch rates of cod

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ARTICLE INFO

Edited by A.E. Punt

Keywords:
Cod pots
Atlantic cod
Pot fishery
Alternative gear

ABSTRACT

The escalating conflict between gillnet fisheries and the growing seal populations in Baltic Sea has increased the need to reduce direct effects in form of reduced or damaged catches. This study describes the design and catch rates of 20 different seal safe cod (*Gadus morhua*) pot designs suitable for the Baltic Sea. Catches in numbers of individuals and total catch weight were recorded in 2762 pot hauls with pots varying in terms of size, shape, number of entrances, entrance length, pot placement in relation to the sea floor and catch holding chamber. The aim was to investigate the how the different designs and soak times affected the catch rates under similar conditions. Volume and soak time was significantly positively correlated with catch rates and round bottom-standing pots with a fish holding chamber, funnels and 5 entrances had the highest catch rates. The findings are important for the development of cod pots, which can allow the fishers to continue fishing in areas of high seal density with static gear and hence low-carbon emission and minimum bycatch of marine mammals and sea birds.

1. Introduction

Interactions between seals and fishing activities is an increasing problem and challenge the livelihood of many small-scale coastal fishermen (Cosgrove et al., 2013; Fjälling, 2005; Königson et al., 2009; Rafferty et al., 2012). In the Baltic Sea in particular, grey seal depredation is frequent and the conflict between seals and commercial gillnet fisheries has escalated following the recovery of grey seal (*Halichoerus grypus*) and harbour seal (*Phoca vitulina*) populations (Jounela et al., 2006; Kauppinen et al., 2005; Königson et al., 2009; Harding and Härkönen, 1999; Härkönen et al., 2013). In the Baltic the population of grey seals has grown from 3000 to 3600 animals in the mid-1970 s to approximately 38,000 grey seals counted in 2019 (Harding and Härkönen, 1999; ICES, 2020). The grey seal population is responsible for the bulk of the damages causing economic losses in the small-scale fisheries in the Baltic (Blomquist and Waldo, 2021). Damages include visible losses where the seals have only eaten parts of the fish and hidden losses where the catch is entirely removed from the net without leaving any trace or fish flee from the vicinity of the fishing gear (Königson et al., 2007, 2009). Hidden losses in the cod gillnet fisheries are substantial and on average 4.1 fish are lost for each fish found damaged by seals (Königson et al., 2009).

In response, earlier research has investigated the potential use of cod pots as alternative fishing gear to gillnets as the pots provide a better protection of the cod catches against depredation (Bryhn et al., 2014; Hedgärde et al., 2016; Königson et al., 2015a, 2015b; Ljungberg et al., 2016). Cod pots can have catch rates similar to those of gillnets in certain periods of the year Königson et al. (2015a). Furthermore, pots have the advantages that they are species and length selective, have low impact on the seabed and are fuel- efficient (Suuronen et al., 2012). They also have low bycatch of marine mammals and sea birds and are thus mentioned in the FAO guidelines on bycatch as an alternative to minimise bycatch when no strategies appear viable (FAO, 2021).

The main challenge for widespread use of cod pots is attaining commercially viable catch rates and numerous fishing trials have been conducted to investigate pot catch efficiency (Anders et al., 2016; Bagdonas et al., 2012; Furevik et al., 2008; Furevik and Løkkeborg, 1994; Jørgensen et al., 2017; Ljungberg et al., 2016). Emerging questions in relation to design and fish behaviour include whether pots should be bottom-standing or floating (Anders et al., 2016; Collins, 1990; Suuronen et al., 2012), which shape has the highest catches (Furevik and Løkkeborg, 1994) and whether the number and design of entrances

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https://doi.org/10.1016/j.fishres.2023.106609
Received 30 June 2022; Received in revised form 2 January 2023; Accepted 3 January 2023
Available online 17 January 2023

influence the catch rates (Jørgensen et al., 2017; Ljungberg et al., 2016). However, within and among pot experiments several gear parameters often vary, e.g. size, shape, entrances and number of entrances (Furevik and Løkkeborg, 1994). This makes it difficult to determine how single variables affect catch rates.

The overall aim of this study was to identify the relative impact of different aspects of placement, design and soak time that lead to high catch rates in cod pots. The study included three trials. The first trial investigated effects of size and placement (bottom-standing vs floating pots) on catch rates. The second evaluated the effects of catch holding chamber and entrance design. Finally, the third trial evaluated the number and length of entrances of the pot. The effects of pot size, shape and soak time were evaluated in all trials. The study was conducted using trial and error. Thus alterations were made on the basis of the results from the previous trials.

2. Materials/methods

The study was conducted in the Baltic Sea north east of Bornholm, Denmark in collaboration with a commercial fisher operating a small gillnet vessel (9.9 m; 13.6BT) from 2014 to 2016 (See Appendix, Fig. 1). The vessel had a hydraulic hauler installed to haul heavy pots. Most pots, however, could be hauled by the existing gillnet hauler on-board.

The study was separated into three trials investigating a total of 20 pot types/modifications. All pots were built of the same net materials except for one, *Carapax*, which does not follow the standard specifications mentioned in the following. Fig. 1 shows an example of a pot and names used to identify specific parts. The pot frames were made from 8 mm stainless steel. Sides, top and bottom of the pot were built in green polyethylene (2.5 mm twine, 30 mm mesh size) while the entrance sides were made of black knotless nylon (2 mm twine, 200 mm mesh size) leading to a round entrance (diameter: 16 mm) into the entrance chamber. The pots were equipped with 45 mm mesh size selection panels covering a section of the side of the pot to avoid the catch of undersized fish. All pot types and dimensions are listed in Table 1 and Appendix. During each set, four to nine pots of different types were placed in random order along a bottom line with 40 m spacing between pots. The line was set approximately perpendicular to the current.

All pots were baited with approximately 300 g of frozen and cut herring (*Clupea harengus*) placed in white bait bags in the middle of the entrance chamber of the pot. Date, time, depth and position of all sets and hauls were recorded. Fish catches were separated into two length classes, above and below minimum landing size. In 2014 the minimum landing size was 38 cm while in 2015 and 2016 it was reduced to 35 cm (the change in minimum landing size did not influence the results and conclusions as the study focused on the proportions of catches between the different pot types). For each category, total number and weight of

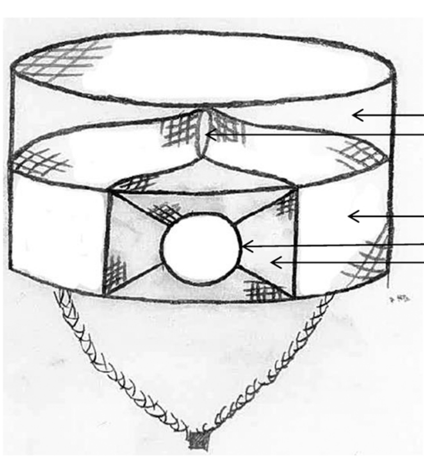


Fig. 1. Visualization of the pot terms used in the paper

cod per pot was recorded. Catch per unit effort (CPUE) for cod above the minimum landing size was calculated in two ways, as the number of cod per pot per fishing hour and the weight of cod per pot fishing hour. All data were collected mainly by an independent observer though in a few cases, data was collected by the fisher. During most trials with observers, 1–4 pots were fitted with underwater cameras. The cameras were used to record details of the catch process and cod behaviour in relation to different pot types and modifications. These data are not reported within this paper but video footage from Trial 1 and 2 are published by Hedgärde et al. (2016) and are used in the discussion below.

2.1. Trial 1: effect of size and placement on catch rates

The purpose of Trial 1 was to test how size and placement (bottom-standing vs floating) affected the catch rates. The trial was conducted between 19th of September and 8th of November 2014 and had 40 prototype cod pots, ten each of four types.

Round L was a large round bottom-standing pot with 3 entrances, an entrance chamber and an upper fish holding chamber. This pot type was used as a reference pot and was thus present in all three trials. A reference pot is needed for comparison between the three trials. In Trial 1 the bottom-standing *Round L* was tested together with three types of floating pots (*Pentagonal M1, Pentagonal L, Carapax*) were the pentagonal pots only differed according to size. The *Carapax* pot was a floating two chamber pot with one entrance. They were made from 1.2 mm black nylon twine, using 27.5 mm mesh size and with 50 mm mesh size in selection panels. As the parameters of *Carapax* e.g. shape, size, colour and mesh size were not equal to the other pots, *Carapax* could not support test of size or placement but was simply included to get information on *Carapax* catch rates. All pots were hauled daily for the whole trial. Further specifications and Figures of all pot types can be found in Table 1 and Appendix.

2.2. Trial 2: effects of fish holding chamber and type of entrance

The purpose of Trial 2 was to test the effects of the fish holding chamber, type of entrance, and again to test how size and bottom-standing vs floating affected the catch rate. This trial was conducted from 3rd to 30th of May 2015. Before beginning the fishery, all pot types described below were tested in a flume tank to assess pot stability and correct positioning. They were all tested with currents 0.5, 1 and 1.5 m/s similar to current speed in the trial area.

Subsequently, the trial was conducted with 70 prototype cod pots of 8 different pot types. 1–10 pots of each 8 pot types were used, see Table 1 for the number of hauls of each pot type. *Round L* were used again in Trial 2 unaltered as a baseline. *Carapax 2* was equal to *Carapax 1* except that the selection panel was changed to 45 mm to be equal with all other pots. The tests in the flume tank revealed that additional floats were needed to stabilise *Pentagonal M1,* as they tended to tilt back and forth. In Trial 2 *Pentagonal M1* was thus changed to *Pentagonal M2* as more floats were added to the pot type. To test if catch escape could be reduced, plastic spikes were placed around the inner ring of the entrance pointing into the inside of the entrance chamber of all *Pentagonal L* pots (Fig. 2.3). This modification was named 'sun-entrance'. No other parameters were changed on *Pentagonal L* but it was renamed *Pentagonal L-Sun*. To test the effects of placement of the fish holding chamber, two new types of Pentagonal pots were investigated. *Pentagonal S* had the fish holding chamber placed beside the entrance chamber and not as an upper holding chamber like the other types. *Pentagonal M2-NC* had the same dimensions as *Pentagonal M2,* but with no fish holding chamber. To further test the effect of pot size, *Round M* was investigated. *Round M* was a bottom-standing pot with three entrances and an upper fish holding chamber. *Round M* was thus similar to *Round L* except for the dimensions, as *Round M* was smaller than *Round L*. The last pot type in Trial 2 was *Fisher,* built by a Swedish fisher who claimed to have high catch rates using this pot type. The *Fisher* pot was a large rectangular

Table 1
Overview of all pot types, short description and number of samples per Trial.

Short name	Comment	Shape	Volume (m3)	Chambers	Entrance type	Entrance Long/Short	Number of entrances	Floating/ Botttom	Trial 1	Trial 2	Trial 3
“Carapax 1″		Oval	0.9	1	Open	L	1	F	338		
“Carapax 2″	Selection panels were changed to 45 mm	Oval	0.9	1	Open	L	1	F		76	
”Pentagonal M1″		Pentagonal	0.4	1	Open	L	1	F	338		
”Pentagonal M2″	Adjusted with additional floats in comparison with M1	Pentagonal	0.4	1	Open	L	1	F		68	74
”Pentagonal M2-NC”		Pentagonal	0.4	0	Open	L	1	F		112	
”Pentagonal L”		Pentagonal	0.6	1	Open	L	1	F	339		
”Pentagonal L-Sun”		Pentagonal	0.6	1	Sun	L	1	F		156	
“Pentagonal L-Fun”		Pentagonal	0.6	0	Fun	L	1	F			87
”Round L ”		Round	1.5	1	Open	L	3	B	217	171	37
“Round L-short3″		Round	1.5	1	Fun	S	3	B			61
“Round L-short5″		Round	1.5	1	Fun	S	5	B			50
“Round L- Fun”		Round	1.5	1	Fun	L	3	B			87
“Round -NC”		Round	1.5	0	Open	L	3	B			46
“Pentagonal S”		Pentagonal	0.4	1	Open	L	1	F		153	
“Pentagonal S-Fun”		Pentagonal	0.4	0	Fun	L	1	F			99
“Round M”		Round	0.6	1	Open	L	3	B		124	
“Fisher”		Square	1.5	0	Fun	L	4	B		17	
“Square L”		Square	1.3	1	Open	L	4	B			70
“Square M”		Square	0.6	1	Open	L	4	B			53
“ Pentagonal_M2-fun”		Pentagonal	0.4	0	Fun	L	1	F			6

bottom-standing pot with four entrances, one on each side. It was made from black nylon (1.2 mm black nylon twine and 27.5 mm whole mesh) and had no fish holding chamber but funnels similar to Fig. 2.2 (2 mm red nylon) were attached to the entrances to prevent catch escape. Only a single *Fisher* pot was deployed in Trial 2 to allow a comparison of catch rates.

2.3. Trial 3: effect of presence/absence of funnel entrances and entrance number and length

The first purpose of Trial 3 was to test the presence/absence of funnels in the entrances (see Fig. 2) and varying the entrance numbers and lengths. The second purpose was to test the effect of fish holding chambers in round bottom-standing pots and pot size. Trial 3 was conducted from 1st of May 2016–1 st of June 2016 and was conducted with 9 prototype pots (see Table 1). *Pentagonal M2* and *Round L* were used again as baselines. *Round L-Fun* tested the effect of entrance funnels. *Round L-Fun* had the same dimensions as *Round L* but had funnels attached to all three entrances (see Appendix, Fig. 2). *Round L-short3* and *Round L-short5* tested the effect of entrance length and number of entrances. Except for the entrances and attached funnels both bottom-standing pots had the same dimensions and chambers as *Round L*. *Round L-NC* had the same dimensions as *Round L* but no holding chamber in order to test the effect of holding chamber. To test the effect of size two new pot types were deployed: *Square L* and *Square M*. These were square bottom-standing pots with 4 entrances (one on each side), an entrance chamber, and an upper fish holding chamber. The only difference between the two types was the size.

2.4. Data & statistical analysis

The pots were categorised by pot shapes (round, pentagonal or square), location relative to the sea floor (standing on seafloor or floating). The confounding of pot shape and position in the water column (only pentagonal pots were floating) precludes separate estimation of these effects. Furthermore, the data set is not balanced (there are different numbers of combinations of pot designs and other factors such as e.g. geographical position) and pot catches are highly variable (Königson et al., 2015a). This implies that the simple method of estimating mean catch rates by pot type under the assumption of normal distributed data is not applicable. Instead, a statistical model was used accounting for pot design and the statistical distribution of catch rates. The study was conducted was conducted using trial and error. Some alterations were made on the basis of the results from the previous trials and some was ideas from the fisher, gear manufacturer or researcher. In addition there were practical limitations in terms of number of pots and

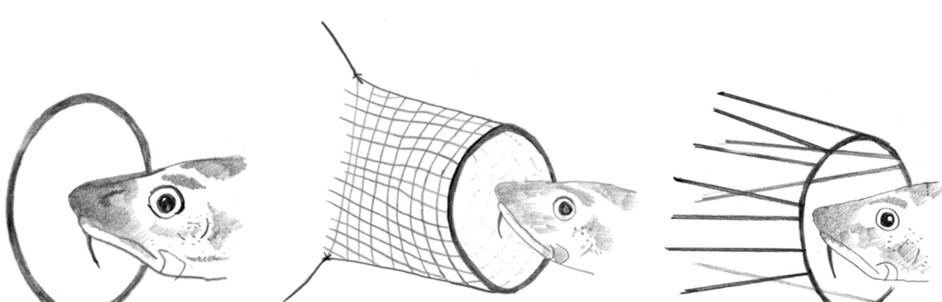


Fig. 2. Entrance designs. Left side: (1) open entrance. Middle: (2) funnel entrance. Right side: (3) sun entrance.

pot size that would make a completely balanced study impractical.

The response variable total catch in each pot per haul (CPUE), was modelled both as counts (C_n) and as total weight (C_w) using different distributional assumptions. C_w is continuous and non-negative and consequently modelled with a Tweedie distribution (Tweedie, 1984). C_n is count data with a big spread in values and consequently modelled with a negative binomial distribution.

Each trial period can be analyzed separately or in a combined model. The latter is generally preferable since this allows information to be shared among trials, and hence more narrow confidence bands can be obtained compared to the separate analyses. However, care must be taken in the combined analysis not to combine parameters across trials when such a reduction of the parameter space is not supported by the data. As a simple check of consistency, both separate and combined analysis of the data was performed.

The effects of the individual pot modifications were analysed in a feature specific model, where the pot effect is decomposed into shape, size, entrance and holding chamber effects, assuming that interaction effects between pot features is negligible (e.g., the effect of size does not depend on the number of entrances). Data were also analysed using a pot specific model where a separate parameter is estimated for each unique pot type. The pot specific model allows interaction effects to occur but does not allow us to discern the effects of the individual pot properties.

2.5. Pot specific model

For both types of response (weight or numbers), the full non-additive model for the mean value is as follows:

$$\log(\mu_i) = \text{pot·type(i)} + \text{trial(i)} + f_{1,\text{trial(i)}}(\text{lon}_i, \text{lat}_i) + \alpha\log(\text{hours}_i) + f_2\,(\text{depth}_i) + \text{outer(i)} + \text{U(i)}_{\text{chain,id}}$$

where μ is the expected value of the response (C_w or C_n), pot.type(i) maps the *i*th pot to a categorical effect for each type of pot, U(i)chain.id $\sim N(0, \sigma_u^2)$ is a block random effect for all the pots located on the same chain on the same day, f_1 is a 2-dimensional thin plate regression spline on the geographical coordinates (one distinct for each trial), α is the regression coefficient for the effect of soak time, and f_2 is a Duchon spline with first derivative penalization for the effect of bottom depth. Finally, outer(i) is an indicator variable for whether the pot was in one of the two outer positions in the chain (see Table 2.) Smoothness selection was carried out with the maximum likelihood (ML) method (Wood, 2011).

Table 2
description of model variables for both pot specific (P) and feature specific (F).

Variable	Description	Included in model
Cn	Catch in numbers (above minimum landing size only)	
Cw	Catch weight (below minimum landing size only)	
lon,lat	Longitude, latitude	P, F
trial	Which of the three trials (period)	P, F
pot.type	Type of pot (20 levels)	P
shape	Shape of pot (round, square)	F
chamber	Indicator for whether the pot contained a chamber	F
chamber.fun	Indicator for the combination of chamber and funnel entrance	F
hours	Soak time	P, F
outer	Indicator for whether the pot was in one of the two outer positions in the chain	P, F
depth	Average depth for the chain	P, F
chain.id	Unique chain identifier for each combination of position and day	P, F
has5	Indicator for having 5 entrances instead of 3	F
entrance. length	Length of entrance (short or long)	F

2.6. Feature specific model

In the feature specific model, *pot.type* (a factor with 20 levels) is replaced with functions of volume, shape, entrance type, number of entrances and absence or presence of holding chamber (see Table 2 for variable description). In this model it is assumed that there are no interactions between shape, volume, and soak time except for the interaction between having a funnel entrance and a holding chamber, e.g. changing the soak time will increase (or decrease) the expected catch with the same percentage regardless of the shape and entrance type. The pot types *Fisher*, *Carapax* and *pentagonal* (floating) pots were removed from the dataset in the feature specific model as their design varied fundamentally from the other pot types. The main effect of entrance type was not included, because in the reduced dataset the funnel entrance was not tested without having a holding chamber, so only the interaction effect between holding chamber and funnel can be estimated.

The full model was.

$$\log(\mu_i) = \text{shape(i)} + \text{entrance·length(i)} + \text{has5(i)} + \text{chamber(i)} + \text{chamber·fun(i)} + \text{trial(i)} + f_{1,\text{trial(i)}}(\text{lon}_i, \text{lat}_i) + \alpha\log(\text{hours}_i) + f_2\,(\text{depth}_i) + \beta\log(\text{volume}_i) + \text{outer(i)} + \text{U(i)}_{\text{chain,id}}$$

All variables also present in the pot specific model were the same, see Table 2 for additional variables.

3. Results

A total of 1232, 876 and 654 hauls were conducted under trial 1, 2 and 3, respectively (Table 1). In all three trials the pots mainly caught cod, but occasional catches of dab also occurred.

In trial 1 observations during hauling of the floating pots indicated that they had not been floating correctly as mud was occasionally seen on the pots. Results from the floating pots (*Pentagonal M1*) should thus be interpreted with caution as they most likely did not fish optimally. Furthermore, the selection panel of *Carapax1* had a mesh size of 50 mm, 5 mm larger than the in other pots. According to Ovegård et al. (2011), this mesh size has a 50% retention of all cod with a length of 42 cm, while mesh sizes of 45 mm retain 50% of the cod at a length of 38 cm. Thus, the *Carapax* pot has a larger chance for cod up to 42 cm of length to escape and thus lower catch rates.

The results in terms of the parameter of interest from the negative binomial model (catch in numbers) were similar to those obtained from the Tweedie model (catch in weight), and therefore only results from the Tweedie model are reported in the following as weight was considered to be of greater importance to fishers than numbers.

3.1. Pot specific models

Pot catch efficiency was evaluated relative to the *Round L* pot (Fig. 3). The *Round L* reference pot has consistent high catches in all three trials, strengthening confidence in this pot providing high catch rates under variable conditions. None of the pots attained significantly higher catches than the *Round L* reference pot. While the *Round L-short5* pot was estimated to have slightly higher catch rates, the difference was not significant. The *Fisher* pot also had catch rates that did not differ significantly from *Round L* despite its square shape, in contrast to the results from the other squared pots. The height of the *Fisher* pot was less than the other square pots, which may have prevented the *Fisher* pot from tilting.

Model outputs from both models are available in Appendix, Table 2.

3.2. Feature specific

The size of the pot has a significant positive effect on the catch (larger pots catch more). A doubling of volume was found to have a greater effect than doubling soak time. Doubling the volume provided 56%

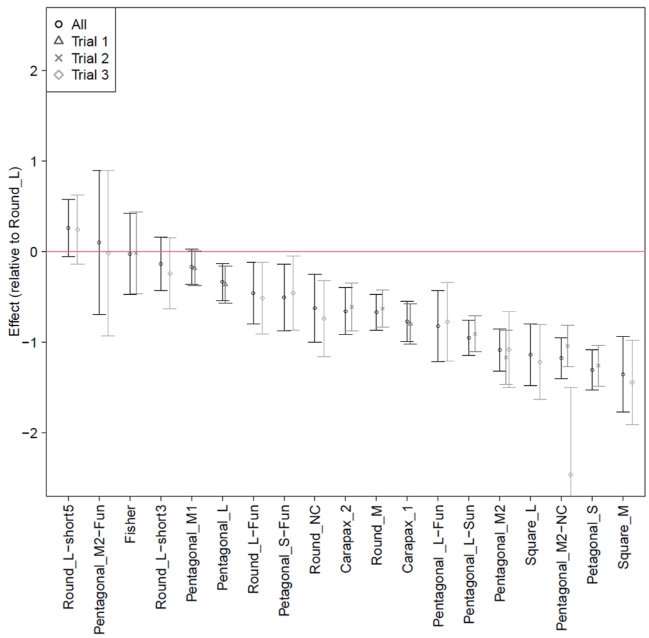
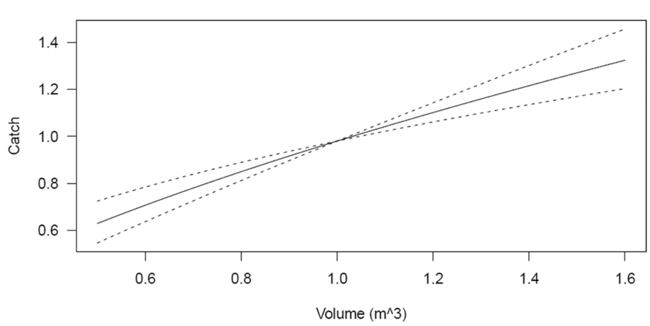


Fig. 3. Pot specific model: Estimated effects of pot type by trial with 95% confidence intervals. The effects are on log-scale and relative to the "*Round_L*" pot (y-value zero), such that a value of e.g. -0.5 indicates exp(-0.5) = 0.6 times the catch of the "*Round_L*" pot.

higher expected catch, whereas doubling soak time only increased the expected catch by 22% (Fig. 4). Individual feature effects from the feature specific model are shown in Table 3 below. Square pots are found to have lower catches compared to round pots with expected square pot catch rates being only 40% of those of round pots. Having a holding chamber increases the expected catches by 27%. The effect of having both funnel and holding chamber was substantially greater than that of having the holding chamber alone (adding 107%). The effect of having 5 entrances compared to 3 was significantly positive (42% increase) and the same was found for having a short entrance compared to a long (43% increase). Finally, the results revealed that the pot position in the chain is important as the inner pots caught less (17% decrease) than pots in the outer position (Table 3).



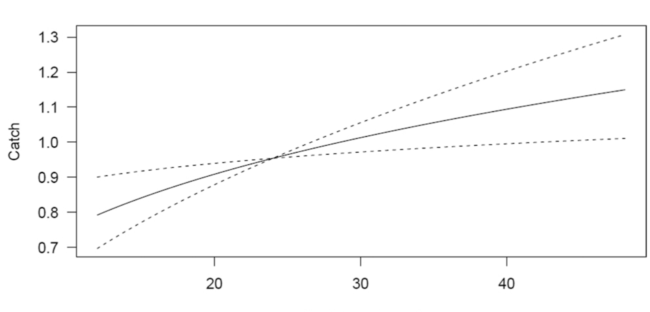


Fig. 4. Index of the feature specific model: Effect of Volume (top) and soak time (bottom).

Table 3
Estimated parameters from the feature specific model.

Parameter	Log estimate	SD	Estimate	Lo	Hi
Log(volume)	0.64	0.10	**1.89**	1.54	2.33
Log(hours/24)	0.27	0.09	**1.31**	1.09	1.57
Shape:Square	-0.92	0.18	**0.40**	0.28	0.57
Chamber	0.24	0.20	**1.27**	0.85	1.92
Chamber and funnel	0.73	0.20	**2.07**	1.39	3.09
Has 5 entraces	0.35	0.16	**1.42**	1.04	1.95
Placed as inner pot	-0.19	0.07	**0.83**	0.72	0.95
Short entrance length	0.36	0.17	**1.43**	1.01	2.01

4. Discussion

This study demonstrated the effect of pot design, placement, volume and soak time on catch rates of cod. Volume of the pot, presence of a holding chamber and soak time was significantly positively correlated with the catch rates. Also the number of entrances, entrance length and pot position in the chain were important features. While shape of the pot was significant in the model, this may not be a universal result as the square pots tended to tilt due to missing weight and insufficient float.

4.1. Pot size

Pot size had a significant positive effect on catch rates. This is important to fishers as fishing vessels often have limited space so pots should preferably be as small as possible without decreasing catch rates. Lower CPUE of smaller pots could be explained by a faster gear saturation where arriving fish stop prior to entering due to number of individuals already caught in the pot, or exit rates are increasing with numbers of fish already in the pot (Bacheler et al., 2013). The saturation effect will depend on the catch rate in the area and the estimate of 56% more catch when doubling the volume will depend on abundance of cod in the area and range of volumes investigated. Earlier pot trials have also indicated that larger pots are more efficient than smaller ones. Bagdonas et al. (2012) found that large pots (volume 14.4–19.2 m^3) caught more than twice as many cod as standard pots (volume 1.8 m^3). Munro (1974) also suggests that increased catches could be explained by the larger volume which makes it more difficult to locate the exits hence postponing gear saturation. To maximise vessel catch rates, fishers would need to calculate what is most economically valuable: many small pots with lower CPUE or fewer large pots with higher CPUE. The handling time of pots of different size was not recorded here, but as it is faster to handle small pots compared to large pots, this may also affect the optimal pot size for the fisher.

4.2. Pot Shape

The pot shape was important to catch rates and *Round_L* had significantly higher catch rates than *Square_L*. As the *Square_L* and *Square_M* had not been fishing properly, as indicated by mud on the sides, it is thus difficult to determine if this is a general result. The results do indicate that floats and weights are needed for the pots to be correctly positioned on the seabed. It is thus possible that square pots with appropriate floats and weighs will have higher catch than found during these trials if properly equipped with floats and weights. Furevik and Løkkeborg (1994) tested a circular pot in comparison to a number of rectangular cod pots and in their study, the circular pot had similar CPUE to the rectangular. However, in strong currents, the circular pod tumbled and thus did not fish efficiently. Other trials have used different shapes e.g., conical (Agnew et al., 2001; Clausen and Fujioka, 1985), chevron (Collins, 1990; Munro, 1983), Z-shaped (Munro, 1983; Whitelaw et al., 1991), D-shaped (Ljungberg et al., 2016; Wolf and Chislett, 1974) and rectangular (Bagdonas et al., 2012; Furevik and Skeide, 2003; Jørgensen et al., 2017; Westerberg et al., 2008). However, due to differences in other parameters than shape these different studies cannot be directly compared. The round shaped pot was not preferred by the fisher due to problems with handling the pot on board: round shaped pots are not easy to stack and move along the deck in bad weather. This indicates that other qualities than expected catch rates may affect the preferred pot shape.

4.3. Entrances

The critical phase in pot fishing is when the fish moves into the entrance area and increasing the number of entrances in pots on the seabed increased catch rates. *Round L-short5* had higher CPUE than *Round L-short3*, presumably due to a higher chance for one entrance to be oriented towards fish approaching. Previous studies of the number of entrances. Jørgensen et al. (2017) found higher catch rates of cod and haddock in floating pots with one entrance compared to floating pots with two entrances while Furevik and Løkkeborg (1994) found that floating pots with two entrances had higher catches of cod compared to pots with one entrance, while there was no change in the catch rates of cusk (*Brosme brosme*). Despite the contradictory results the logic in floating pots would be to have one entrance as number of entrances is likewise the number of exits and since floating pots can be turned with the current, fish would mainly come from one side supporting the choice of only one entrance. Bottom-standing pots could, however, benefit from more entrances as there will be a higher probability that one entrance is set in the current direction. However, it would be necessary to prevent catch escape through the multiple exits e.g. by use of a fish holding chamber.

Increased entrance length decreased catch rates significantly and *Round L-short3* (short entrances) had higher catch rates than the *Round L-Fun* (long entrances). However, the effect was only just significant. Li et al. (2006) also found short entrance lengths to have higher catches when investigating entrance lengths in round traps for Arabesque greenling (*Pleurogrammus azonus*) while Furevik and Løkkeborg (1994) found longer entrances to be more catch efficient. Chladek et al. (2021a) found no significant difference for the entry rates when testing long and short funnels. However, cod only exited only through the short funnel. It is possible that optimal entrance length differs according to target species.

Catch escape prevention features also impacted catch rates and the *Pentagonal_L* had significantly higher catches than the *Petagonal_L-Sun*. Others catch escape prevention measures include Neptune fingers providing increased cod catches in crab pots by Carlile et al. (1997) while Königson et al., (unpubl. data) found Neptune fingers to reduce cod catches in cod pots. Neptune fingers are stiffer than the spikes used here. Ljungberg et al. (2016) found that even though entrances with funnels induced a higher rate of cod swimming out of the entrance again and increased time when entering, funnels result in a higher net effect in catch. Our results, however, showed a lower catch rate when using both holding chamber and funnel compared to holding chamber alone. It, however, should be noted that we did not test funnels without holding chamber and interactions effects thus cannot be ruled out. Chladek et al. (2021b) has since found transparent acrylic fingers to present a promising new approach to increase pot-catch efficiency.

4.4. Catch holding chamber

The idea behind a catch holding chamber is to make it more difficult for the fish to find its way out and thereby retain the fish in the pot. In these trials, the effects of catch holding chambers were tested in two ways. First, the effect of catch holding chamber was tested in round pots. The results showed that pots without catch holding chambers had a significantly lower catch than pots with catch holding chamber. Second, *Pentagonal S* tested if the catch holding chamber could be placed vertical instead of horizontal. Video recordings of *Pentagonal S*, however, revealed that cod were moving freely between the two chambers (Hedgärde et al., 2016). The holding chamber design of the *Pentagonal S* had thus not worked properly as the cods could easily swim between the two chambers. Other studies of chambers confirm that holding chamber pots had higher catch rates of cod than one chamber pots (Furevik and Skeide, 2003) as two chamber pots have reduced catch escape (Munro, 1983).

4.5. Bottom-standing versus floating pots

Bottom-standing pot catch rates were higher than that of floating pots. Anders et al. (2016) revealed from video analysis that cod tended to approach a pot along the seabed. Thus, cod was more likely to encounter the bottom-standing pot than the floated pot, which supports the results that bottom-standing pots have higher catch rates. Floating pots can, however, have other benefits such a reduction in crab bycatches (Furevik et al., 2008). Königson et al. (2015a) also showed that floating cod pots can be seen as an alternative to gillnet and hook fisheries as floating pots with two chambers did during certain periods give equal catches per day as to commercial gillnet catches in the same area. However, in this study we designed the different pot types in the way we thought would be the most optimally for each type in order to catch most cod. E.g., a floating pot would not fish optimal with 4 entrances, as the cod will only use the one that is in the line with the current, and the others will only function as exits. Opposite to this a bottom-standing pot with one entrance would not fish optimal as the effect of placing the entrance in line with the current is small. The positioning of cod in the water column will, however, change with different oxyclines, haloclines and seasons (Schaber, 2011) and hence the relative catch rates of floating and bottom-standing pots may differ in areas with different hydrographic features.

4.6. Soak time

Catch rates increased with soak time and doubling soak time provided 22% higher expected catch. The catch curve did not reach a plateau at high soak times, possibly because only 5% soak times extended beyond 3 days. Königson et al. (2015a) found that catch rates increased until soak time reached 6 days while Furevik and Skeide (2003) found that soak times over 24 h did not increase catch rates. Bjordal and Furevik (1988) investigated soak times between 6 and 24 h but there was no correlation between catches and soak time. Furevik (1994) concluded that cod could survive in pots for long periods (20 days) and still be in good condition, though some cases the fishes will harm themselves and die within 2–3 days (Luckhurst and Ward, 1985). During long soak times isopods and amphipods have also been shown to harm catches (Agnew et al., 2001). Optimal soak-time, however, will depend on the bait's durability, area and the pot's ability to hold the catch and possibly also temperature as this will affect the energy expended by the cod in the trap.

As a final remark this is the most comprehensive study collected on cod pot modifications until date and the results are important in the search for finding alternative fishing gear to gillnets as pots can protect the catches against seal depredation. The study is unique as it can separate the relative effect of the factors like soak time, volume, shape and entrances. The main findings show that by doubling the volume and soak time one can increase the catches by 56% and 22% respectively and it underlines the importance of a holding chamber to increase the catches. It is although likely that fishers will have different preferences for pot design due to the amount of space and equipment arrangements onboard. Fishers tends not to like pots that are too big and especially the round shaped pot was not preferred by the fisher due to problems with handling as round shaped pots are not easy to stack and move along the deck in bad weather. This indicates that other qualities than expected catch rates may affect the preferred pot shape. It is, however, very important that the pots are made easily collapsible but also that they fit for the individual vessel. This will allow the fishers to continue fishing in areas of high seal density with static gear and hence low-carbon emission and minimum bycatch of marine mammals and sea birds.

CRediT authorship contribution statement

Lotte Kindt-Larsen: Idea, Data collection, Data analysis, Manuscript, Funding. **Casper W. Berg**: Data analysis, Statistical validation, Manuscript. **Maria Hedgärde**: Idea, Data collection, Data analysis. **Sara Königson**: Idea, Data collection, Manuscript, Funding.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgements

A very special thank you and in memory of fisherman Henrik Frigiof who worked with us during whole project. Henrik became a pioneer of cod pot fisheries in Denmark and never gave up. Klaus Hjort Hansen for working late hours, sharing ideas and manufacturing all pots. Anna Rindorf and Finn Larsen for reviewing the manuscript and contribution of helpful comments. Thank you to the two reviewers whose comments significantly improved the paper. All drawings of pots and pot features are made by Lotte Kindt-Larsen. The study was funded by GUDP (Grønt Udviklings-og Demonstrationsprogram) under the Ministry of Food, Agriculture and Fisheries of Denmark (Grant number 34009–14-0803) and the Swedish Agency for Marine and Water management through the 'Seals and Fisheries' Programme.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2023.106609.

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