Fisheries Research 288 (2025) 107470

Contents lists available at ScienceDirect

Fisheries Research

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

From semi-controlled environment to field trials: Testing pot entrance designs for Atlantic cod (*Gadus morhua*)

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ARTICLE INFO

Handles by Shannon Bayse

Keywords:
Alternative gear
Fish pots
Passive gear
Sealsafe fishing gear
Sustainable fishing

ABSTRACT

Gillnet fishing is associated with challenges, including bycatch of endangered, threatened, and protected (ETP) species and conflicts with marine mammals. Fish pots represent a sustainable alternative to gillnets due to their low bycatch risk of ETP species; furthermore, they can be designed to minimize seal predation. However, improvements in catch efficiency are necessary to enable their commercial implementation. Among the key factors influencing pot catch efficiency, the design of the pot entrance plays a crucial role. Therefore, optimizing the entrance is essential to improve catches. This study evaluated the catch efficiency of different experimental pot entrance designs under commercial fishing conditions (e.g., commercial fishing vessel and fishing grounds), building on findings from previous experiments in semi-controlled environments. We investigated the effects of entrance design parameters, including funnel netting colour, funnel length, and acrylic fingers as fish retention device on the catch rates of Atlantic cod (*Gadus morhua*). The colour of the funnel netting (transparent vs. white) had no significant effect on catch efficiency. In contrast, increased funnel length and the addition of acrylic fingers at the entrance significantly improved catch rates. Catch performance was also compared with a pot design used by a commercial fisher, which yielded higher catch rates than all experimental variants, indicating that design features beyond entrance configuration contribute to overall efficiency. These findings demonstrate the value of integrating semi-controlled experiments with field trials and the need for further design optimizations to support the development of more effective and sustainable fishing gear.

1. Introduction

Set nets, such as gillnets, are one of the most widely used fishing gear around the world, due to their affordability and easy handling (He, 2006). Although they are size-selective (Salvanes, 1991; Holst et al., 2002) and have little impact on the seabed (Savina et al., 2018), gillnet fishing is responsible for the bycatch of other species, including endangered threatened and protected (ETP) species such as marine mammals (Hamilton and Baker, 2019; ICES, 2023; Read et al., 2006; Reeves et al., 2013), diving birds (ICES, 2023; Sonntag et al., 2012; Żydelis et al., 2013), marine turtles (Lewison et al., 2014; Wallace et al., 2010) and elasmobranchs (Bradai et al., 2018; Camhi et al., 2009; Oliver et al., 2015). In the Baltic Sea, bycatches particularly affect harbour porpoises (*Phocoena phocoena*) (Carlen et al., 2021; Kindt-Larsen et al., 2023b; Owen et al., 2024), grey (*Halichoerus grypus)* (Vanhatalo et al., 2014) and harbour seals (*Phoca vitulina)* (Glemarec et al., 2021) and diving birds as the common eider (*Somateria mollissima*), great cormorant (*Phalacrocorax carbo*) and common guillemot (*Uria aalge*) (Glemarec et al., 2020).

Additionally, in some areas, gillnet fisheries face challenges with catch predation by seal species (Königson et al., 2015b), causing significant costs to coastal fishers due to catch loss and damage gears (Königson et al., 2007; Waldo et al., 2020). One fishery particularly affected is the Baltic Sea gillnet fishery (Glemarec et al., 2024; Königson et al., 2009). A potential solution to address both the bycatch of ETP species and seal depredation is the use of alternative fishing gear, such as fish pots (Kindt-Larsen et al., 2023a; Königson et al., 2015b; Shester and Micheli, 2011).

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https://doi.org/10.1016/j.fishres.2025.107470
Received 31 January 2025; Received in revised form 11 July 2025; Accepted 11 July 2025
Available online 15 July 2025

Pots are passive gears, consisting of a transportable enclosed structure with one or more entrances designed to allow target species, such as fish, crustaceans, or molluscs to enter while preventing their escape (Suuronen et al., 2012). Pots are classified as LIFE (low impact and fuel efficient) fishing gear, e.g. due to their low energy use and minimal seafloor impact compared to active fishing methods (Kopp et al., 2020; Shester and Micheli, 2011; Suuronen et al., 2012). They can be designed to reduce seal predation (Königson et al., 2015b) and can have a lower risk of bycatch of marine mammals and diving birds compared with other traditional fishing gear, including gillnets (Shester and Micheli, 2011). Pots can be made size selective in relation to target species by providing escape windows through which undersized individuals can escape (Ovegard et al., 2011). Furthermore, pots also hold live catches, allowing for the return of non-wanted specimens to the sea with a high chance of survival (Suuronen et al., 2012). In addition, the catch has minimal physical damage delivering products of high quality (Meintzer et al., 2018), which could lead to better market prices and hence economic benefits.

However, the efficiency of pots varies across fisheries and their targeted species. In some Caribbean pot fisheries, many different species are caught, and a pot is rarely lifted without fish in it (Earle, 1889; Munro et al., 1971). Nevertheless, in other fisheries such as the Baltic Sea cod pot fishery, catch rates are currently not commercially viable (Königson et al., 2015a). It is known that the design of the fishing gear has an important influence on catch efficiency (Meintzer et al., 2018). Multiple studies have focused on how pot design affects catch rate, investigating factors such as pot size (Hedgärde et al., 2016), shape (Kindt-Larsen et al., 2023a), position in the water column (e.g. bottom standing or floating pots (Furevik et al., 2008)), and the number and design of the entrances (Jørgensen et al., 2017; Ljungberg et al., 2016).

Studies have shown that the number of Atlantic cod (*Gadus morhua*, hereafter referred to as “cod”) that approach the pot is higher than the number of cod that finally enter (Meintzer et al., 2017), with the passage through the entrance funnel being the most critical event (Ljungberg et al., 2016; Thomsen et al., 2010; Valdemarsen et al., 1977), indicating that pot entrances are bottlenecks that limit the catch rate. The final catch in a pot is determined by the number of fish entering the pot versus the number of fish leaving the pot. The entry and exit rate is influenced by the entrance design (Chladek et al., 2021a). To reduce the exit probability, pots can be equipped with fish retention devices (FRDs) (Carlile et al., 1997; Chladek et al., 2021b), which allow fish to enter while impeding their escape and thus increasing catch efficiency.

Currently, there is no established commercial pot fishery in the Baltic Sea, and consequently, no standardized pot type is in use. However, some studies have explored the possibility of different cod pot types as an alternative to gillnets to avoid bycatch of ETP species and mitigate seal depredation (Kindt-Larsen et al., 2023a; Königson et al., 2015a; Stavenow et al., 2016). Additionally, some fishers have begun to test different pot designs on a trial basis. Often, these trials involve simultaneous changes to several design elements based on experience rather than systematic testing, making it difficult to isolate the specific design parameters responsible for differences in catch rates. Similar challenges have been observed in industry-led gear development processes, where simultaneous alterations to several gear features sometimes resulted in unexpected or even opposite effects (Veiga-Malta et al., 2019).

To understand the contribution of specific design changes, previous studies (Chladek et al., 2021a, 2021b) evaluated the entry and exit ratios of cod using different pot entrance designs. In their experiments, the authors used wide open entrances with white netting and a length of 50 cm as a reference design. They found that certain modifications increased catch efficiency: (1) changing the colour of the mesh to transparent increased cod passages into the pot, (2) increasing the length of the funnel reduced cod exits, and (3) adding a new FRD called acrylic fingers decreased cod exits without deterring entry. However, these experiments were conducted in a semi-controlled environment.

In this study, we investigated entrance designs previously tested by Chladek et al. (2021a), (2021b), aiming to evaluate whether their performance remains consistent in commercial fishery conditions. Specifically, we tested the following research questions:

i) Does changing the entrance colour from white to transparent increase the catch rate?

ii) Does increasing the length of the entrance funnel increase the catch rate?

iii) Does adding acrylic fingers as a FRD increase the catch rate?

iv) How do pots with experimental entrance designs perform compared to a fish pot design used by a commercial fisher?

2. Material and methods

2.1. Study area and investigation period

The field experiment was conducted in the Baltic Sea, northwest of the island of Bornholm, Denmark (Fig. 1), from March 9th to May 20th 2023. The fishing locations were on commercial fishing grounds with water depths between 18 m and 32 m. The selection of the fishing location and the execution of experiments were conducted in collaboration with a commercial fisher, experienced in set net and pot fishing operation using a small gillnet vessel (LOA: 9.10 m, engine power: 127 hp).

2.2. Experimental set-up

The set-up of the experiment (Fig. 2) consisted of 8 strings (A-H), each with 4 identical experimental pots but different entrance configurations (see specifications of entrance designs below). An additional pot used by a commercial fisher was added for reference in each string, making a total of 40 pots. All pots were bottom set. The position of the pots within each string was randomized at the beginning of the experiment and remained fixed throughout all deployments. The total length of the string was 300 m, with a distance of 50 m between the pots, and 2 m from each pot to the main line. To ensure the pots always landed in the correct upright position, the bridle and 10 floats (Castro ANULAR, buoyancy: 410 g) were attached to the upper side of each pot. Before deployment, each pot was baited with approximately one and a half frozen medium sized Atlantic herring (*Clupea harengus*, ~57–116 g) placed inside a bait bag (14 mm mesh size knot to knot; Wileman et al., 1996) hanging from the centre of the pot (approx. 25 cm off the bottom). Due to weather and operational conditions, strings were not deployed simultaneously. As a result, initial deployments and soak times differed between the strings (Appendix A1. Haul_overview).

2.3. Pot specifications, design of entrances and FRD

A one-chambered bottom standing pot design (85 cm wide, 110 cm long, and 70 cm high; Fig. 3, right) was selected to be used in this study (Kindt-Larsen et al., 2023a). Pots were built with a 10 mm stainless steel frame, and each frame bar was covered with 8–10 mm polypropylene (PP) rope to protect against abrasion. The pot is collapsible on deck for easy storage, but can be fixed to remain rigid in the water to prevent seal predation. This type of pot was being used by the fisher before the trials. However, since it was not possible to obtain the exact model, the experimental pots were built by a different manufacturer using the original as a template. Even though there is no current fishery using pots, we refer to the pot used by the fisher as "commercial pot". Both the experimental and commercial pots had the same dimensions and were covered with polyethylene (PE) netting with a 20 mm mesh size knot to knot (Wileman et al., 1996). However, they differed in the colour and twine thickness of the netting: the commercial pot used green PE netting with a 1.6 mm twine thickness, whereas the experimental pots used black PE netting with a 1.2 mm twine thickness (Table 1). This difference in netting material was not an intentional design variable but resulted from constraints in the materials available from the

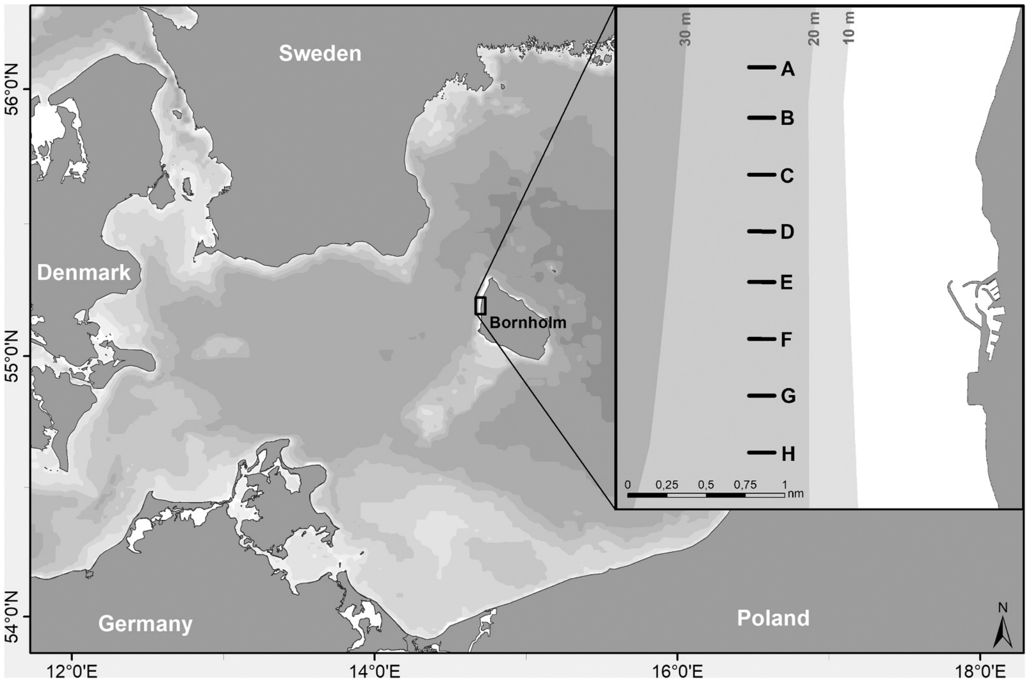

Fig. 1. Map of the Southern Baltic Sea and the fishing area northwest of Bornholm Island, Denmark (black square), with positions of the strings and depths in the fishing area.

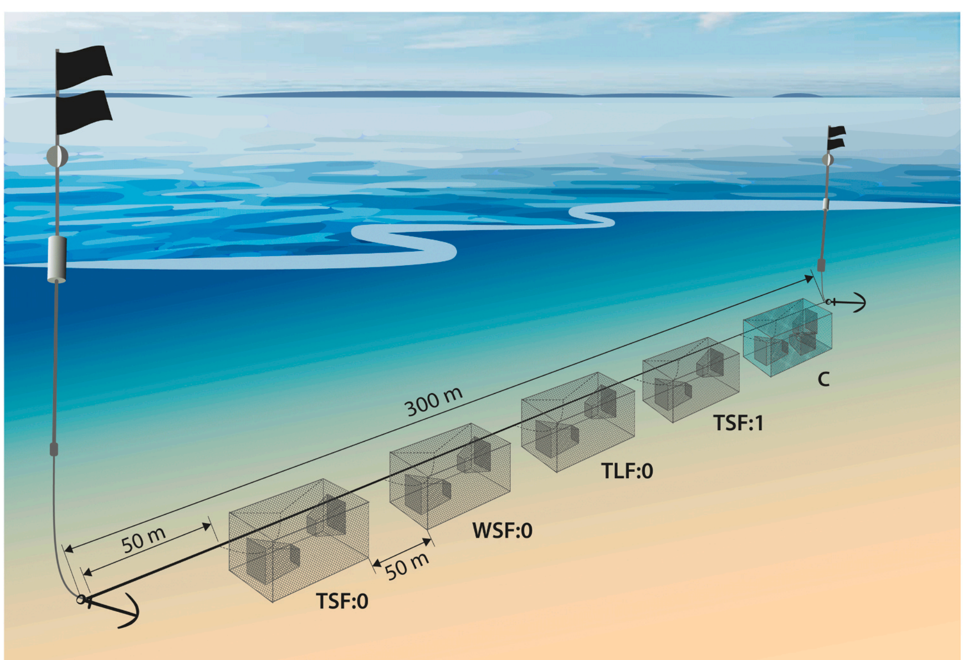

Fig. 2. Schematic drawing of one of the eight strings used in the study, showing the four experimental pot types used with different entrance designs (TSF:0: Transparent netting; WSF:0: White netting; TLF:0: Transparent netting + Long; TSF:1: Transparent netting + Fingers), and one Commercial reference pot (C). Pots used in each string were randomly distributed within each string. The distance between the pots and the main line, the separation between them and the total length of the string are shown in the drawing.

manufacturer. All pots were equipped with a 40 mm mesh size escape window covering a section of one side of the pot to exclude cod under 35 cm (Ovegard et al., 2011). One corner of the escape window was made of biodegradable cotton twine, which would degrade over time, thus preventing the pot from continuing to fish in the case of losing the gear.

The entrance designs of the four experimental pots were based on configurations previously tested by Chladek et al. (2021a), (2021b), who highlighted the potential of longer funnels and the use of transparent netting to improve pot performance. In this study, we evaluated two netting colours (transparent and white) and two funnel lengths (52 cm and 72 cm). One pot was also equipped with acrylic fingers as a FRD (Fig. 4, TSF:1).

The transparent entrance design (TSF:0; T = Transparent, S=Short

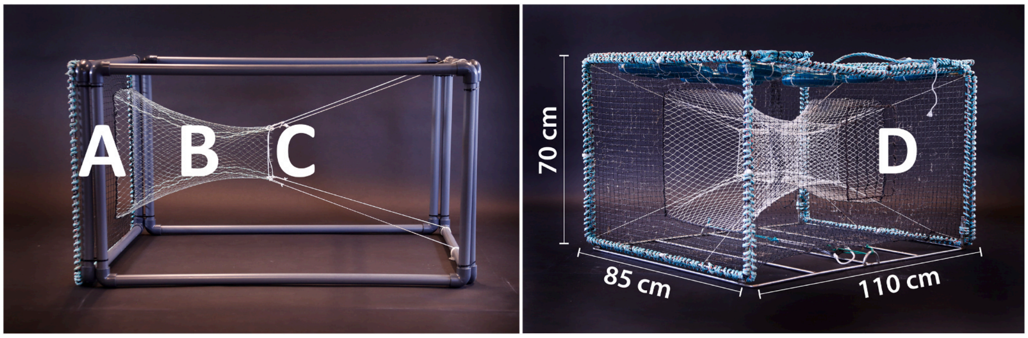

Fig. 3. Elements and dimensions of fishing pots used in the study. Picture left: nomenclature used for parts of pot entrance: A) outer opening; B) funnel; C) inner opening. For demonstration purposes, the entrance was mounted into a PVC model frame with the dimensions of the actual pots. In these cases, only one entrance is shown. Picture right: dimensions (height, width and length) of the experimental pot and escape window (D).

Table 1
Specification of pot and entrance designs, tested in commercial fishing operations.

Pot/entrance name	Transparent netting	White netting	Transparent netting + Long	Transparent netting + Fingers	Commercial reference pot
Acronym	TSF:0	WSF:0	TLF:0	TSF:1	C
Netting of pot chamber (colour, material, twine thickness, mesh size knot to knot)	Black, polyethylene (PE), 1.2 mm, 20 mm	Black, polyethylene (PE), 1.2 mm, 20 mm	Black, polyethylene (PE), 1.2 mm, 20 mm	Black, polyethylene (PE), 1.2 mm, 20 mm	Green, polyethylene (PE), 1.6 mm, 20 mm
Number entrances	2	2	2	2	3
Outer opening dimension	43 × 43 cm	43 × 43 cm	43 × 43 cm	43 × 43 cm	46 × 46 cm
Inner opening shape	Square	Square	Square	Square	Slit
Inner opening dimension	18 × 18 cm	18 × 18 cm	18 × 18 cm	18 × 18 cm	20 cm high
Funnel netting colour	Transparent	White	Transparent	Transparent	Green
Funnel length	52 cm	52 cm	72 cm	52 cm	30 cm
Fish retention device (FRD)	None	None	None	Acrylic fingers	Narrow/slit inner opening
Parameter tested	Control	Funnel netting colour	Funnel length	FRD	Inner opening shape/FRD, Funnel netting colour, Funnel length, netting of pot chamber

funnel, F:0 = no finger) was used as a reference for the comparison between the four experimental entrance designs (Table 1). Each experimental design differed from the reference in one parameter: funnel netting colour (WSF:0; W=White), funnel length (TLF:0; L=Long funnel), or the addition of a fish retention device (FRD), called acrylic fingers (Chladek et al., 2021b) (TSF:1; F:1 = Fingers). The inner opening of all four experimental entrances was wide open, with square dimensions of 18 × 18 cm (Table 1). Although a wide opening could potentially result in a high exit rate, and hence a rather low final catch rate, we used this design (Fig. 4) to ensure consistency with Chladek et al. (2021a). To prevent the entry of seals, all experimental fish pots were equipped with a non-stretchable rope as seal exclusion device (SED) to limit the opening of the inner entrance to a diameter of 20 cm (Königson et al., 2015b).

An additional pot used by a commercial fisher was added to each string as a reference. The entrances of this commercial pot were made of green polyethylene netting with a slit-shaped inner opening of 20 cm height and a funnel with 30 cm length. A metal ring with a 20 cm diameter as SED was added to the funnel to prevent the entry of seals (Königson et al., 2015b).

2.4. Data acquisition

The experiment and data acquisition were conducted through assisted self-sampling, where the fisher followed a protocol to record the date, time, soak duration, depth and catches (number of individuals by species) for each pot in every string. A scientist occasionally joined the fisher to provide support and ensure protocol compliance. After data acquisition, all individuals were released alive at sea.

The boat was equipped with a GPS logger (Renkforce GT-730FL-S, Hirschau, Germany) to record the position of each string. Five data loggers (Onset® HOBO® U20L-02; Onset Computer Corp., Pocasset, MA, USA) were attached to five of the pots to measure the depth and temperature. Additionally, one oxygen data logger (miniDOT®, PME MiniDOT; Vista, CA, USA) was attached to one of the pots to record dissolved oxygen in the area at fishing depth. To get a closer view of the performance of the FRD, a camera (Insta360 ONE RS; Shenzhen, China) was occasionally placed inside the pot. It was connected to a Lithium-ion Battery (14.8 V, 18 Ah, 266 Wh; Blue Robotics, Torrance, CA, USA) to extend the camera operation time and record up to 46 h.

2.5. Data analysis: models for cod catches

The cod catches (number of fish) obtained during the commercial fishing trials were modelled using Generalised Linear Mixed Models (GLMM) for count data. The initial GLMM used a log link function assuming a Poisson distribution for the response variable, and the following fixed effects structure:

$$\text{Log (nCod)} \sim \text{intercept} + \text{pot} + \text{temperature} + \text{depth} \quad (1)$$

In Eq. 1, *pot* is a categorical variable quantifying the effect of the different entrance pot designs on the expected cod catches. The environmental factors *temperature (°C)* and *depth (m)* were included as continuous covariables due to their potential influence on cod catches, as suggested by previous studies (Li et al., 2018; Righton et al., 2010; Wang et al., 2014). Soak time was included in the full model as offset. Consequently, model outputs are scaled in terms of catch per unit effort (n x hour^{-1}). Two random effects were added to the model structure allowing random variation of the intercept. One of the random effects considered was the grouping factor *trip,* which accounts for unexplained

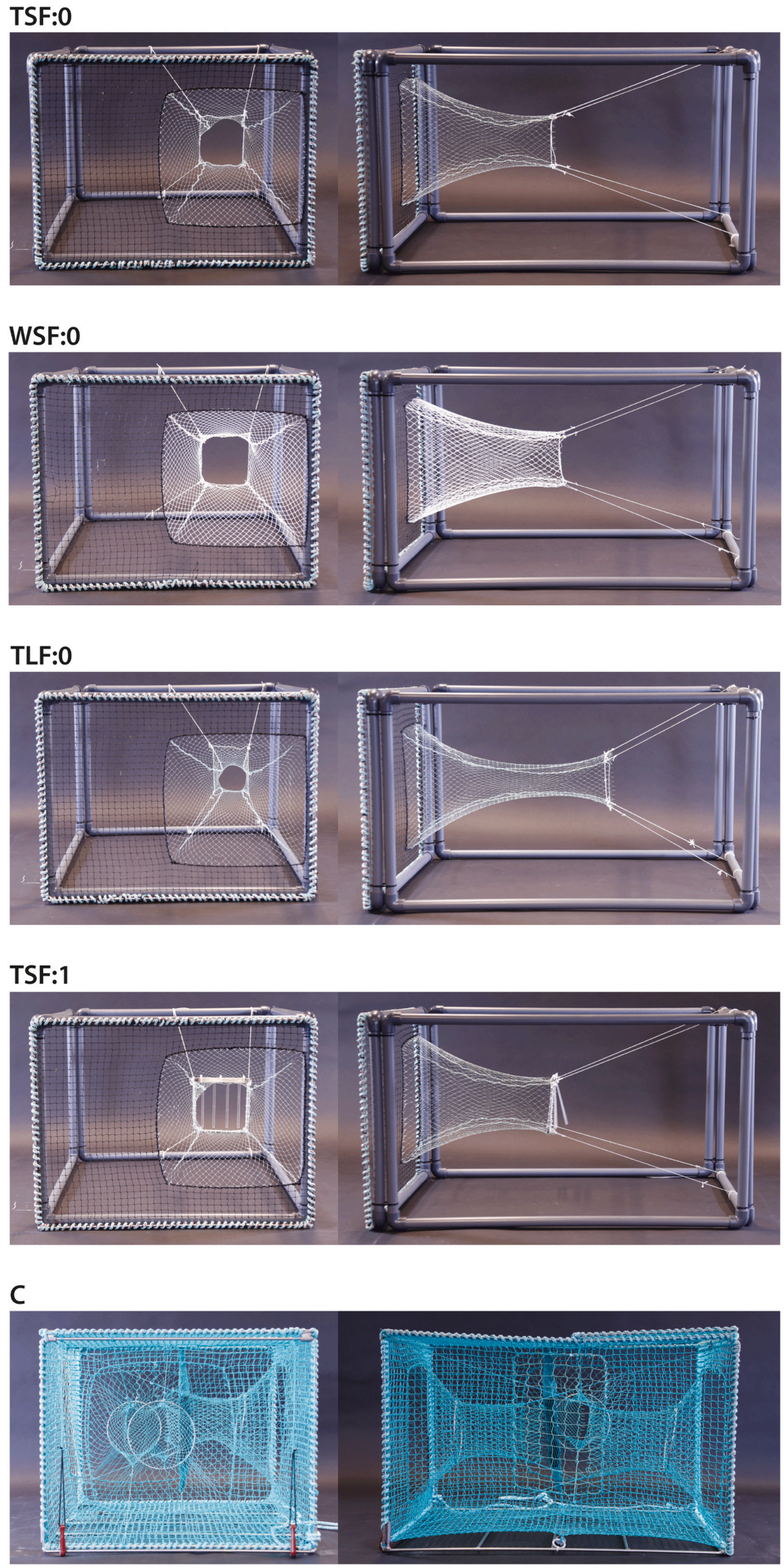

Fig. 4. Entrance designs tested during fishing. Left: Front view; Right: lateral view. From top to bottom: (TSF:0: Transparent netting; WSF:0: White netting; TLF:0: Transparent netting + Long; TSF:1: Transparent netting + Fingers; C: Commercial reference pot). For the experimental pots (TSF:0, WSF:0, TLF:0, TSF:1) the entrances were mounted into a PVC frame with the dimensions of the actual pots and only one entrance is shown for demonstration purposes.

variation in cod catches observed across fishing trips. The second random effect was *string*, accounting for variation in catches across pot strings. The latter random effect was added to the model without considering its nested structure within *trip*. Consequently, the nested codification of *string* within *trip* was avoided by using a unique identifier for every string deployed, so each identifier would only occur once. Simpler random effect structures were evaluated by excluding one of the two sampling levels from the random structure.

By removing one or more fixed effects specified in Eq. (1), seven additional simpler models were estimated. All eight models were considered potential candidates for modelling the catch data collected during the sea trials and therefore estimated and ranked by decreasing Akaike Information Criterion, AIC (Akaike, 1974).The model with the lowest AIC was selected for further analysis. The model diagnosis was made by examining the distribution of the residuals and possible over-dispersion. If the model showed signs of overdispersion ($\frac{deviance}{d.o.f} >> 1.0$), a negative binomial distribution would be considered as an alternative assumption for the response variable.

To assess the ability of the best candidate model to describe the data, the marginal predictions of cod catches and associated 95 % confidence intervals (CI) were estimated and plotted against the empirical catch data. Additionally, prediction intervals (PI) accounting for all three sources of variation in the model (fixed effects, random effects and model residuals) were constructed using the percentile method (Efron, 1979) on simulated prediction distributions generated using parametric bootstrapping. If pot design was retained in the fixed effects structure of the best candidate model, an evaluation of differences in catch efficiency among the different pot designs was performed using pairwise Tukey's post-hoc test (Tukey, 1949).

A pairwise Tukey post-hoc test was performed using the selected model to compare the effects of different pot entrance designs on cod catches. Pairwise comparisons between entrance designs were standardized by fixing the soaking time at 47 h, corresponding to the median soaking time across all pots. Tukey's pairwise comparison is based on the ratio of the average catches predicted by the model for the two entrance designs being evaluated. A ratio below one indicates that the entrance design taken as test in the numerator is less efficient at catching cod compared to the reference entrance design taken as reference in the denominator. When comparing the transparent reference entrance design (TSF:0) with the other experimental designs, only one factor differed between each pair (funnel netting colour, funnel length or the addition of an FRD), enabling the isolation of each factor's influence on cod catch rate.

The GLMMs described above were fitted using the lme4 package (v. 1.1–35–1) (Bates et al., 2015) in R (v. 4.2.1) (R Core Team, 2023). The bootstrap-based 95 % marginal PIs were built using the parametric bootstrapping and simulation facilities provided by the lme4 package. The packages DHARMa (v. 0.4.6) (Hartig, 2024) and emmeans (v. 1.10.5) (Searle et al., 1980) were used for model diagnosis and Tukey's post-hoc tests, respectively.

3. Results

3.1. Description of fishing operations and catches

Between March and May 2023, a total of 218 strings with 5 pots each (four experimental pots of each entrance design and a commercial reference pot, Table 1) were hauled, resulting in 1090 fished pots. The target species of this study was cod, with a total of 1673 individuals caught (Table 2). Other caught species were: 68 European plaice (*Pleuronectes platessa*), one eelpout (*Zoarces viviparus*) and one sea scorpion (*Myoxocephalus scorpius*). All specimens captured were alive and active when the pots were hauled. No bycatches of seals, porpoises, seabirds or other ETP species were recorded. Detailed information about haul specifications (trip, string, date, depth, temperature, soaking time) and catch numbers of cod and other species for each pot and trip are given in the supplementary material (Appendix A1:Haul_overview).

Table 2
Catch of cod in each pot entrance design.

Entrance	Cod (n) Total	Mean number of cod (n) per pot per trip (min-max)
Transparent netting (TSF:0)	93	0.43 (0 – 4)
White netting (WSF:0)	116	0.53 (0 – 6)
Transparent netting + Long (TLF:0)	165	0.76 (0 – 7)
Transparent netting + Fingers (TSF:1)	193	0.89 (0 – 5)
Commercial reference pot (C)	1106	5.07 (0 – 16)
Total catch	1673	

The highest catches were obtained by the commercial reference pot (C) with a total of 1106 cod (Table 2). From the four experimental entrance designs tested (TSF:0, WSF:0, TLF:0, TSF:1), the entrance design Transparent netting + Fingers (TSF:1) had the highest catch of cod with a total of 193, followed by the Transparent netting + Long (TLF:0) entrance with 165 cod. The White netting entrance (WSF:0) caught 116 cod and the reference Transparent netting entrance (TSF:0) 93 cod.

The median soak time was 47 h, ranging from 4 h to 149 h, due to practical reasons, e.g. bad weather, skipper decision and practical operation. The median fishing depth was 23 m with a minimum of 18 m and a maximum of 32 m, with the maximum depth difference in one string being 6 m. The temperature ranged from 4°C at the beginning of the experiment, to 8°C at the end, with a median of 6°C. The minimum dissolved oxygen (DO) level recorded during the entire period at fishing depths was 8.5 mg/l, which does not fall below any critical levels for cod survival (Plante et al., 1998).

Cameras were installed on three occasions inside a pot with the entrance design Transparent netting + Fingers (TSF:1). Bad weather and poor visibility limited the video collection. Consequently, the short available video recordings do not allow sufficient analysis of cod behaviour. However, the footage that was collected revealed that the acrylic fingers used as FRD did not always function consistently, as they occasionally failed to maintain verticality, leaving the entrance partially open. Additionally, some cod appeared to hesitate or abort entry, seemingly due to the presence of the FRD. Videos also showed that most cod swam against the current when approaching the pots. Finally, seals were occasionally observed in the experimental fishing area.

3.2. Models for cod catches

The full model (Eq. 1) and related simpler models were successfully fitted to the data without convergence issues. An inspection of fit statistics related to the fitted models showed a ratio between model deviance and d.o.f below 1.3. Therefore, model overdispersion was not considered a concerning issue and the assumption that the cod catches followed a Poisson distribution was kept. Simpler models resulting from the removal of one of the random effects considered (*trip* or *string*) led to a much poorer model fit. Therefore, the original random effects structure with *trip* and *string* being included independently in the model was considered the best one to account for natural variation in cod catches not explained by the fixed effects included in the models.

All top four model candidates included pot as a fixed effect, while leaving out the *pot* variable implied a drastic worsening in model fit (Table 3). Therefore, these results reveal pot design to be a relevant factor influencing cod catches. The model with the lowest AIC among the top four model candidates included only pot design as fixed effect (model 1). Although models 2 and 3 showed slightly lower deviance than model 1, the limited power of temperature and depth as explanatory variables did not overcome the preference of AIC for simpler model

Table 3
Model selection table showing the fitted models ranked by AIC. The best candidate model with the lowest AIC is highlighted in bold.

	Fixed effects			Fit statistics		
Model ID	Pot	Temperature	Depth	Deviance	AIC	dAIC
1	**x**			**3117.5**	**3131.5**	**0.0**
2	x		x	3116.2	3132.2	0.7
3	x	x		3117.4	3133.4	1.9
4	x	x	x	3134	3116	2.6
5				4832.465	4838.465	1707.0
6			x	4831.2	4839.2	1707.7
7		x		4832.4	4840.4	1708.9
8		x	x	4841.0	4831.0	1709.5

structures. Consequently, model 1 was ultimately selected as the best candidate and used for further analysis.

The selected model described well the catch rate of the different pot entrance designs (Fig. 5). Predictions were generated using the median soaking time during the trials (47 h). For the Transparent netting (TSF:0) entrance design, the predicted catch was 0.30 cod/pot (PI: 0.02–4.45). The White netting (WSF:0), had a predicted catch of 0.37 cod/pot (PI: 0.02–5.54), while the Transparent netting + Long (TLF:0), resulted in a predicted catch of 0.53 cod/pot (PI: 0.04–7.86). For the Transparent netting + Fingers (TSF:1), the predicted catch was 0.62 cod/pot (PI: 0.04–9.19). The commercial reference pot (C), had the highest predicted catch 3.54 cod/pot (0.24–52.53). Overall, CIs, data prediction and PIs provided by the selected model fitted successfully with the registered data. The distribution of the residuals of the selected model did not show any worrying deviations or systematic trends, nor did it suffer from overdispersion.

The Tukey post-hoc test comparison (Table 4) between the Transparent netting (TSF:0) and the White netting (WSF:0) entrance designs showed no significant differences in relative catch rates, suggesting that colour alone does not affect catch rate. When comparing the Transparent netting (TSF:0) with the Transparent netting + Long (TLF:0) entrance design significant differences were found. The ratio (TSF:0 / TLF:0 = 0.564) indicated that increasing the funnel length increased the relative catch rate. Similar results were found when comparing the White netting (WSF:0) with the Transparent netting + Long (TLF:0) entrance. Pairwise comparisons between the Transparent netting (TSF:0) and the

Table 4
Pairwise comparisons of expected cod catch rates of different pot entrance designs (TSF:0: Transparent netting; WSF:0: White netting; TLF:0: Transparent netting + Long; TSF:1: Transparent netting + Fingers; C: Commercial reference pot) and their associated p-values. Comparisons were standardized by fixing the soaking time at 47 h. Ratios below 1 indicate lower catch rates for pot type in the first column (reference) compared to the second (test), while ratios above 1 indicate higher catch rates. Significant results are marked with asterisks according to significance levels (*** $p < 0.001$, * $p < 0.05$).

Reference design (numerator)	Test design (denominator)	ratio	p-value
TSF:0	WSF:0	0.802	0.482
TSF:0	TLF:0	0.564	***0.001
TSF:0	TSF:1	0.482	***< 0.001
WSF:0	TLF:0	0.703	*0.025
WSF:0	TSF:1	0.601	***0.001
TLF:0	TSF:1	0.855	0.555
TSF:0	C	0.084	***< 0.001
WSF:0	C	0.105	***< 0.001
TLF:0	C	0.149	***< 0.001
TSF:1	C	0.175	*** < 0.001

Transparent netting + Fingers (TSF:1) entrance showed significant differences. The ratio (TSF:0 / TSF:1 = 0.482) indicated that adding a FRD increased the relative catch rate. Similar findings were observed when comparing the White netting (WSF:0) with the Transparent netting + Finger (TSF:1) entrance design. Finally, no significant differences were found when comparing the Transparent netting + Long (TLF:0) with the Transparent netting + Fingers (TSF:1) entrance design.

Pairwise comparisons showed that the commercial reference pot (C) had significantly higher catch rates than all experimental pots. However, when comparing the commercial reference pot with the experimental pots, more than one factor differed between designs, preventing the isolation of specific factors influencing cod catch rate.

4. Discussion

This study assessed the effects of entrance design modifications on the catch rate of fish pots under commercial fishing conditions. Building on previous semi-controlled net pen experiments (Chladek et al., 2021a, 2021b), we tested the influence of funnel netting colour, funnel length,

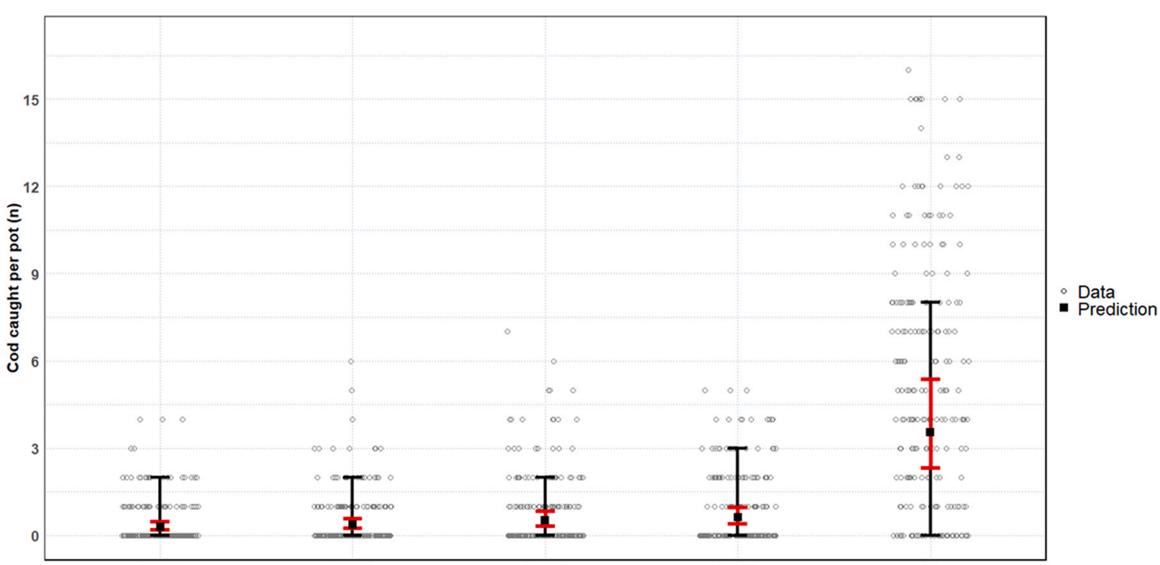

Fig. 5. Cod catch comparison for the four experimental pot entrance designs tested (TSF:0: Transparent netting; WSF:0: White netting; TLF:0: Transparent netting + Long; TSF:1: Transparent netting + Fingers), the Commercial reference pot (C) and their predictions based on the selected GLMM. The 95 % confidence interval (CI) and predicted interval (PI) of the predicted values are represented by the red and black lines, respectively. Predictions were made using the median soaking time during the trials (47 h).

and the inclusion of acrylic fingers as a FRD. While funnel netting colour (transparent vs. white) had no significant effect, both increased funnel length and the use of acrylic fingers were associated with higher catch rates. These findings are consistent with results from earlier experimental studies and highlight the importance of validating gear modifications under field conditions to ensure practical applicability. The consistently higher catch rates observed for the commercial pot design relative to the experimental variants suggest that additional design parameters may be critical. Further research into the interaction between pot design features and fish behaviour is needed to enhance catch performance and support the development of fishing gear that is both effective and sustainable by minimizing bycatch of non-target and protected species.

The present study did not find significant differences in the catch between entrances with transparent and white netting (TSF:0 vs WSF:0). Consequently, no effect of colour on the final catch efficiency was found. In contrast, Chladek et al. (2021a) found that the colour of the funnel netting influenced the number of behavioural interactions between cod and pot entrances as well as the entry and exit rates through the entrances. The funnel with transparent netting had a higher number of interactions and higher entry rates compared to the funnels with white or green netting. On the other hand, the exit rates were higher, resulting in lower overall catch efficiency. However, differences in the conditions of the two experiments may be a potential explanation. While Chladek et al. (2021a) conducted their experiment in a controlled environment at 3 m depth, the present experiment was conducted under fishing conditions in the open Baltic Sea at depths between 20 and 30 m. At different depths, the colour changes and so does the perception by the fish (He, 2010). The significantly higher catch rates obtained by the commercial reference pot are most likely not explained by the green colour of the entrance, as demonstrated in this study and Chladek et al. (2021a).

In this study, we found that increasing the funnel length, from 52 to 72 cm (TSF:0 vs TLF:0) significantly increased the relative catch efficiency in experimental pots, which almost doubled (TSF:0 = 0.30 cod/pot vs TLF:0 = 0.53 cod/pot). This is consistent with the findings of Chladek et al. (2021a), who found that the exit probability decreased significantly when the length of the funnel was increased. This led to an approximate doubling of the final catch efficiency of the long funnel compared to the standard funnel in their study. In contrast, the commercial reference pot has an even shorter funnel length (30 cm). Giving the results from this study, Chladek et al. (2021a) and Furevik and Løkkeborg (1994), the significantly higher catch rates obtained by the commercial reference pot are most likely not explained by the funnel length. On the other hand, Kindt-Larsen et al. (2023a) found that increasing funnel length decreased catch rates for cod in round pots. But these findings may be due to the shape of the pot used and the behavioural diversity among cod individuals (Meager et al., 2018).

It should be considered that while increasing funnel length could improve catch efficiency, there are practical limits. For instance, an excessively long funnel may cause fish to turn around before finally entering the pot. In addition, the observations of Chladek et al. (2021a) suggest that cod inside the pot often follow a search pattern guided by the net wall and frequently touch the net with their snout or pectoral fins. If the funnel is too long and the inner opening is therefore too close to the wall of the pot, cod can find the exit more easily, which increases the exit probability. Furthermore, a long funnel reduces the available space inside the pot. Several studies indicate that larger pots with more volume capture more fish (Bagdonas et al., 2012; Hedgärde et al., 2016; Kindt-Larsen et al., 2023a). The optimum funnel length should therefore be long enough to increase the retention probability of the pot, but not excessively long in relation to the pot dimensions.

The addition of acrylic fingers as a retention device to the transparent netting entrance (TSF:0 vs TSF:1) resulted in a significantly increased catch rate. Moreover, the pots with entrances made of transparent netting and acrylic fingers (TSF:1) yielded the highest catches among the four experimental entrance designs tested. These results are consistent with the findings of Chladek et al.(2021b), who found that the exit probability decreased significantly when acrylic fingers as FRD were added to white funnels. Similarly, Carlile et al. (1997) found that modified crab pots equipped with FRDs caught more Pacific cod (*Gadus macrocephalus*) than pots without FRDs.

However, it should be noted that while FRDs are beneficial in preventing fish from escaping, they can also deter fish from entering the pot (Salthaug, 2002; Winger et al., 2016), thereby decreasing the catch rate. Although Chladek et al. (2021b) stated that the transparent fingers would not deter fish from entering, video observations of our experiment indicated that some cod actually saw the FRDs and subsequently avoided entering. It is plausible that the cod perceived the FRDs or the metal structure to which they are attached, which may have deterred them from entering the pot. Camera recordings also revealed that the acrylic fingers were not effective throughout. During periods of strong currents, the fingers can lift, creating a partially open entrance and allowing the cod to exit. Similarly, gravity caused the fingers to open when the pots were not placed horizontally but on a rock, for example. These FRDs, therefore, need to be optimised for future use in commercial fishing.

The commercial reference pot did not include an FRD. However, its slit-shaped inner entrance opening may have reduced the cod exit rate. Consequently, the significantly higher catch rates obtained by the commercial pot are most likely explained by this narrow funnel design, which differed from the wide, square openings used in the experimental pots. That would be consistent with the results of Furevik and Løkkeborg (1994) and Chladek et al. (2021a), who observed that narrow entrances make it more difficult for cod to escape. On the other hand, narrow entrances can also reduce the entry of cod into the pots. Pol et al. (2010) found that cod do not like to pass through narrow entrances. Notably, Chladek et al. (2021a) tested narrow entrances under semi-controlled conditions, observed low catch efficiency and advised against their use. Despite this, a similar entrance design used by a fisher in the present study yielded the highest catch rates. This apparent contradiction suggests that additional factors beyond entrance design, such as overall pot design, environmental conditions, fish behaviour, and fisher operations, which cannot be fully replicated in controlled settings, may also influence cod catch rates. Therefore, combining semi-controlled experiments with field trials is advisable to fully evaluate entrance modifications and ensure their practical applicability.

Another factor that may have contributed to the higher catch rate of the commercial pot was the fact that it had three entrances, whereas the experimental pots had only two. Several studies found that increasing the number of entrances increases the catch rate (Furevik and Løkkeborg, 1994; Kindt-Larsen et al., 2023a; Meintzer et al., 2017). Likely because fish tend to swim against the current following the smell of the bait and having more entrances increases the chance for one entrance to be oriented towards the approaching fish (Løkkeborg et al., 1989; Meintzer et al., 2017; Valdemarsen et al., 1977). In our video observations, we could also confirm that cod approached the pots against the current. Another difference between the commercial and experimental pots was the colour and thickness of the pot chamber netting, which may have influenced the visual contrast between the entrance and the pot chamber. The commercial pot used green and thinner netting, matching the entrance colour, while the experimental pots used thicker black netting that contrasted with the white or transparent entrances. He (2010) emphasized that the visual contrast of the fishing gear against its background is crucial and suggested that it was more important than how bright the gear is.

5. Conclusion and outlook

In this study, we compared how specific entrance design parameters (colour, length and the addition of a fish retention device - FRD) affected catch rates in experimental pots. Differences in catch rates were found for funnel length and the use of FRD, confirming previous experiments in semi-controlled net enclosures.

In addition, the use of a commercial reference pot resulted in more efficient catch rates than those observed in the experimental pots. This outcome was anticipated, given the design of the experimental pot entrances with their wide opening. A logical subsequent step would be to assess whether narrowing the experimental entrances could enhance cod catches. In particular, it would be of interest to determine whether the long funnel entrance, which demonstrated the highest catch rates among the experimental entrances, would further increase catches if closed, potentially exceeding those observed in the commercial reference pot. It would be advisable for future studies to systematically quantify fish entry and escape rates to enhance understanding of the mechanisms driving the changes in catch efficiency.

This study focused solely on cod catches. However, due to the poor state of cod stocks in the Baltic Sea (ICES, 2024a, 2024b), fishing for cod is no longer viable. For this reason, fishing is increasingly switching to other species such as flatfish. Although the entrances tested in this study were specifically designed for cod, they also incidentally caught some flounder. This suggests that fish pots may also have potential for catching flatfish. Further research should investigate how entrance designs could be modified to better suit the morphology and benthic behaviour of flatfish.

All fish were caught alive, resulting in high-quality catches with minimal physical damage, a crucial factor that could increase the market value and economic benefits for fishers. Bycatch of non-target fish species was low, and those occasionally caught could be returned alive to the sea, underlining the minimal environmental impact of this gear. Another factor contributing to the sustainability of this gear is the reduced risk of bycatch of ETP species, as none were caught with any of the pots used. This was supported by video recordings showing the presence of seals in the experimental fishing grounds, although no predation of the catch, gear damage or seals caught in the gear were observed. In contrast, fishers using gillnets in the same fishing area reported cod predation and damage to nets by seals. This highlights that pots could be a viable alternative to gillnets in areas where seal predation is a significant problem, thereby reducing conflict and economic losses.

CRediT authorship contribution statement

Sara A. Berzosa: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Thomas Noack:** Writing – review & editing, Visualization, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Lotte Kindt-Larsen:** Writing – review & editing, Resources. **Peter Ljungberg:** Writing – review & editing, Resources. **Flemming Dahlke:** Writing – review & editing, Supervision. **Daniel Stepputtis:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Andrea M. Milanelli:** Writing – review & editing. **Juan Santos:** Writing – review & editing, Validation, Software, Methodology, Formal analysis, Data curation. **Uwe Lichtenstein:** Writing – review & editing, Resources, Methodology.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGTP in order to improve language clarity and grammar. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Funding

The study was funded by the German Federal Agency for Nature Conservation (Bundesamt für Naturschutz, project no. 3521892012, Entwicklung und Erprobung von Fangtechniken zur Minimierung der Konflikte zwischen der Stellnetzfischerei und Zielen des Meeresnaturschutzes in der deutschen AWZ der Ostsee, mit Fokus auf Beifangvermeidung von Meeressäugetieren und Meeresvögeln — STELLA2).

The Deutsche Wildtier Stiftung contributed to the project by funding the further education of the lead author.

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 would especially like to thank the fisher Arki Munch Petersen for his dedication and hard work in conducting the fishing trials, Michael Dahse for his technical assistance and support during the development, set-up, and execution of the experiment and Annemarie Schütz for the figure illustrations.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2025.107470.

Data availability

The data that supports the findings of this study are available in the supplementary material of this article.

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