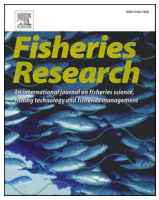
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Full length article



# PearlNet performance: Catch efficiency and practicality of a potential odontocete bycatch reduction tool in set net fisheries

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ABSTRACT

Incidental capture in fishing gear, especially in bottom set nets, represents a significant cause of mortality for odontocete worldwide. Given that these species depend on echolocation for spatial orientation and prey detection, the PearlNet aims to mitigate this impact by enhancing the acoustic visibility of nets through the incorporation of small acrylic glass spheres in standard nets. This modification can potentially enable odontocetes to recognize them as a physical barrier, which may lower the risk of unintended interactions. However, for mitigation measures to be implemented in commercial fisheries, they must not compromise fishing performance. This study aimed to evaluate the PearlNet's relative catch efficiency on fish species and handling time in a commercial fishery in the Baltic Sea. Plaice and flounder were the most abundant species caught during the trials. The catch efficiency of the PearlNet relative to standard nets for these species was, respectively, 106.49% (95% CI: 99.72–113.84) and 101.08% (95% CI: 94.33–110.40), revealing similar catch efficiency between gears. Furthermore, the PearlNet did not affect the handling time of the gear. These results confirm the feasibility of using PearlNets, which will facilitate future studies evaluating the effectiveness of PearlNet in reducing odontocete bycatch in commercial fisheries.

## 1. Introduction

Set nets, such as gillnet and their variations (e.g., trammel nets), contribute about 10 % of the total fish landings worldwide (He et al., 2021) but are linked to high bycatch rates (Pérez Roda et al., 2019). This includes marine mammals (Hamilton and Baker, 2019; Read et al., 2006; Reeves et al., 2013), sea birds (ICES, 2023; Sonntag et al., 2012; Žydelis 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). Especially for toothed whales (*Odontoceti*), bycatch is considered one of the most serious direct threats worldwide (Hamilton and Baker, 2019; Sonne et al., 2024; Wade et al., 2021). A possible reason for their entanglement in set nets is the poor acoustic visibility of the netting, which reduces the whales' ability to detect it through echolocation (Goodson, 1997). Consequently, the distance at which the whale detects the net is usually very short (Kastelein et al., 2000), limiting the reaction time. This can lead to entanglement and subsequent asphyxiation (IJsseldijk et al., 2021).

Various mitigation strategies have emerged (Lucas and Berggren, 2022), including acoustic deterrent devices (so-called Pingers) (EU, 2019) and improvement of the acoustic visibility of the net. Pingers are used to scare the animals away from the net and have demonstrated positive results in reducing odontocete bycatch (Dawson et al., 2013; Lucas and Berggren, 2022; Omeyer et al., 2020; Paitach et al., 2022), but may also cause habitat exclusion (Amano et al., 2017; Carlström et al., 2002; Cox et al., 2001) and behavioral changes. Furthermore, habituation and population effects have been suggested (Beest et al., 2017; Cox et al., 2001; Kindt-Larsen et al., 2019). Alternatively, it was proposed to increase the acoustic reflectivity of the nets using materials like barium sulfate or iron oxide (Koschinski et al., 2006; Mooney et al., 2007; Trippel et al., 2003). Although trials conducted in Canadian gillnet fisheries showed a reduction of harbor porpoise (*Phocoena phocoena*)

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bycatch (Koschinski et al., 2006; Trippel et al., 2009, 2003), it was unclear whether visibility or net stiffness was responsible for the results. Furthermore, this mitigation tool was ineffective for other odontocete species (e.g., *Pontoporia blainvillei* (Bordino et al., 2013)), and it can reduce the catch of target species (Larsen et al., 2007).

A recent study by Kratzer et al. (2020) has shown that changing the material properties of the yarn has a limited effect on the reflectivity. Consequently, they explored the possibility of increasing the acoustic reflectivity of bottom set nets by adding objects with strong echo properties and developed the so-called PearlNet. The PearlNet was thought to increase the detectability of the netting, potentially allowing the whales to recognize it as an impenetrable barrier and consequently being able to avoid it. Using a comprehensive simulation study, they found that spheres made of acrylic glass (Polymethyl methacrylate, PMMA) have a strong acoustic target strength due to resonance effects. The resonance depends on the sphere's size and the sound's frequency (Kratzer et al. 2020, 2022). Therefore, the acoustic properties of the PearlNet can be adjusted to different echolocation frequencies of other odontocete species by changing the size of the sphere.

Following Lucas and Berggren (2022), bycatch mitigation tools should be effective in bycatch reduction but also support sufficient catches of commercial species. Consequently, studies proving that a modified gear does not affect the catch efficiency of target species, fishing strategies and effort invested are a first step to verify if the PearlNet is reducing odontocete bycatch. Comparative studies evaluating the catch performance of the PearlNet relative to standard nets have been conducted in the Turkish Black Sea (Kratzer et al., 2021) and the Danish Baltic Sea (Kindt-Larsen et al., 2024). In Turkey, however, the limited amount of data prevented a statistical evaluation of the PearlNet's effect on catches. In Denmark, the study found no significant difference in catches of cod (*Gadus morhua*) between the PearlNet and standard nets. However, that study did not include species-specific analyses for flatfishes, a key target species group in global fisheries (Baptista et al., 2022; Nair and Gopalakrishnan, 2014).

Previous research in other fishing gears has shown that the catch rate and size selectivity of flatfish species can be influenced by their morphology and by factors such as the mesh opening angle, behavior and swimming characteristics (Fonteyne and M'Rabet, 1992; Winger et al., 2004; Ryer, 2008; Bak-Georgsen et al., 2025; Bak-Jensen et al., 2024). Although most previous studies have not focused on set nets, their findings provide valuable insights into how factors such as fish morphology and mesh geometry can influence catch efficiency. The acrylic spheres used in the PearlNet could affect catch efficiency and how fish become enmeshed by altering the morphology of the netting, modifying net movement, vibration, or visibility. Understanding these potential mechanisms is therefore essential for evaluating whether the PearlNet performs differently across species. This gap is particularly relevant in the Baltic Sea, where the importance of flatfish species has grown in recent years due to the decline of Atlantic cod stocks and the implementation of management restrictions (Council Regulation (EC) 2020/1781), increasing the need for alternative target species. In this context, the overall aim of this study is to investigate the catch efficiency of the PearlNet for plaice (*Pleuronectes platessa*), flounder (*Platichthys flesus*), dab (*Limanda limanda*) and turbot (*Scophthalmus maximus*).

This study also examines the handling of the PearlNet, recognizing that gear retrieval is a critical and time-consuming stage in set net fisheries. Previous research by Kratzer et al. (2021) showed that PearlNets made of multifilament natural yarn, as used in the Black Sea, can present handling issues due to the entanglement of the spheres in the netting. This entanglement can potentially compromise the gear's commercial acceptance. Considering that standard nylon netting is widely used in global fisheries, this research also evaluates the performance of the PearlNet when made from this material. Thus, we aimed to analyze the catch efficiency of the PearlNet and its practical viability under commercial trammel net fishery conditions. These results are essential to convince fishers to use the PearlNet in potential long-term monitoring programs aimed at evaluating its effectiveness in reducing the bycatch of toothed whales.

## 2. Materials and methods

### 2.1. Study area and experimental setup

The trials were conducted in the western Baltic Sea, ICES Subdivision SD22, between October and November 2022 on a commercial set net fishing boat (LOA: 9.84 m) targeting flatfish. Four strings of trammel nets (three layers of netting), each 500 m long and 1.40 m high, were deployed by a local fisher. Each string consisted of 10 individual net panels of 50 m length. The net was made of multifilament nylon yarn. The inner and the outer netting had nominal mesh openings (ISO, 2017) of 150 mm and 700 mm, respectively, according to supplier specifications referring to the fully stretched meshes, resulting in 20.5 and 2 meshes in the vertical direction, respectively (Fig. 1). The nets were produced by a local netmaker who also equips many fishers in the region, and the specifications are consistent with previous studies of similar fisheries in subdivision SD22 (e.g., Ern et al., 2022). The hanging ratio in the horizontal direction was 1:2 for the outer net and 1:2.7 for the inner net. The floatline had a buoyancy of 2.4 kg/100 m, and the leadline had a weight in water of 7.1 kg/100 m.

The experimental setup followed a split-plot design, with the 10 net panels of each string arranged alternately between the standard net and the PearlNet (Fig. 1). All the panels had the same characteristics, except that the PearlNet panels were equipped with transparent acrylic glass spheres (hereafter referred to as pearls). Each pearl was manually attached with acrylic glass adhesive directly next to each knot of the outer net, ensuring an optimal pearl-to-pearl distance of approximately 30 cm both vertically and horizontally. This distance corresponds to the minimum spacing that porpoises recognize as too narrow to swim through, as defined by Kastelein et al. (2000) and later confirmed by Kratzer et al. (2020). The diameter of the pearls was chosen based on the echolocation frequency of harbor porpoise (Kratzer et al., 2020), resulting in a pearl diameter of 8 mm ($\pm$ 0.15). The pearls were produced with a slit (width 0.8 $\pm$ 0.1 mm) in the middle using injection molding, the same method used by (Kratzer et al., 2020).

For each deployment, we recorded: (1) the day and time of setting and retrieving the net, (2) retrieval duration, (3) weather conditions, (4) water depth, (5) the total weight of each fish species per net panel, and (6) the total length of each fish caught. The fishing positions of the nets were tracked onboard every two seconds during each retrieving process with a GPS logger (Renkforce GT-730FL-S).

### 2.2. Data analysis

#### 2.2.1. Length-dependent catch comparison

To investigate a possible deviation in the catch efficiency of the PearlNet relative to the standard net on individual length classes of the captured species, length-dependent catch comparison analyses were conducted (Grimaldo et al., 2019). For a given species, the experimental catch comparison rate ($CC_l$) obtained after pooling the catch data across strings and deployments can be calculated as:

$$CC_l = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left\{np_{ijl}\right\}}{\sum_{i=1}^{m}\sum_{j=1}^{n}\left\{np_{ijl} \quad + \quad ns_{ijl}\right\}} \tag{1}$$

In Eq. (1), $np_{il}$ and $ns_{il}$ are the total number (counts) of fish in the length class $l$ captured in string $j(j\epsilon\ 1,\ldots n)$, and $n$ is the total number of strings deployed in deployment $i(i\epsilon\ 1,\ldots m)$. A value of $CC_l = 0.5$ indicates equal catch efficiency for the PearlNet and standard net designs. The lower the value is below the equal catch efficiency value (0.5), the smaller the catches of the length class $l$ in the PearlNet compared to the standard net and, therefore, the lower the relative catch efficiency of the

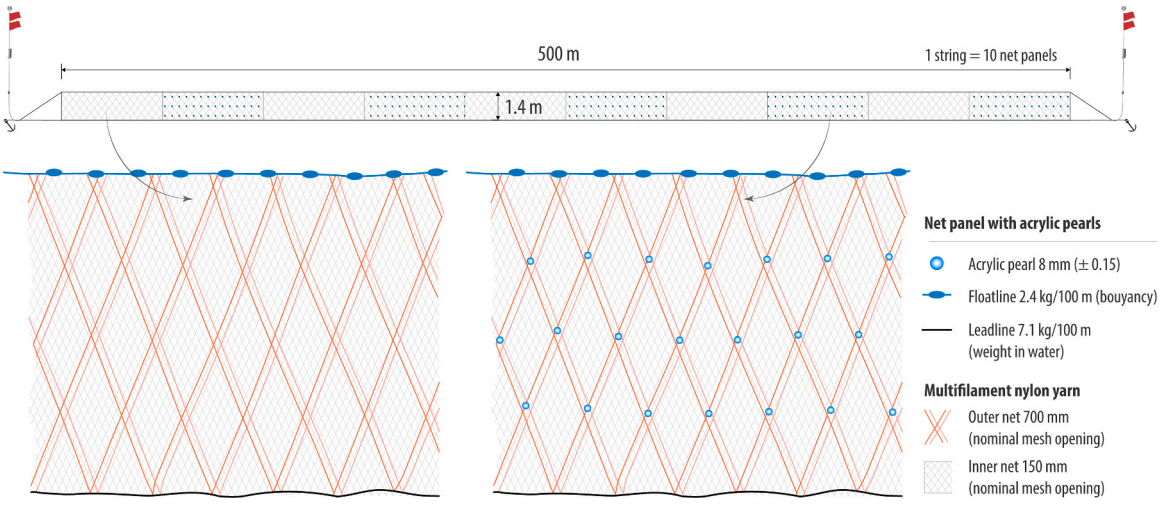



**Fig. 1.** Top: Illustration of the experimental setup following a split-plot design, where the PearNet (dotted net panels) and standard net (regular net panels) were positioned in each experimental net string according to an alternating treatment design. Bottom: illustration of net panels without (left) and with (right) pearls attached to the large mesh outer net.

PearlNet. The opposite applies to values above the equal catch efficiency value.

The comparative assessment of the PearlNet effect across length classes is done by using catch comparison curves. In this study, the catch comparison curve is defined as:

$$CC(l) = \frac{\exp(\alpha + f(l))}{1.0 + \exp(\alpha + f(l))} \quad (2)$$

Where $f(l) = \sum_{v=1}^{4} l^v$ is a smooth function with a polynomial basis of order 4. Leaving out one or more of the polynomial elements led to 15 additional models. Estimations of the catch comparison curves were obtained using multimodel inference (Burnham and Anderson, 2004; Herrmann et al., 2017) and taking into consideration all the 16 models fitted. Specifically, the models were ranked and weighed in the estimation according to their AICc values (Burnham and Anderson, 2004). The AICc is calculated as the AIC (Akaike 1974), but it includes a correction for finite sample sizes in the data.

Based on the catch comparison curves obtained from Eq. (2), length-dependent analysis was conducted to quantify the magnitude of the PearlNet effect and its estimation uncertainty across the captured length range. This approach was chosen taking into consideration that several of the studied species are traditionally managed and valued according to specific lengths. The magnitude of the PearlNet effect was evaluated by quantifying the deviation of the predicted value of the curve at length class $l$ from the equal catch efficiency value. To obtain interpretable magnitudes of the gain/losses in relative catch efficiency associated with specific length classes, the predicted catch comparison curve for a given species was derived into the so-called catch-ratio curves:

$$CR(l) = 1.0 - \left(\frac{CC(l)}{1.0 - CC(l)}\right) \quad (3)$$

According to Eq. (3), a value of $CC(l) = 0.5$ equals to $CR(l) = 1.0$, being both values related to equal catch efficiency. A value $CC(l) = 0.4$ equals to $CR(l) = 0.66$, implying a loss in cath efficiency of $100 \times (1.0 - CR(l)) = 33.33\%$.

The estimated catch comparison curves and associated catch ratio curves are presented with 95% pointwise confidence intervals (CIs, Efron, 1979), forming altogether a confidence band around the predicted curve. The width of the estimated CIs is used in this study as a measure of precision in estimation of the predicted catch comparison/ratio curve at length class $l$. Under the background assumptions of the experimental design and modelling approach, the 95% CIs are interpreted as the range of parameter values supported by the collected data (Rafi and Greenland, 2020). The interpretation of the resulting catch comparison curve ($CC$) and catch ratio curve ($CR$) focuses on overall patterns across length classes in relation to the reference values marking equal catch efficiency ($CC = 0.5$; $CR = 1.0$), as well as the uncertainty in estimation. Overall, model results were reported and discussed in broad trends.

The pointwise 95% CIs were estimated using the percentile method on bootstrap distributions of the predicted $CC(l)$ and $CR(l)$ curves. To obtain such bootstrap distributions, a hierarchical data generation process, similar to that proposed by Grimaldo et al. (2019), was implemented. However, while Grimaldo et al. (2019) only used two strings per deployment, in the current study a total of four strings were used per deployment. In order to capture the variability in catches between strings within deployment, the bootstrap data generation process applied in this study considered a three-level resampling scheme instead of the traditional two-level resampling used in Grimaldo et al. (2019). Therefore, on each bootstrap interation, i) deployments, ii) strings within deployment, and iii) fish catches within string were hierarchically resampled with replacement. The third-level resampling on fish catches was applied separately for the PearlNet and the standard net. The resampled data was pooled across strings and deployments in order to obtain average estimations of relative catch efficiency of the PearlNet compared to the standard net. Further details of the bootstrap scheme applied can be found in the Supplementary Material.

The length-dependent catch comparison analysis described above was implemented and conducted in R (R Core Team, 2024). Catch comparison curves (Eq. (2)) were fitted using the Generalized Linear Model function (GLM) available in the R (v. 4.2.2) package stats (R Core Team, 2024). Model averaging was conducted using the dredge function in the R package MuMIn (Bartoń, 2024). The routines and functions used in the analysis, along with example data, are available at https://github.com/xansantos/selma.

### 2.2.2. Fishery usability indicators

The catch comparison analysis described in the previous section focused on making an assessment of the relative catch efficiency of the standard net and the PearlNet on individual length classes of the study species. However, the curves estimated by Eqs. (2) and (3) do not provide point estimates that can be used to answer more relevant questions, such as 'What is the catch efficiency of the PearlNet relative to the standard net in overall terms?' and 'What is the catch efficiency when catch fractions defined by management reference sizes are considered?'.

To answer such questions, the following three catch ratio indicators were estimated based on the catch data.

$$CR+ = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{a=l\geq mcrs} np_{ija}}{\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{a=l\geq mcrs} ns_{ija}} \times 100 \quad (4)$$

$$CR- = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{b=l<mcrs} np_{ijb}}{\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{b=l<mcrs} ns_{ijb}} \times 100 \quad (5)$$

$$CR = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{l} np_{ijl}}{\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{l} ns_{ijl}} \times 100 \quad (6)$$

Indicators in Eqs. (4), (5), and (6) are estimated for each species studied and calculated as the ratio of the overall catches (in numbers) obtained in the PearlNet to catches obtained in the standard net and converted to percentages by multiplying the estimated value by 100. Due to the paired-gear experimental method applied, each string $j$ within deployment $i$ will produce catch data from both the PearlNet ($p$) and the standard net ($s$). Point estimates are therefore obtained by pooling the catch data over deployments and strings. Furthermore, catch fractions above species Minimum Conservation Reference Sizes (MCRS, $CR+$), ratio of catch fractions below MCRS ($CR-$), and the total catch ($CR$) were considered. The reference sizes used here for plaice (25 cm), flounder (23 cm), turbot (30 cm), and cod (35 cm) follow the MCRS legislated for these species in the Western and Central Baltic Sea (EU, 2019). Dab and whiting (*Merlangius merlangus*) have no MCRS in the study area and, therefore, indicators per catch fraction ($CR+$, $CR-$) were not considered for these species. The 95% percentile CIs (Efron, 1979) associated with the fishery usability indicators were obtained using the same bootstrap scheme described in the previous section. The indicators analysis was conducted using R (R Core Team, 2024).

#### 2.2.3. Retrieval time

The potential effect of using the PearlNet and other fishing variables on gear retrieval time is assessed by the following model:

$$\log(t_{ik}) = \beta_0 + b_i + (\beta_1+\gamma_i)Catch_{ik} + \beta_2 Pearl_{ik} + \beta_3(Pearl_{ik} * Catch_{ij}) + \beta_4 SWI_{ik} + \beta_5 Wind_i \quad (7)$$

In Eq. (7), the response variable $t_{ik}$ is the elapsed time taken by the fisherman to retrieve the net panel $k$ from the sea and manually collect the catches entangled in it. The model assumes that retrieval time is dependent on the number of fish caught per panel retrieved from deployment $i$ ($n_{ik}$). A bivariate examination of the relationship between catches and retrieval time suggested a square root transformation of the natural value. Therefore, $n_{ik}$ was square-rooted and added to the model as $Catch_{ik} = n_{ik}^{\frac{1}{2}}$. $Pearl_{ik}$ is a dummy variable with only two possible values; the value $Pearl_{ik} = 0$ indicates that the panel $k$ being retrieved within deployment $i$ is a standard net, while $Pearl_{ik} = 1$ is the indicator for the PearlNet. In addition to the main effects associated with $Catch_{ik}$ ($\beta 1$) and $Pearl_{ik}$ ($\beta 2$), the model also considers an interaction effect ($\beta 3$) term between both panel-level predictors. Catch profile in terms of species diversity per panel was also considered to potentially influence retrieval time. Catch diversity was described by calculating the Shannon-Wiener diversity index (SWI) (Herrmann et al., 2022; Shannon, 1948) for each panel $k$ within deployment $i$ retrieved and incorporated as a main effect in the model ($\beta 4$). Weather conditions can also affect the handling of the gear and thus, the retrieval time. Therefore, the average deployment-level wind force measured using the Beaufort scale was added to the model as an indicator for the weather conditions during the retrieval process of the net ($\beta 5$). The coefficients $b_i \sim N(0, \sigma_b)$ and $\gamma_i \sim N(0, \sigma_\gamma)$ are deployment-level random effects added to the model to account for unmeasured variation in the model intercept ($\beta 0$) and mean slope quantifying the catch effect ($\beta 1$), respectively. The model described in Eq. (7) was fitted as a Generalized Linear Mixed Model (GLMM), assuming a gamma distribution of response and using the log function as link between the response and the predictors.

Considering the full model structure of Eq. (7), including five fixed effects as predictors, 31 additional submodels were formulated by leaving out one or more descriptors at a time, all of them considered potential candidates to model the observed variation in retrieval time. The candidate models were automatically ranked by a decreasing value of BIC (Bayesian Information Criterion) (Burnham and Anderson, 2004). BIC is known to penalize model complexity to a greater extent than AIC and AICc (Brewer et al., 2016), therefore tending to select simpler models among a set of candidates with similar explanatory properties. The 32 candidate models were fitted in the R language (Version 4.2.1) using the package glmmTMB (Brooks et al., 2017), and ranked based on BIC using the package MuMIn (Bartoń, 2024). The model check was based on residual inspection using the tools available in the DHARMa package (Hartig and Lohse, 2022).

## 3. Results

### 3.1. Description of fishing operations and catches

A total of 20 deployments were carried out during the trial (Fig. 2, Table S1 in the Supplementary Material). The average fishing depth was around 8 m, ranging from a minimum of 3 to a maximum of 18 m. The average soaking time was 31 h and 35 min, with the shortest duration being 16 h and 7 min and the longest lasting 51 h and 0 min. Overall, 5068 kg of fish were caught during the trial, 2484 kg (49%) using the standard net and 2584 kg (51%) using the PearlNet. A total of 12 fish species were recorded across both gear types, with plaice and flounder constituting the vast majority of the catch, accounting for 94.92% in the standard net and 95.19% in the PearlNet. Other species captured in lower abundances included dab, turbot, cod, and whiting (Table S2 in the Supplementary Material). Visual inspection of the size-structure of the species caught revealed negligible variation between gears (Table 1, Fig. 3). It is important to note that the present study did not assess PearlNet's effectiveness in reducing bycatch of harbor porpoise, nevertheless, no bycatch of marine mammals was observed in any of the nets during the study.

### 3.2. Length-dependent catch comparison

The catch comparison model estimated for plaice, the most abundant species in the catches, yielded a predicted curve with a flat shape that closely matches the reference line at $CC = 0.5$. This indicates the catch efficiency of the PearlNet and the standard net to be very similar for all length classes evaluated (Fig. 3, Figure S1). Further, the very narrow 95% pointwise CIs associated with the most abundant length classes ($25 \leq l \geq 40cm$) indicate little variation in the catch comparison rates between deployments and between strings within deployments. However, a reduced precision in estimation is found for length classes at the tails of the observed length distribution. This reduced precision can be related to the limited number of small ($l < 25cm$) and large ($l > 40cm$) individuals caught. Considering the average catch comparison curve and associated CIs, there is no clear trend indicating differences in catch efficiency between the tested nets for plaice. A similar pattern was found for flounder, the second most captured species. For this species, the predicted curve was estimated close to the reference line of $CC = 0.5$ in the range of lengths $25 \leq l \geq 40cm$, representing most of the catches of the species (Fig. 3). For smaller ($l < 25cm$) and large ($l > 40cm$) length classes, the curve shows an increasing trend expressing slightly higher relative catch efficiency of the PearlNet on the tails of the species length

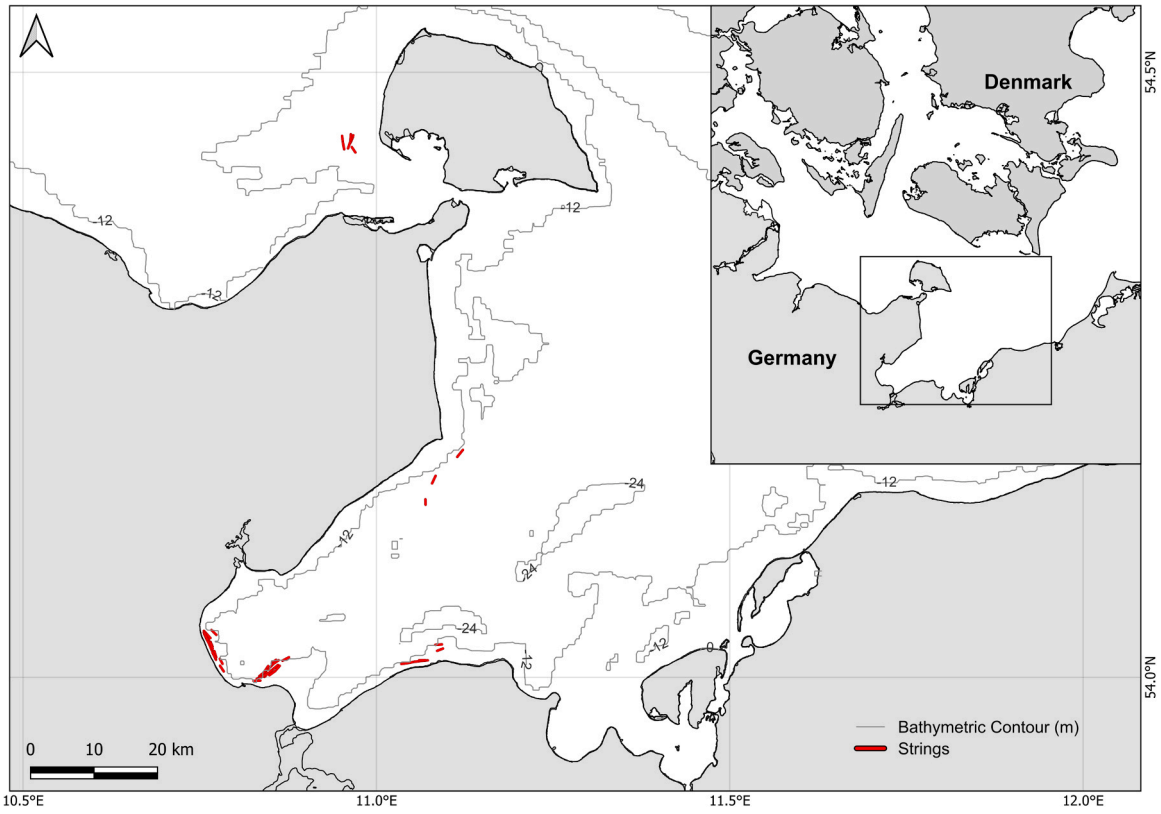



**Fig. 2.** String positions (red lines) recorded during each deployment operation in the trial.

**Table 1**
The average length ± SD (minimum-maximum) (cm) for the main species caught in the standard net and the PearlNet.

| Gear | Average length ± SD (minimum–maximum) | | | | | |
|---|---|---|---|---|---|---|
| | Plaice | Flounder | Dab | Turbot | Cod | Whiting |
| Standard net | 30.60 ± 3.12 (22-45) | 32.60 ± 3.20 (21-45) | 27.52 ± 3.15 (20-39) | 28.00 ± 4.96 (23-46) | 34.46 ± 7.49 (22-52) | 25.52 ± 2.10 (21-31) |
| PearlNet | 30.67 ± 3.15 (19-45) | 32.57 ± 3.37 (27-47) | 27.09 ± 3.33 (20-41) | 29.10 ± 4.55 (22-42) | 33.85 ± 4.98 (27-52) | 26.45 ± 3.94 (20-46) |

distribution. Based on visual inspection of the estimated pointwise CIs, no clear trend was observed suggesting differential catch efficiency for flounder across the evaluated lengths.The catch comparison curves obtained for species with lower catch abundances (dab, turbot, cod and whiting) showed greater functional variability and estimation uncertainty than those for plaice and flounder. The catch comparison curve for dab matches the reference line between the length classes $27 \leq l \geq 37cm$, and a positive trend is also observed on the tails of the curve for lengths $l < 27cm$ and $l > 37cm$ (Fig. 3). Similarly, the catch comparison curve for turbot is showing an increasing trend in catch efficiency $l \leq 40cm$ (Fig. 3). In particular, the catch ratio curve estimated for turbot suggest that the PearlNet could be twice as efficient as the standard net in catching turbot of about 35 cm in length (Figure S1 in Supplementary Material). The average catch comparison curve for cod described higher catch efficiency of the standard net for length classes $l < 29cm$ and $l > 43cm$, and the opposite for length classes $30 \leq l \geq 42cm$ (Fig. 3). In average, the PearlNet showed higher catch efficiency than the standard net for whiting independently of the fish size (Fig. 3). Due to the limited catches of dab, turbot, cod and whiting, the curves comparing the catches of these species were associated with wide CIs that in all cases contained the reference value $CC = 0.5$ for equal catch efficiency. Therefore, it could be possible to obtain such results under either equal catch efficiency or a wide range of different catch efficiencies.

### 3.3. Fishery usability indicators

In line with the results of the catch comparison analysis described above for the most abundant species, the catch indicators were estimated close to the reference value for equal catch efficiency between the PearlNet and the standard net (100%, Fig. 4). The catch ratio indicator *CR* (95% CI) for plaice and flounder was estimated at 106.49% (99.72–113.84%) and 101.08% (94.33–110.40%) respectively, indicating a similar catch efficiency between gears. In addition, plaice was mainly caught above the MCRS, while flounder was caught exclusively above it. This explains the low CIs for $CR+$ observed for plaice and the absence of $CR-$ for flounder (Fig. 4). The analysis for dab and whiting only shows the total catch ratio (Fig. 4). Dab showed a potentially higher catch efficiency for the PearlNet, but the wide CIs that cross the reference line (85.50 – 142.86%) prevent any precise evaluation of the results. The indicators for turbot, cod, and whiting were associated with very wide confidence intervals, expressing the very low precision in estimation due to the low catches obtained for these species during the trials.

### 3.4. Handling and retrieval time

The fisher encountered some minor problems during the clearing process of the PearlNet, as the spheres occasionally got entangled in the meshes. However, by straightening and shaking the net, the fisher was able to resolve these entanglements quickly. The average handling time (± SD) of the standard net and the PearlNet was 3 min 40 s (± 2 min 40 s) and 3 min 56 s (± 2 min 45 s), respectively.

Among the 32 models considered for describing the observed retrieval time, the model that only included Catch as a predictor was the

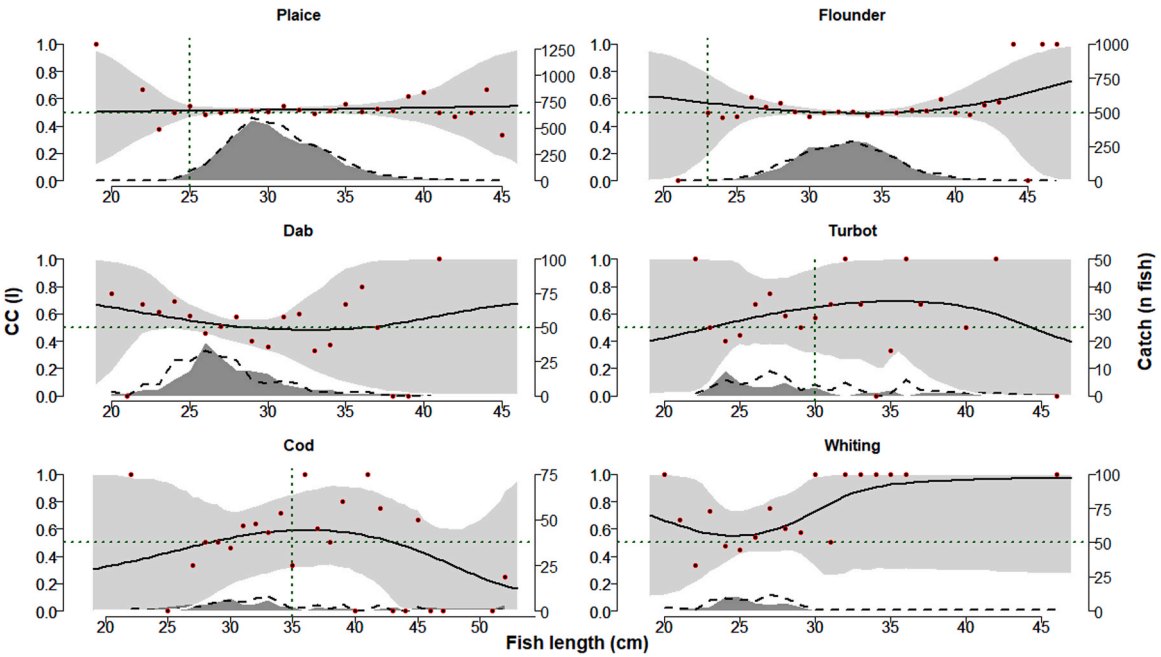



**Fig. 3.** Average catch comparison curves ($CC(l)$, solid line) estimated for plaice, flounder, dab, turbot, cod, and whiting. Grey shadow areas: 95% confidence intervals of the estimation. Circles: species catch comparison data ($CC(l)$). Horizontal green dotted line: reference for equal catch share among PearlNet and standard net ($CC = 0.5$). Vertical green dotted line: species reference size. Pooled catches are represented at the bottom of the plots by a black dashed line (PearlNet) and a dark grey polygon (standard net).

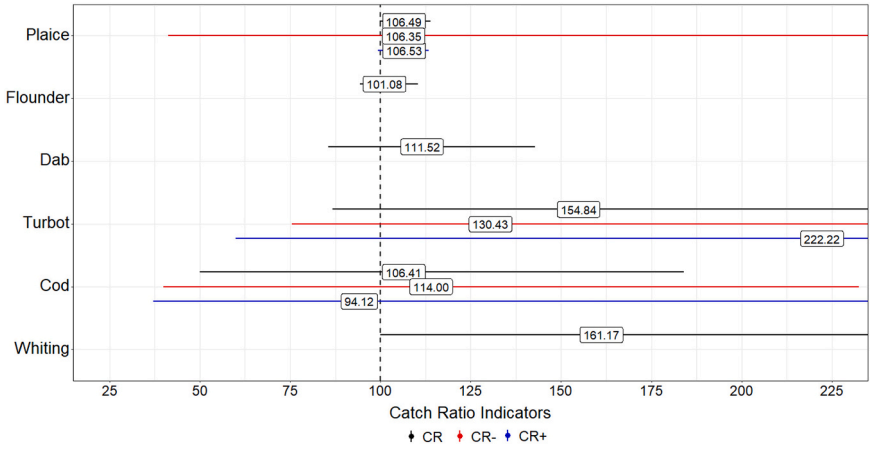



**Fig. 4.** Catch ratio indicators, as defined in Eqs. (4), (5), and (6), are categorized by species. Rectangular labels indicate the average values of the estimated indicators, while horizontal bars illustrate the 95% confidence intervals. Black bars represent the total catch ($CR$), red bars indicate the catch fraction below the Minimum Conservation Reference Size (MCRS) ($CR -$ ), and blue bars represent the catch fraction above MCRS ($CR +$ ).

best candidate model according to BIC ranking (Table S3 in Supplementary Material). Consequently, the information contained in the Pearl variable was not influential enough to be included in the best candidate model. This is consistent with the apparent similar distribution of the observed retrieval times of the PearNet and standard net (Fig. 5). In general, the curves predicted by the selected model at deployment level described well the observed retrieval times per panel (Fig. 5). The trend of increase in retrieval time with increasing catches is also well captured by the predicted curves, which show an exponential form, especially evident in those deployments with large variation in catches per panel (deployments 5 and 6). In contrast, for deployments with lower catches and low variation, the predicted curves are nearly linear (e.g., deployments 1, 2 and 4).

## 4. Discussion

This is the first study to assess the species-specific relative catch efficiency of the PearlNet for flatfish. It also provides the first analysis of handling time when using a nylon filament PearlNet, showing only minor influence on a commercial fishery. Our results demonstrated no clear change in catch rates for plaice and flounder when using the PearlNet compared with the standard net. Although the results suggest an impact on the catch of dab, turbot, whiting, and cod, the limited data collected for these species prevented definitive conclusions regarding the effect of PearlNet. It is important to highlight that this study was conducted during a single season, so these results may vary with seasonality, species composition and net configuration.

Regarding the relative catch efficiency of the PearlNet, our results are consistent with those observed in trammel net fisheries targeting cod

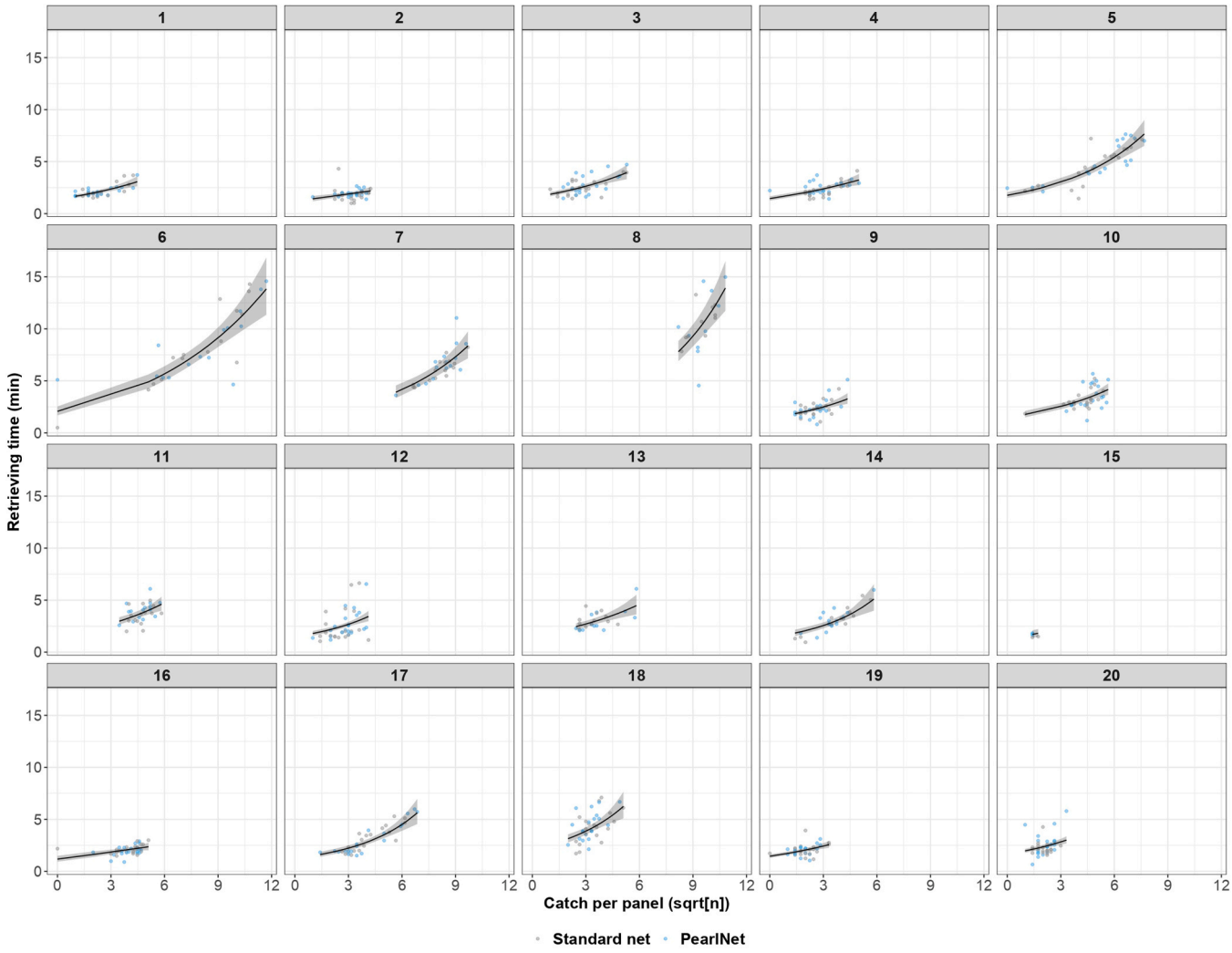



**Fig. 5.** Retrieval times of trammel net panels by individual deployment and their relation to catch abundance, calculated as the square root of the total number of fish caught per panel. Round marks represent experimental catches in standard panels (grey) and PearlNet panels (blue). The black line is the conditional deployment time predicted by the model selected by BIC, and the grey bands represent the 95% confidence intervals associated with the predicted values.

and flatfish in the Danish Baltic Sea (Kindt-Larsen et al., 2024), where the PearlNet did not influence the catch rate of target species. However, Kindt-Larsen et al., 2024 focused on cod catches and did not analyze other species separately and, consequently, they were unable to determine whether PearlNet influenced the catches of other species. In addition, differences across length classes were not considered. In contrast, the present study examined species-specific catch data for flatfish and analyzed catch ratios across different length classes, offering a more comprehensive evaluation. As plaice and flounder were both the dominant species in catches and the main targets in the western Baltic Sea (ICES, 2019), understanding how the PearlNet affects their catches is crucial for facilitating broader acceptance of the gear among fishers in the future. Another study assessing the catches of target species using the PearlNet was conducted in the Turkish Black Sea, mainly targeting Black Sea turbot (*Scophthalmus maeoticus*) (Kratzer et al., 2021), however, due to insufficient catch rates, the result was not significant. Instead, the authors developed a model for thornback ray (*Raja clavata*), the most abundant species caught. This analysis revealed no difference in catches between the PearlNet and the standard net (Kratzer et al., 2021).

Beyond catch efficiency, another aspect of PearlNet performance that has been examined is the time required for gear retrieval. Although our results showed no impact of the use of pearls on the retrieval time, minor issues with entanglement during the clearing process of the PearlNet were reported. One reason for this could be the manual gluing process of the spheres (Kratzer et al., 2020), where the glue did not fully penetrate the slit in some cases, resulting in some dry glue on the surface. This excess glue may have made the netting more prone to entanglement. However, despite this, the entanglement of the PearlNet did not seem to present a significant issue for the fisher in this study, as the fisher continued using the gear commercially following the trial period. This is consistent with the descriptive results given by Kindt-Larsen (2024), where no significant problems were reported. However, these results using nylon nets contrast with the results of the pilot trial conducted in a commercial fishery in the Turkish Black Sea, where the PearlNet showed a negative impact of 28% on handling time compared to the standard net (Kratzer et al., 2021). During the trials in the Black Sea, the net became entangled mainly after passing the specific net hauler used in this fishery. The reason for this could be attributed to the net material and mesh size: while the Turkish trial used multi-filament natural yarn with 400 mm stretched mesh opening, our study utilized multi-filament nylon trammel net with a mesh opening of 150 mm in the inner net and 700 mm in the outer net.

This study represents an important step for the evaluation of the PearlNet by demonstrating its practicality and catch efficiency in commercial fishing operations. Effective bycatch mitigation requires not only technical success but also the confidence and participation of fishers, who must be assured that new gear will not compromise their

catch or increase operational effort. By showing that the PearlNet performs similarly to conventional nets in both catch efficiency and handling time, this study can potentially provide a solid foundation for cooperative research between scientists and fishers in the future. To date, the only experiment evaluating its efficacy in reducing odontocete bycatch was carried out in a small-scale fishery in the Turkish Black Sea, focusing on harbor porpoise bycatch (Kratzer et al., 2021). Although the results indicated lower harbor porpoise bycatch in the PearlNet compared to a standard net, the difference was not statistically significant. This is mainly due to the overall low number of deployments and the nature of the data associated with marine mammals' bycatch, often associated with low numbers and frequent zeros. Therefore, the next step could involve a long-term monitoring program in collaboration with local fishers by replacing a fraction of standard nets in areas where toothed whales occur in sufficient numbers to allow statistical comparison. Such studies are essential to determine the PearlNet's bycatch reduction potential, and, if shown to be effective, it could make an important contribution to cetacean conservation while maintaining catch rates and fishing operational practicality in commercial fisheries.

Another crucial area for further investigation is the development of alternative PearlNet production methods that could enhance cost-efficiency and sustainability while ensuring the maintenance of acoustic efficacy. This includes (1) exploring new designs that not only reduce investment costs but also optimize production processes, mainly by replacing the current manual assembly with more automated and industrialized methods, which would also eliminate issues related to glue use, and (2) investigating alternative materials that could simplify recycling, since the pearl and the net are currently made from different materials, making effective recycling more difficult. Importantly, these steps should be pursued only if the PearlNet concept is proven effective in reducing bycatch in comparative experiments, thereby ensuring that its wider adoption in fisheries supports both conservation goals and long-term sustainability.

## CRediT authorship contribution statement

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

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

During the preparation of this work, the authors used ChatGPT only to improve the language clarity and grammar. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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## 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.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2026.107702.

## Data availability

Data will be made available on request.

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