



Estimating escapees using automated video analysis: Assessing the sorting efficiency of the Excluder in the North Sea sandeel fishery

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ABSTRACT

The Excluder, a net-based sorting device, has been introduced in the North Sea industrial trawl fishery to reduce unwanted bycatch. This study evaluated the sorting performance of the Excluder by combining traditional catch composition analysis with automated video analysis of underwater recordings. A total of 31 hauls were observed across two years (2021 and 2022), using trawls with and without the Excluder. Underwater cameras recorded fish behaviour and escapement through the Excluder's exit opening, and an object detection model was trained to estimate number of escapees across four taxonomic groups. Results showed that the Excluder allowed nearly complete escapement of demersal species such as gadoids, flatfish, and gurnards, with estimated sorting efficiencies approaching 100%. Pelagic species (herring and mackerel) were retained to a larger extent and frequently exhibited signs of injury, raising concerns about post-release survival. Although the automated video analysis likely underestimated true escapee numbers due to visual occlusion during mass exits, the method provided valuable behavioural and ecological insights and proved effective for assessing gear performance without the need to handle live fish and bring them out of their natural habitat.

1. Introduction

The development and adoption of selective fishing gear is vital not only for protecting marine biodiversity but also for maintaining profitable, socially acceptable, and legally compliant fisheries in the face of growing global demand for seafood (FAO, 2020; Hall et al., 2000). The process of developing selective fishing gear is typically an iterative cycle that combines biological knowledge, engineering design, industry commitment, and scientific evaluations of gear modifications (Kennelly and Broadhurst, 2002).

Evaluation of the effect of gear modifications on the catch composition in trawls has traditionally been conducted through either catch comparison experiments, where the catch of the test gear is compared to the catch of a baseline/control gear, or by recapture of the escapees (e.g. by using codend covers or collection bags) (Wileman et al., 1996). One of the main drawbacks of these methods, apart from that they generally are expensive and difficult to conduct, is that it normally leads to the

death of the unwanted catch. This mortality is not only problematic if the unwanted catch consist of sensitive and/or protected species, the use of marine vertebrates for experimental purposes is also considered an ethical problem (Madsen et al., 2022; Sloman et al., 2019), that should be reduced as far as possible according to legal framework and the 3 R principles (European Parliament, Council of the European Union, 2010; Russell and Burch, 1959). The development of underwater camera systems and automated image analyses by computer vision have provided a new alternative to the traditional methods for the evaluation of gear modifications. Instead of catching the escapees and bringing them out of the water for collection of basic metrics such as species and number, it is now possible to collect this data in the fishes natural environment (Simon et al., 2020). Observation of the catch in the gear, and observation of the escapees exiting the gear, can also provide valuable insights regarding the behaviour of the animals in relation to selectivity processes (Bayse and He, 2017) and the vitality of those individuals that are released back into the wild (Petetta et al., 2025).

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The fishery for lesser sandeel (*Ammodytes tobianus*) has historically been one of the largest commercial fisheries in the North Sea, with landings up to 1.2 million tonnes during the 1980s (ICES, 2022). In the early 2000s the stock biomass declined significantly and since then yearly landings have fluctuated below 500,000 tonnes (ICES, 2022). The standard gear for this fishery is a small meshed (16 mm) bottom trawl without any selection device. Bycatch rates are estimated to be around 2% (ICES, 2017), which despite being a relatively low figure can mean significant bycatch of some species due to the large total catch volume in this fishery. To reduce bycatch, the industry has tested and increasingly implemented a sorting system called the “Excluder” (Eigaard et al., 2024). The Excluder is an all-net section with an inner selection tunnel that is inserted as an extension piece in front of the trawl codend. To reach the codend, fish must pass through the meshes of the inner selection tunnel. Fish that do not pass through the inner netting are released from the trawl through an opening in the end of the device (Fig. 1). This innovative net based solution is particularly beneficial for trawlers using net drums because it can be rolled onto the drum easily, enhancing both operational efficiency and safety compared to a grid sorting system (Eigaard et al., 2021). However, due to the lack of on-board scientific observers in this fishery, and that there has been only one scientific evaluation on the effect on the catch of the Excluder (Eigaard et al., 2024), much is still unknown about unwanted catches in this fishery and the effect on them by the introduction of this new sorting system solution. The results from the catch comparison experiment conducted by Eigaard et al. (2024) were largely inconclusive due to wide confidence limits affected by low bycatch proportions during the sea trials.

In this study, we employ both traditional catch comparison methods and modern computer vision techniques to evaluate how catch composition in the industrial sandeel fishery relates to the sorting efficiency of the Excluder. The study also aims to compare the effectiveness of these two approaches in assessing catch sorting performance. Data was collected during active commercial fishing under the umbrella of the Swedish secretariat for selective fishing, which is an initiative commissioned by the Swedish Agency for Marine and Water Management (SwAM) to the Institute of Aquatic Resources at the Swedish University for Agricultural Sciences (SLU-Aqua), with the purpose of gather and evaluate ideas of new gears from the fishing industry on how to

minimize unwanted catches (Nilsson et al., 2018).

2. Material and methods

2.1. Fishing vessels, fishing grounds, and used gears

Trained scientific personnel from SLU participated in two fishing trips in the North Sea sandeel fishery (2021 and 2022), observing a total of 31 trawl hauls, performed by two different commercial vessels (GG 203 Ginneton; LOA: 57.6 m, GG 505 Polar; LOA: 62 m). The fishing was conducted both with and without the Excluder mounted in the trawl and several different trawl designs were used (Table 1). The Excluder used during 2021 was of the same type as tested by Eigaard et al. (2024) and was manufactured by Egersund Trawl, Thyborøn, Denmark. The extension piece was a total of 27.5 m long, with an outer cover made of 16 mm diagonal mesh (2400 meshes around). The inner tunnel with the selection net was 15.0 m long and made of knotless square mesh with a nominal size of 72 mm. At the end of the inner tunnel, a plastic sheet was mounted to reduce water flow and to increase probability of contact with the selective surface (by forcing the catch towards the square meshes of the selection net). The exit hole at the end of the inner tunnel releasing the escapees was directed downward (towards the bottom panel of the trawl) and measured 0.80×1.20 m. The Excluder used during 2022 was manufactured by Cosmos trawl (Skagen, Denmark) and differed somewhat from the model used during the previous year. The total length of the extension piece (30 m) and outer meshes (16 mm) was similar, but the inner tunnel was longer (23.5 m), and the square meshes of the selection net in the inner tunnel was smaller (nominal size 67 mm). There were two plastic sheets fitted to reduce water flow and to force the catch towards the selection net, the distance from the start of the tunnel and the first sheet (70×70 cm) was 11.7 m, and the distance from the start to the second sheet (45×45 cm) was 20.7 m. The exit hole at the end of the inner tunnel releasing the escapees was directed upwards (towards the top panel of the trawl) and measured 0.7×3.0 m (Fig. 1).

The sandeel fishing areas in the North Sea vary from year to year, partly due to varying annual TAC in each management area (ICES, 2022) and partly because of where commercial fishermen believe the fishing conditions are favourable. In general, the fishing takes place on shallow (30–80 m) sandbanks, often adjacent to deeper areas. In 2021, large parts of the EU fishing fleet involved in this fishery gathered on a few fishing banks east of England, where conditions for large catches of sandeel were considered favourable (Fig. 2). Since the banks where the sandeel gathers are relatively small (some only a few nautical miles long), this fishing is not conducted as linear tows but rather as elliptical paths. After the trawl has been deployed and reaches the bottom, it is towed for 30 min to several hours along the sandbank. When the end of the bank is reached (or if the fisherman notices a significant decrease in the amount of fish visible on the sonar/echo sounder), the trawl is lifted from the bottom (the trawl doors are brought to the surface), and the vessel makes a nearly 180-degree turn. Once the turn is complete, the trawl is lowered back to the bottom, and the trawling continues. Each such turn causes the trawl to lose its symmetry and catch efficiency. When analysing catch per unit effort (CPUE), we assumed that the time during which the gear was not fishing optimally was equivalent per trawl hour between the hauls conducted with the Excluder and the hauls conducted without the Excluder. The fishing in 2022 was performed in the central part of the North Sea, ICES area 4.a and 4.b (Fig. 2), and conducted using the same method as the previous year (elliptical tows on sandbanks at 40–80 m depth).

2.2. Catch data collection

At the end of each haul the catch in the codend was pumped on board the vessel together with large quantities of water in accordance with these vessels normal practice when emptying the trawl. When the catch/

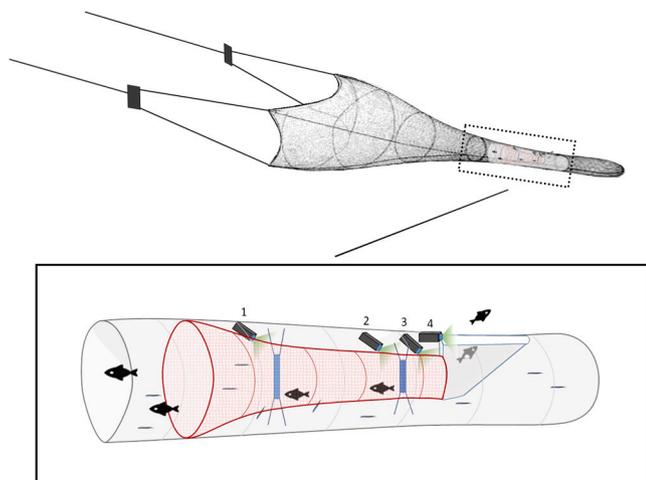


Fig. 1. Sketch showing where in the trawl the Excluder is mounted, its working principle, and the positions used for the recording of underwater video. The inner red tunnel represents the selection tunnel made of square mesh with the centrally mounted blue plastic sheets. The exit hole was directed downwards in the excluder that were used in the observed fishery in 2021 and upwards (as in the sketch above) in the excluder that were used in the observed fishery 2022. Estimates of escapees were made from recordings from camera position number 4. (Note that the drawing is not true to scale).

Table 1

Model names, manufacturers, and dimensions for each trawl in terms of opening height in meters and spread between trawl doors in meters. "Excluder" indicates the number of hauls when the trawl had an Excluder installed, and "Control" indicates the number of hauls when the trawl was used without the Excluder.

Year	Model	Manufacturer	Opening	Spread	Excluder	Control
2021	Cosmos LW	Cosmos Trawl, Skagen, Denmark	27	190	2	3
2021	Egersund 1150	Egersund Trawl, Thyborøn, Denmark	28	145	6	6
2021	Slugehals	Nordsøtrawl, Thyborøn, Denmark	22	130	0	1
2022	Cosmos LW	Cosmos Trawl, Skagen, Denmark	27	190	11	0
2022	Slugehals	Nordsøtrawl, Thyborøn, Denmark	22	130	3	0

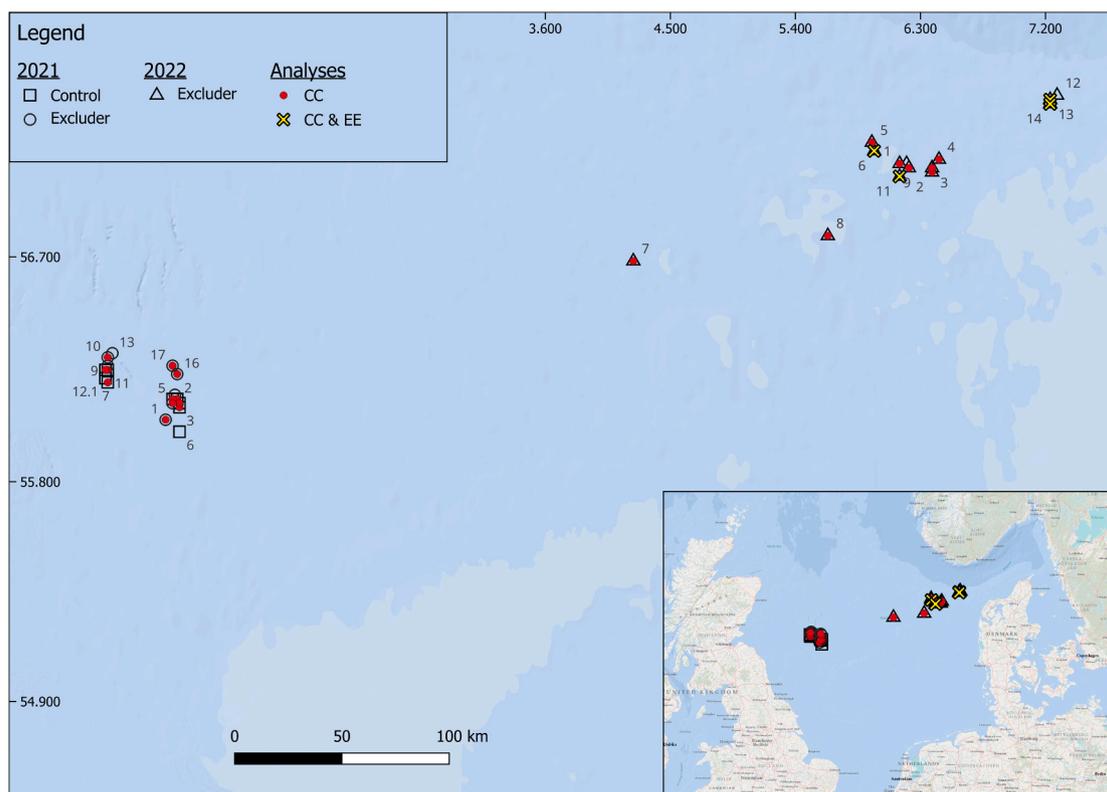


Fig. 2. Map of the Northeast Atlantic showing positions for the observed hauls during 2021 (square = trawl without Excluder, circle = trawl with Excluder) and 2022 (triangle = trawl with Excluder). Red circle indicates hauls used in the analysis of Catch Composition (CC) and yellow cross indicates hauls used for both the analysis of Catch Composition and the Estimations of Escapes (EE) via automated image analysis.

water mix enters the vessel, water and larger solid material (normally larger fish individuals) are separated from the catch of smaller solid material (normally fish of target species) by mechanical sorting. The first grid of this mechanical sorting device (called the “water separator”), that extracts larger solid material, has adjustable bar spacing and is continually regulated during the pumping to optimize the amount of landed catch of the target species while simultaneously sorting out as much as possible of the unwanted catch of larger species (the “selectivity” of this grid would consequently differ between hauls). Material that could not pass the first grid was directed to a Pallet Box on deck. All the fish catch in the Pallet Box for each haul was sorted by species, weighed, and length measurements were recorded for all individuals up to a sample size of about 30 kg per species (one full basket). If the catch of one species was larger than one basket (applied only to haddock and mackerel), a subsample of 15 – 20 kg was used for recording of length measurements. Smaller solid material that passed the first grid in the water separator was directed by an open top shoot to the Refrigerated-Salt-Water (RSW) tanks under deck (i.e. catch destined for landing). For each haul 2–3 litres of the catch flowing in the open top shoot towards the RSW tanks was collected every 30 s during the entire duration of pumping. The sample of the catch directed towards the RSW tanks corresponded to an average total catch weight sampling fraction of

0.51 % (Min = 0.25 % and Max 1.10 %) across all 24 hauls included in the analysis. Hauls resulting in catch less than 10 tons were excluded due to higher uncertainty in the estimation of the total catch volume, and one haul from 2022 was not sampled due to severe weather conditions. The collected sample from the RSW tanks was sorted according to species, weighed, and length measurements were recorded for all individuals except for lesser sandeel (and herring in haul 8 and 13, 2022). For lesser sandeel (and herring in haul 8 and 13, 2022) an additional sample level was introduced for the length measurements by conducting the measuring on only 2.5 – 5.0 kg of the catch in the sample of this species. This additional sampling level was necessary due to the high number of individuals in the first sampling level. The total catch transferred to the RSW tanks was estimated for each haul by the vessel crew, based on visual inspection of the tank indicators (graduations). For each haul separately, the ratio between the weight of the sample from the open top shoot and the estimated total catch was used as subsampling factor for the subsequent catch composition analysis.

2.3. Catch composition analysis

Catch composition was quantified by relative species dominance in weight in accordance with the method described by Eigaard et al.

(2024). The analysis was conducted for hauls with and without the Excluder and for each year separately. The relative species dominances (d) are numbers in the interval [0.0;1.0] that quantify the fraction of the total landed catch by species i in haul j , which was estimated using the following equation:

$$d_{ij} = \frac{(Wa_{ij} \times q_j) + Wb_{ij}}{\sum_{i=1}^K \{(Wa_{ij} \times q_j) + Wb_{ij}\}} \quad (1)$$

where j represents the haul and i is the species index (species ID). Wa_{ij} is the weight of species i in the subsample taken after the water separator and Wb_{ij} is the total weight of species i before the water separator. Parameter q is the subsampling factor, and K is the total number of species considered. Average species dominance was estimated for each year and trawl configuration by using:

$$d_j = \frac{\sum_j \{(Wa_{ij} \times q_j) + Wb_{ij}\}}{\sum_{i=1}^K \sum_j \{(Wa_{ij} \times q_j) + Wb_{ij}\}} \quad (2)$$

where the summation j is over all hauls with or without Excluder and separated per year. 95 % confidence intervals for the mean values of dominance were produced by the bootstrapping method (Efron and Tibshirani, 1994) with 1000 repetitions using the R package 'boot' (Angelo and Ripley, 2024). The bootstrapping procedure enables estimation of the uncertainty around the dominance values at species level without having to make any prior assumptions about the distributions in the hauls (Herrmann et al., 2022). Differences in mean values of relative species dominance were examined by assessing confidence interval overlap.

2.4. Recording of underwater video

GoPro® Hero 7 Black in underwater housings with external power banks and Paralenz® Vaquita cameras were used for recording underwater video (1920 × 1080 pixels, 30 fps) during active commercial trawling both years. However, since the mounting and dismounting of the cameras required effort from the crew, and the skipper of the vessels decided when this extra effort was possible, cameras were not used on all hauls. In 2021, focus of the recordings was to acquire observations of the symmetry of the Excluder and the internal selection process for catch retention (entry of fish through the selection net into the codend).

Cameras were also placed in two different positions around the exit hole to evaluate if video recordings could be used to collect information on species and number of individuals escaping the trawl through the Excluder. Based on observations from 2021, focus for the underwater recordings in 2022 was the internal selection process by the plastic sheets in the Excluder and recording of escapees by the exit hole. Positioning of cameras in the trawl during each haul is presented in Table 3 and Fig. 1.

Recorded video was screened for successful footages of desired observation area with VLC media player (<https://www.videolan.org>). VLC was also used for observing the symmetry of the gear, and the behaviour of the fish inside the Excluder, from camera position 1–3. Recordings from camera position 4 during 2022 were only classified as successful if the picture covered the exit hole and had sufficient visibility to observe escapees leaving the trawl during 90 – 100 % of the extent of the haul.

2.5. Estimation of escapees via automated video analysis

Successful video recordings from camera position 4 during 2022 were used for estimation of escapees in accordance with the workflow presented in Fig. 3. Video was annotated using VIAME (Video and Image Analytics for the Marine Environment) (<https://www.viametoolkit.org/>) and Label studio (<https://labelstud.io/>). Extraction of frames (images) from video for producing Train/Validation/Test data sets (Everingham et al., 2010) and for conversion of video to lower frame rate was done by using ffmpeg (<https://ffmpeg.org/>). Training, testing and deployment of the object detection model was done through Visual Studio Code (VS Code) (<https://code.visualstudio.com/>) using the Ultralytics Python package available from <https://www.ultralytics.com/>. The YOLOv8 pretrained model from Ultralytics (Jocher et al., 2023) was chosen as architectural base for the training due to its proven robustness, speed and accuracy in processing images and video streams (Varghese and M., 2024). Based on observations made during screening of the video, and with the aim of attaining a species composition of the escapees that could be compared to estimated catch composition, the model was trained using a four-class scheme (Table 2, Fig. 4).

Species not belonging to one of the defined classes and specimens showing obvious signs of damage, such as floating upside-down, body twisted in unnatural angle, or missing body parts, were not included during the process of annotating video for model training (Fig. 4). Fish with ventral side up and/or missing body parts look very different from

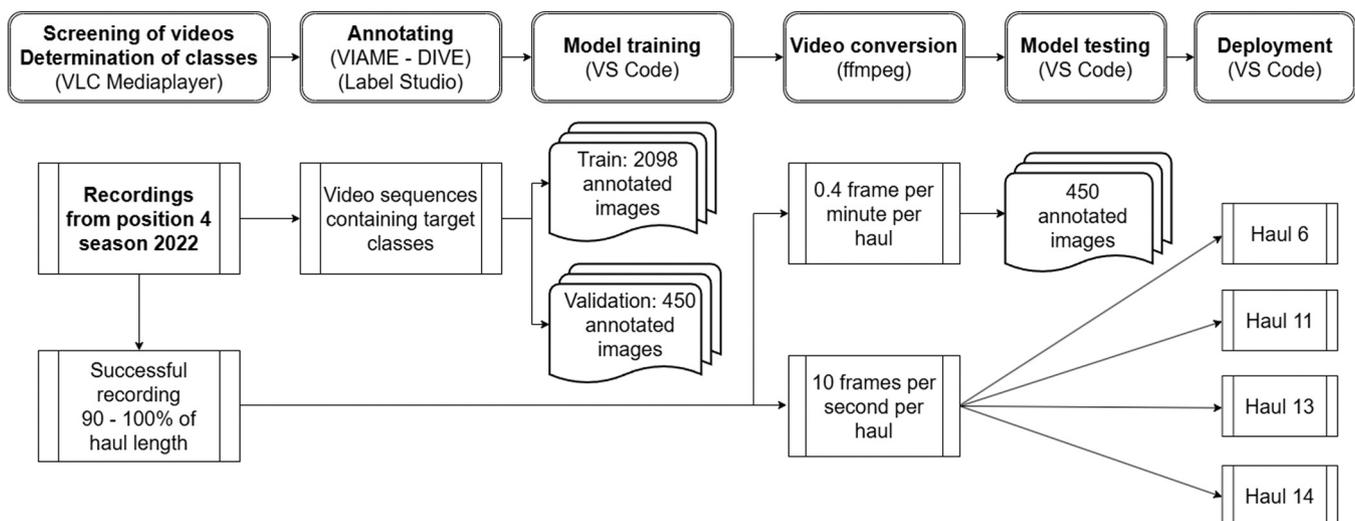


Fig. 3. Flowchart showing how video recordings from camera position 4 during 2022 was processed and used for estimation of escapees via automated image analysis. Due to failures in camera positioning, insufficient light, interrupted recordings, and not all hauls being equipped with a camera, only four of the 14 hauls that were completed during 2022 were classified as successful and used for the estimation of escapees.

Table 2

The four classes used for training the object detection model and associated metrics. “Training” and “Validation” represents the number of individual bounding boxes per class that were used for training of model. “Test” represents number of individual bounding boxes per class that were used for testing model performance and producing the Precision, Recall and F1 score. The Gadoid class consisted mainly of haddock (*Melanogrammus aeglefinus*) but also a few individuals of cod (*Gadus morhua*) and/or whiting (*Merlangius merlangus*). Species within the herring and mackerel family were categorised into one class (HER/MAC) due to difficulties in separating these species when they are viewed from the dorsal side and moving away from the camera. Correspondingly, the Gurnard and Flatfish class could also consist of several different species within the defined species complex.

Class	Training	Validation	Test	Precision	Recall	F1 Score	Species complex
Gadoid	7152	579	378	0.95	0.52	0.68	Gadidae spp
HER/MAC	3255	472	321	0.86	0.45	0.60	Clupeidae spp & Scombridae spp
Gurnard	1261	42	21	0.86	0.57	0.69	Triglidae spp
Flatfish	272	15	15	0.83	0.33	0.48	Pleuronectoidei spp

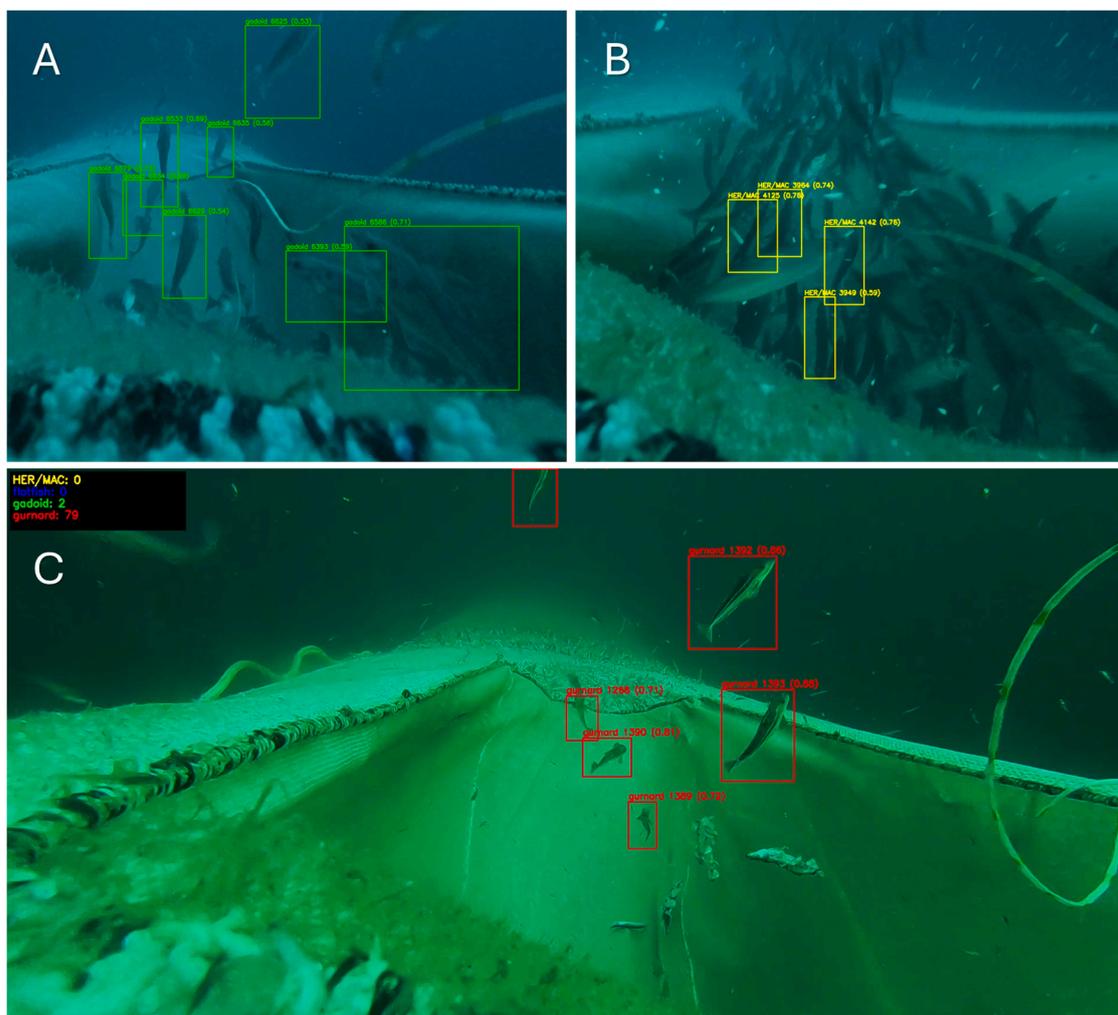


Fig. 4. Screenshots from video recorded at camera position number four during 2022. Picture A is an example of targets with relatively little overlap and minor motion blur, which enables good detection and tracking of individuals and allocation into classes. Picture B is an example of targets with high overlap and high motion blur, which reduces the possibility of detection and tracking of individuals and allocation into classes. Picture C is an example where there is no overlap between targets (gurnard-class), and herring that was excluded from the classification due to obvious signs of damage. Bounding boxes in the pictures are visualisations of the output from the trained detection model for these frames.

fish viewed from the dorsal side swimming away from the camera, and they did not move away from the exit hole in the same manner as those individuals that were still alive (hence biasing the training data with unproportional number of detections). There were also occasions when it was not possible to separate/detect individuals and allocate them to classes due to motion blur in the picture, insufficient light, and/or large numbers of fish swimming out of the exit hole at the same time (Fig. 4). The trained object detection model would consequently underestimate number of individuals when there was large overlap of targets, or the

quality of the picture was not sufficient for detection and allocation of targets into classes.

The trained model was tested on a separate data set (Test) of 450 annotated images subtracted from all hauls (sampling by time series splitting, resulting in about 0.4 images per minute per haul) that were included in the analysis of escapees. Model performance was calculated for each class separately at confidence threshold ≥ 0.7 (priority to reducing false positives) using Precision, Recall and F1-score (Bishop, 2006), according to the following equations:

$$\text{Precision} = \frac{TP}{TP + FP} \quad (3)$$

$$\text{Recall} = \frac{TP}{TP + FN} \quad (4)$$

$$F1 = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}} \quad (5)$$

where TP, FP, and FN are abbreviations for True Positive, False Positive and False Negative. True positive represents correct model predicted class matching the known “truth set”. A False Positive indicates incorrect class detection and False Negative indicates missed detection. F1-score combines precision and recall into a single measure. The highest possible value of an F1 score is 1, indicating perfect precision and recall, and the lowest possible value is 0, if either the precision or the recall is zero. Correct model prediction was defined by using the Intersect over Union (IoU) method (Redmon et al., 2016) where the proportion of the area of overlap between predicted bounding box and ground truth bounding box was ≥ 0.5 , following PASCAL VOC standards (Everingham et al., 2010).

The trained model was deployed on 10 fps video using the same confidence threshold as model testing (≥ 0.7) and ByteTrack (Zhang et al., 2022) for tracking of detections across frames. To reduce possible double counting of individuals in sequences with high visual noise (motion blur, poor visibility, large number of individuals) estimations of number of individuals in each class was based on tracks with a minimum length of 5 frames.

2.6. Estimation of gear sorting efficiency

The sorting efficiency E of the Excluder in terms of proportion released catch was calculated per haul and predefined annotation class (Table 2) based on estimated number of individuals in the landed catch in relation to estimated number of escapees through the exit hole such that:

$$E_c = \frac{N_{ec}}{(N_{ic} \times q) + N_{ec}} \times 100 \quad (6)$$

where N_{ec} is the number of escapees in annotation class c from the video analysis, N_{ic} is the number of individuals within annotation class c in the subsample of the landed catch, and parameter q is the subsampling factor for the haul. When the additional sampling level was used for collection of length measurements (herring, haul 13, 2022), the estimated number of individuals in the landed catch was given by dividing the weight of herring in the catch with mean individual weight of the herring such that:

$$(N_{ic} \times q) = \frac{(W_h/W_s) \times W_t}{(W_m/N_m)} \quad (7)$$

where W_h is the weight of herring in the subsample, W_s is the weight of the total subsample and W_t is the total landed catch weight. W_m represents weight of all length measured herring, and N_m is the number of lengths measured herring.

3. Results

Of the 31 hauls that were observed, 24 hauls (17 with Excluder and 7 without Excluder) were classified as valid and included in the analysis of catch composition (Table 3). Total catch in each of these hauls was between 15 and 157 tonnes, and the proportion of unwanted bycatches (i.e. species other than sandeel) varied between 0 – 40 % (Table 3). The length of the target species (sandeel) in the catch varied significantly between hauls both years (Fig. 5). Spatial grouping of hauls with similar sized individuals suggests this difference was a result of the size structure of the fished population rather than an effect of difference in the

selectivity of the gears (Figs. 2 and 5). The smallest recorded bycatch was juvenile cod (*Gadus morhua*) and *Crystalllogobius sp.* with a total length of 3 cm, whereas the largest bycatch was a humpback whale (*Megaptera novaeangliae*) with an estimated length of 12 m. The humpback whale was caught in the wing of the trawl during a haul when the Excluder was used.

Comparison of catch per unit effort 2021 between hauls with (11.6 ± 6.5 tonnes/h; mean \pm 95 % c.i.) and without (12.7 ± 6.1 tonnes/h; mean \pm 95 % c.i.) the Excluder indicate that the catch efficiency of sandeel was not affected by the Excluder. This result was supported by visual observations made during screening of the recorded video, the number of sandeels observed escaping the trawl through exit hole was low both years, which is also why the target species was not included as a separate class in the estimation of escapees (Table 2).

Bycatch of fish not able to pass through the bars of the water separator grid during the process of transporting the catch to the holding tanks was only observed during 2021 (Table 3). The largest measured individual caught in trawl with Excluder installed was 27 cm and the largest measured individual caught in trawl without the Excluder was 60 cm (Appendix A). The reduction of unwanted catch by the Excluder was not evident from the catch compositions analysis (Table 4), it was however clearly shown by the image analysis of estimated number of escapes. In the 4 hauls that were used for estimation of escapees, 100 % of the gadoids, gurnards and flatfishes were sorted out from the catch, which corresponds to tens of thousands of released individuals (Table 5). The Herring and mackerel class showed more variability than the other classes with a sorting efficiency that ranged from 5 % to 100 % (Table 5). As expected, due to the natural patchiness in spatial distribution of different species, the estimations of escapee class and number varied both within and between hauls (Appendix B).

Based on observations of the fish escaping the trawl, the demersal species (gadoids, gurnards and flatfishes) seemed to be in relatively good condition (swimming normally and with no visible external damages) when exiting. In contrast, the pelagic species (HER/MAC) in many cases showed abnormal swimming behaviour and visible external injuries which suggest that they received substantial damage from passage through the Excluder (Fig. 6).

Observations from camera position 1 – 3 showed that both models of the Excluder were symmetrically inflated and fully functional during active trawling. The square meshes in the inner tunnel were kept open from the beginning to the end of the tunnel and the exit hole was always accessible and unobstructed. Observation of the fish in the gear showed that the sandeel passed through the square meshes of the selection tunnel in large numbers all the way up to the most forward part of the Excluder. HER/MAC were not observed passing through the mesh in the selection tunnel until they were forced towards the tunnel netting by the plastic sheets.

4. Discussion

This study contributes new insights into the efficiency and functionality of the Excluder in the North Sea trawl fishery and presents a framework on how traditional catch composition analysis can be complemented or replaced with AI assisted image analysis of underwater footage. This methodological advancement not only reinforced previous findings presented by Eigaard et al. (2024) but also enabled a behavioural assessment of escapees, offering additional ecological context. Observing interactions with the selection surface highlighted species-specific escape strategies and potential improvements for future gear development.

The conventional sampling alone did not reveal large reductions in bycatch. Similar to the study by Eigaard et al. (2024) the proportion of bycatch varied highly between hauls both with and without the Excluder installed. This variation, and subsequent inconclusive comparison between the catch compositions, were likely due to the small sampling fraction of the catch (because of the large catch volumes) and patchy

Table 3

Detailed description of each haul that was observed during the fishery. Start time is expressed in UTC, start Depth in meters, total Effort (from start to end of haul) in hh:mm. Hauls with the Excluder mounted in the trawl are indicated by Y. Catch (tonne) is the crews estimation of total catch transported into the RSW tanks, Catch BWS (Before Water Separator) is total weight in kg of the catch that was removed by the grid on top of the water separator, Catch AWS (After Water Separator) is estimated unwanted catch in kg transported to the RSW tanks based on the sample taken after the water separator. Bycatch is calculated percentage of unwanted catch (e.i. species other than sandeel) in relation to total catch weight (Catch + Catch BWS). Camera Position indicate if and where cameras were placed in the Excluder, numbering in this column correspond with numbering of camera positions in Fig. 2. Analyses column indicates which hauls that were used for CPUE and catch composition analysis (CC) and estimation of escapees (EE). In 2021, a large part of the trawl was destroyed in haul 6, which is why there was zero catch. In haul 12.1, 2021, the codend was not emptied before the Excluder was mounted in the trawl, and it was consequently not possible to determine if the catch in haul 12.2 originated from trawl with or without Excluder. In 2022, haul 10 was not sampled due to severe weather conditions. * In 2021 haul 10, a young humpback whale (*Megaptera novaeangliae*) was caught in the trawl, the weight of this animal is estimated.

Year	Haul	Start time	Depth	Effort	Trawl model	Excluder	Catch (tonne)	Catch BWS (kg)	Catch AWS (kg)	Bycatch	Camera Position	Analyses
2021	1	2021-05-10 05:20	58	07:10	Cosmos LW	Y	31	0	12	0.0 %	2 & 3	CC
2021	2	2021-05-10 13:30	66	07:30	Slugehals	N	48	10	9	0.0 %	NA	CC
2021	3	2021-05-11 09:00	61	11:45	Egersund 1150	N	48	119	9	0.5 %	NA	CC
2021	4	2021-05-12 04:50	62	03:30	Egersund 1150	N	43	3	3	0.0 %	NA	CC
2021	5	2021-05-12 10:30	65	10:30	Egersund 1150	N	33	75	10	0.5 %	NA	CC
2021	6	2021-05-13 04:45	67	00:45	Egersund 1150	N	0	0	0	0.0 %	NA	-
2021	7	2021-05-13 08:00	56	03:10	Cosmos LW	N	57	65	134	0.5 %	NA	CC
2021	8	2021-05-13 12:30	61	04:10	Cosmos LW	N	114	110	38	0.2 %	NA	CC
2021	9	2021-05-13 18:15	64	02:55	Cosmos LW	N	52	87	0	0.3 %	NA	CC
2021	10	2021-05-14 04:55	65	03:55	Cosmos LW	Y	38	20001*	31	34.5 %	1 & 3	CC
2021	11	2021-05-14 12:00	58	01:30	Egersund 1150	N	1	28	12	6.5 %	NA	-
2021	12.1	2021-05-14 15:40	64	00:50	Egersund 1150	N	NA	NA	NA	NA	NA	-
2021	12.2	2021-05-14 18:00	65	02:40	Egersund 1150	Y	29	5	204	0.7 %	2 & 3	-
2021	13	2021-05-15 04:55	61	05:35	Egersund 1150	Y	1	3	52	6.6 %	1 & 4	-
2021	14	2021-05-15 13:15	61	00:35	Egersund 1150	Y	1	0	0	0.0 %	2 & 4	-
2021	15	2021-05-15 15:10	63	06:10	Egersund 1150	Y	157	0	0	0.0 %	2	CC
2021	16	2021-05-16 04:45	60	05:45	Egersund 1150	Y	71	3	0	0.0 %	4	CC
2021	17	2021-05-16 12:00	60	08:55	Egersund 1150	Y	55	20	2942	5.4 %	NA	CC
2022	1	2022-04-28 05:05	54	06:35	Slugehals	Y	40	0	63	0.2 %	1 & 4	CC
2022	2	2022-04-28 14:25	56	06:35	Slugehals	Y	60	0	5168	8.6 %	4	CC
2022	3	2022-04-29 05:30	55	06:37	Slugehals	Y	70	0	716	1.0 %	3 & 4	CC
2022	4	2022-04-29 13:30	55	07:00	Slugehals	Y	90	0	3741	4.2 %	4	CC
2022	5	2022-04-30 04:55	45	08:10	Slugehals	Y	65	0	0	0.0 %	2 & 4	CC
2022	6	2022-04-30 14:35	45	05:49	Slugehals	Y	30	0	65	0.2 %	4	CC & EE
2022	7	2022-05-01 05:40	44	06:20	Slugehals	Y	30	0	611	2.0 %	3 & 4	CC
2022	8	2022-05-01 16:55	45	03:12	Slugehals	Y	15	0	6022	40.1 %	4	CC
2022	9	2022-05-02 09:45	50	07:50	Slugehals	Y	140	0	0	0.0 %	4	CC
2022	10	2022-05-02 18:35	50	02:13	Slugehals	Y	40	0	NA	NA	NA	-
2022	11	2022-05-03 04:55	50	02:45	Slugehals	Y	20	0	0	0.0 %	2 & 4	CC & EE
2022	12	2022-05-03 18:05	65	02:25	Cosmos LW	Y	5	0	1268	25.4 %	NA	-
2022	13	2022-05-04 05:15	66	05:08	Cosmos LW	Y	120	0	18082	15.1 %	2 & 4	CC & EE
2022	14	2022-05-04 11:42	82	06:13	Cosmos LW	Y	120	0	1339	1.1 %	4	CC & EE

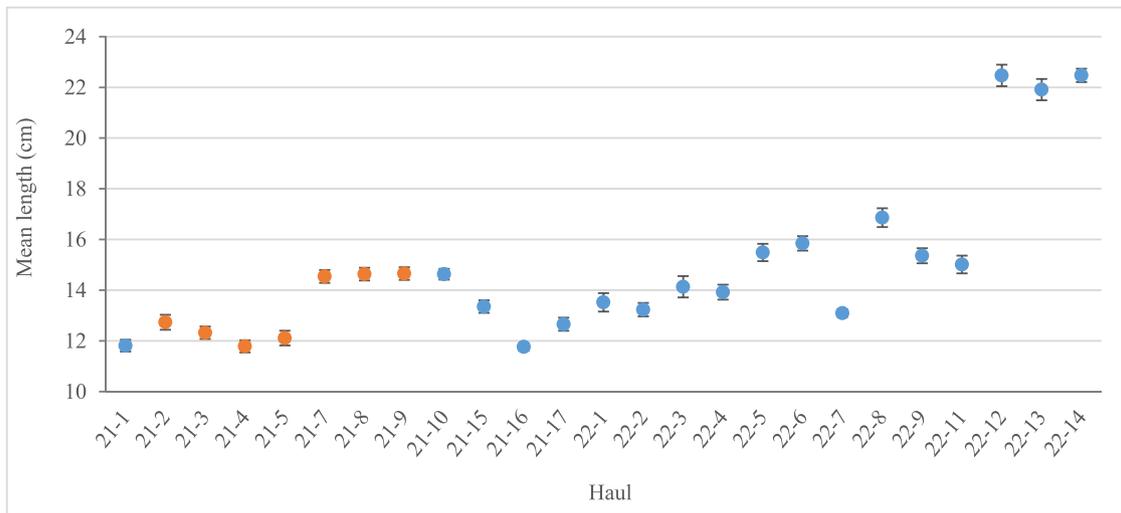


Fig. 5. Mean individual length of sandeel per haul. Blue dots represent hauls with Excluder, orange dots represent hauls without Excluder, error bars represent 95 % confidence interval. Similar sized individuals in neighbouring hauls conducted within the same area (see Fig. 1) suggest that the difference in size of the target species was an effect of the size distribution in the fished population rather than the selectivity of the gear.

Table 4

Catch composition in weight in hauls with and without Excluder (Control) expressed as average species dominance in % for all encountered species per year. Values in () represents 95 % confidence interval. *The cod caught in the Excluder during 2022 were juveniles with a length of 3–4 cm. Species marked with NA are species that were not encountered during 2022.

Species	Control 2021	Excluder 2021	Excluder 2022
Sandeel	99.70 (99.56–99.85)	92.02 (78.24–99.98)	93.96 (88.58–98.17)
Humpback whale	0.00 (0.00–0.00)	6.90 (0.00–20.69)	NA
Herring	0.00 (0.00–0.00)	0.00 (0.00–0.00)	5.50 (1.18–10.80)
Haddock	0.03 (0.00–0.06)	0.79 (0.00–2.35)	NA
Whiting	0.00 (0.00–0.00)	0.29 (0.00–0.87)	0.22 (0.00–0.57)
Mackerel	0.22 (0.09–0.36)	0.00 (0.00–0.00)	0.30 (0.03–0.70)
Squid sp	0.03 (0.00–0.08)	0.00 (0.00–0.00)	NA
Red gurnard	0.00 (0.00–0.01)	0.00 (0.00–0.00)	0.01 (0.00–0.04)
Cod*	0.00 (0.00–0.00)	0.00 (0.00–0.00)	0.01 (0.00–0.03)
<i>Crystallogobius sp</i>	0.01 (0.00–0.02)	0.01 (0.00–0.02)	NA
Sprat	0.01 (0.00–0.02)	0.00 (0.00–0.00)	NA
Angler fish	0.00 (0.00–0.00)	0.00 (0.00–0.00)	NA
Saithe	0.00 (0.00–0.00)	0.00 (0.00–0.00)	NA
Shorthorn sculpin	0.00 (0.00–0.00)	0.00 (0.00–0.00)	NA

spatial distribution of the non-target species. By contrast, the image-based escapee estimates provided direct evidence of the Excluder’s sorting performance in real fishing conditions. These results demonstrate that automated image analysis can not only be used to assess the effectiveness of a bycatch exclusion device in situations when sufficient sampling of the catch is difficult to achieve, but it may also outperform traditional catch comparison methods. The use of underwater cameras eliminated the need to recapture the escapees and removed potential biases from environmental variability between hauls. This approach also avoids the ethical and logistical challenges of traditional catch comparison or recapture experiments, which often lead to mortality of unwanted catch and are difficult and expensive to perform (Sloman et al., 2019; Wileman et al., 1996). Thus, our work highlights how modern computer vision techniques can complement traditional catch sampling and contribute to more cost effective, ethical and precise assessments of gear performance. If the image-based method presented here was applied on a broader scale, it would significantly reduce the number of marine vertebrates used for experimental purposes within fisheries science, in line with the 3 R principles mandated by the EU (European Parliament, Council of the European Union, 2010).

The most notable performance outcome was the near-complete reduction of demersal bycatch species. Gadoids, gurnards, and flatfish were consistently released with sorting efficiencies approaching 100 %.

Although these estimates are associated with some uncertainty due to the small sampling fraction of the landed catch and the precision of the object detection model, the image analysis showed that tens of thousands of individuals were escaping through the Excluder, providing clear evidence of its effectiveness. In contrast, pelagic species such as herring and mackerel showed occasionally much lower escape rates, with substantial proportions retained in the catch. This outcome is likely due to differences in both size, morphology and the behaviour of the different species, as well as the volume of fish entering the Excluder. Herring and mackerel are relatively small and slender species, generally smaller than the 27 cm that was the maximum measured size passing through the selection net, and they form dense schools when herded into fishing gears (Bayse and He, 2017). The recorded video showed that these schools did not disperse and go through the selection net of the inner tunnel without the school was forced towards the selective netting by the plastic sheets. This observation suggests that the sorting efficiency of the Excluder for schooling pelagic species to some extent is density dependant.

Nonetheless, the automated image analysis also presented challenges. While the object detection model achieved moderate to good precision-scores (ranging from 0.83 for flatfishes to 0.95 for gadoids), its recall values (the proportion of all positives that were classified correctly as positives), were relatively low. These performance metrics, and the

Table 5

Estimated sorting efficiency of the Excluder by numbers of individuals in % per annotation class and haul. Landed represents estimated number of individuals within the annotation class in the landed catch, Escapees represent estimated number of individuals within the annotation class escaping the trawl through the exit hole of the Excluder.

Class	Haul	Landed	Escapees	Sorting efficiency
gadoid	6	0	1104	100
gadoid	11	0	565	100
gadoid	13	0	6031	100
gadoid	14	0	26901	100
HER/MAC	6	1304	69	5
HER/MAC	11	0	334	100
HER/MAC	13	258317	24855	9
HER/MAC	14	20287	5650	22
gurnard	6	0	774	100
gurnard	11	0	83	100
gurnard	13	0	27	100
gurnard	14	0	265	100
flatfish	6	0	4	100
flatfish	11	0	326	100
flatfish	13	0	0	NA
flatfish	14	0	0	NA

fact that even with perfect precision/recall the count would still be incomplete due to targets being obscured during mass exits, suggest that the actual number of escapees was likely underestimated. Consequently, the quantified escapee counts are conservative, meaning that the sorting efficiency of the Excluder is likely even higher than the estimates produced in this study. Future improvements in tracking algorithms and a multiple camera approach, could possibly reduce such biases. It should also be noted that the image analysis conducted during this study was only possible to apply to four hauls, all from the same area and year. Hauls from a different area, with a different species and size composition, would likely generate other values for the sorting efficiency.

The estimated proportions of unwanted bycatch in this study ranged from zero and up to 40 % in some hauls, a figure notably higher than the 2 % reported by ICES (2017) in the Sandeel Benchmark. The study by Eigaard et al. (2024) observed similar discrepancies with bycatch proportions up to 30 % in this fishery. Herring was the main contributor to the high bycatch proportions in both studies. It is therefore unfortunate, and potentially problematic, that the herring passing through the Excluder frequently showed scale loss and abnormal swimming

behaviour. If pelagic bycatch species like herring and mackerel exhibit high escape mortality even when excluded before codend entry, the impact on stock dynamics may remain significant despite being reduced in the catches (Suuronen, 2005). The implementation of the Excluder in the sandeel fishery could potentially also change the behaviour in this fishery. If there are large schools of herring in the water on the fishing banks the boats would previously move to another area to avoid large bycatches as bycatches of quota species generally comes with a cost for the individual boats in terms of loss of income. With the Excluder the vessels can continue to fish despite large concentrations of pelagic species and thus potentially generate large volumes of unaccounted mortality. The observed capture of a humpback whale in 2021, though an isolated incident unrelated to the Excluder itself, also underscores the broader issue of marine mammal interactions in the industrial trawl fishery.

From a fisheries management perspective, this study reinforces the Excluder's value as a viable bycatch mitigation tool in large scale fine meshed trawl fisheries. By minimizing demersal bycatches while maintaining sandeel catch efficiency, the device aligns with EU

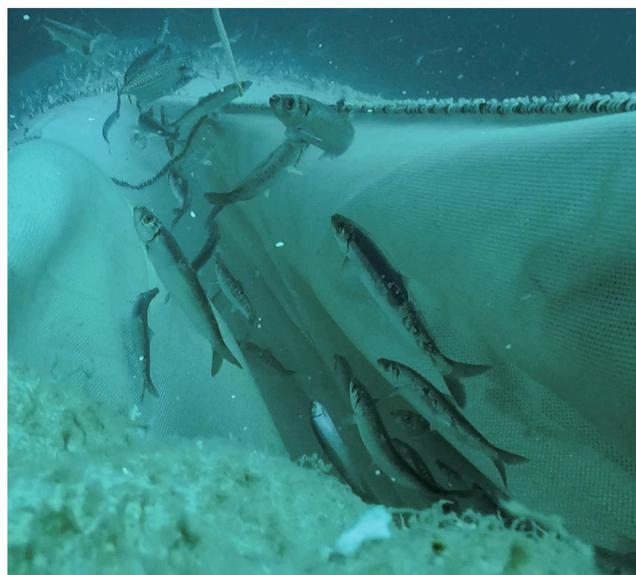


Fig. 6. Herring showing signs of injuries from the passage through the Excluder, such as loss of scales and unnatural swimming behaviour.

objectives to reduce as far as possible unwanted catches and discards under the Common Fisheries Policy. However, successful implementation relies on fishers' willingness to adopt and properly deploy the device. Additionally, long-term monitoring, and complementing escapee survival studies, is essential to better understand the wider ecosystem effect.

CRedit authorship contribution statement

Daniel Valentinsson: Writing – review & editing, Conceptualization. **Mikael Ovegård:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

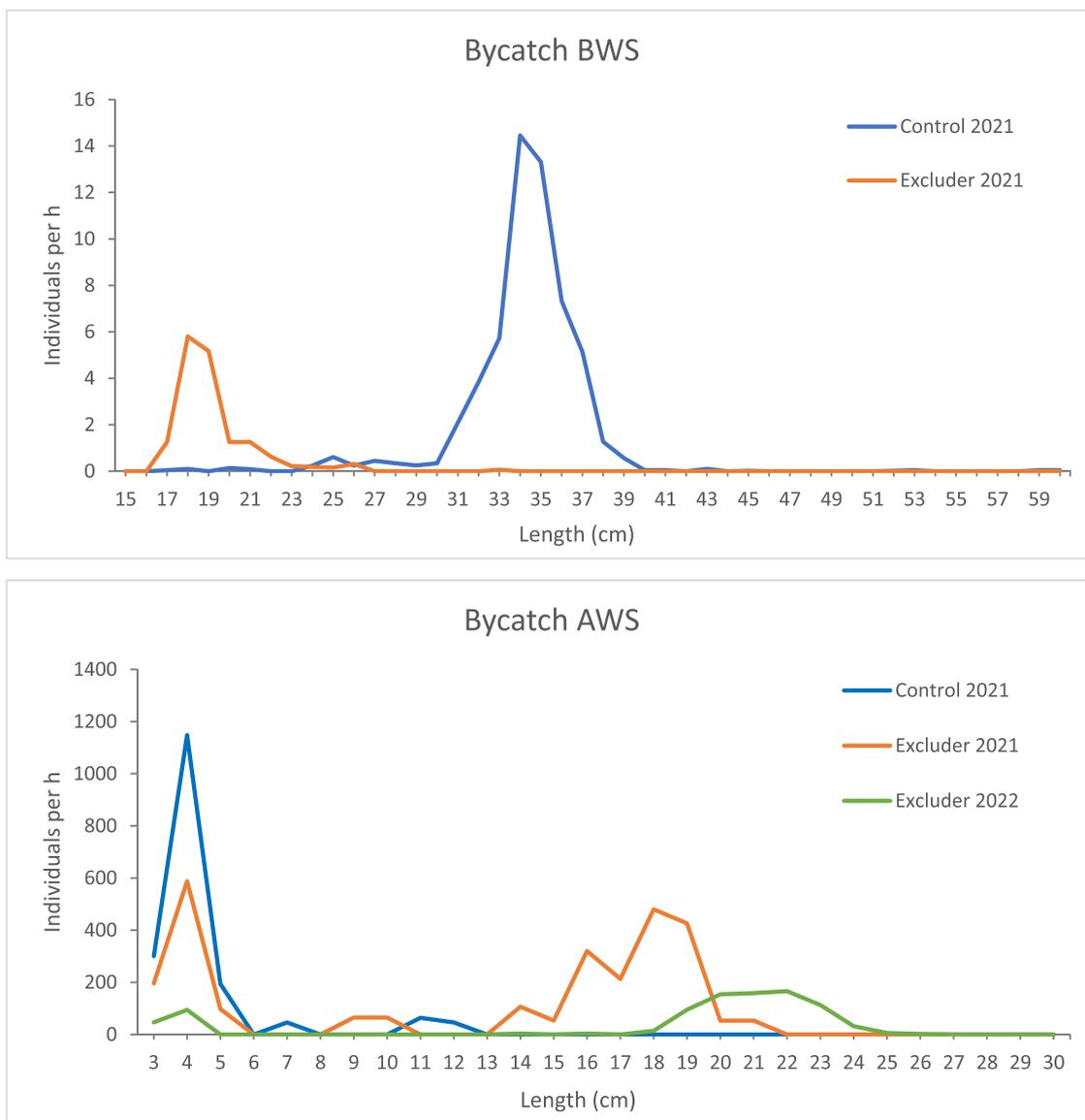
Declaration of Competing Interest

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.

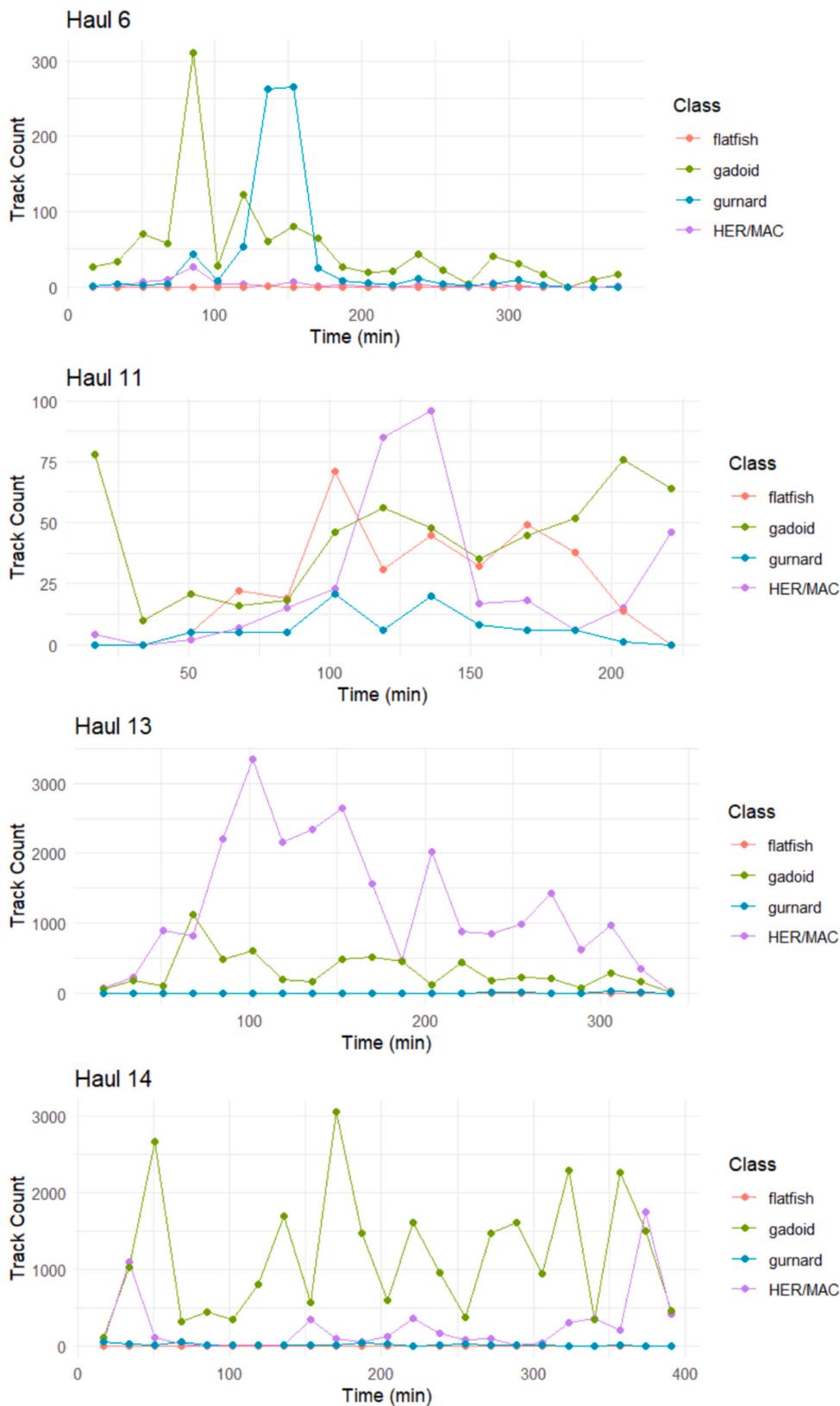
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Appendix A. Length distributions of the unwanted catch that was removed by the grid on top of the water separator (BWS) and in the subsample after the water separator (AWS) presented in CPUE



Appendix B. Number of escapees per annotation class and haul with summaries per video file. The GoPro camera automatically splits recorded video into 4 GB sequences, which gives about 17 min of recorded video per file at 1920 × 1080 resolution and 30 fps



Data Availability

Data will be made available on request.

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