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Reducing flatfish bycatch in roundfish fisheries

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ABSTRACT

Flatfish bycatch is a concern in many demersal trawl fisheries around the world, especially for fisheries operating under discard-ban regulations. We introduce and assess the performance of FRESWIND (Flatfish Rigid EScape WINDows), a concept for a selection device that reduces flatfish bycatch in roundfish-directed fisheries. The new concept was tested for the first time in the Baltic cod-directed fishery, using a commercial twin trawler. The vessel was rigged with two trawls; one standard trawl gear and one incorporating the experimental FRESWIND. Comparison of the catches from both trawls exhibited up to ~68% reduction in flatfish bycatch for the trawl with FRESWIND mounted. In addition, the catch of undersized cod was reduced by ~30%, whereas losses of marketable cod were relatively minor (~7%). Further simulations predicted that, in the commercial fishery, a reduction of more than 50% in flatfish bycatch could be achieved if FRESWIND were adopted. Given these promising results, FRESWIND may also provide a method that significantly reduces flatfish bycatch in other fisheries.

1. Introduction

Discarding is an ethically and ecologically undesirable fishing practice of global concern. It wastes natural resources and severely challenges the sustainability of fisheries (Hall et al., 2000). It decreases the efficiency of fishing operations and changes the trophic flows in foodwebs and entire ecosystems (Catchpole et al., 2005; Greenstreet et al., 1999).

Societal interest groups have discussed the consequences of discarding and potential solutions intensively for decades (Catchpole et al., 2005; Alverson and Hughes, 1996). To date, different strategies have been implemented around the world to reduce or avoid unwanted catches (Condie et al., 2014). For example, one of the main aims of the upcoming European Commission Common Fisheries Policy reform (EU regulation 1380/2013) is to phase out discards by obliging fishermen to keep all catches of species with quota on board, land them, and count them against their quotas. The new policy is controversial because it puts the economic viability of the industry at risk, especially fleets engaged in mixed fisheries, where the bycatch of species with low quota can alter or even stop the normal fishing activities focused on species with less constraining quotas (STECF, 2014). It is a fishing industry priority to reduce and/or avoid the catch of such choke species (those species that can prematurely close a mixed fishery due to the exhaustion of their limited quotas).

Flatfish bycatch contributes substantially to the volume of discards in many demersal trawl fisheries around the world (Storr-Paulsen et al., 2012; Anon, 2011; Branch, 2006; Borges et al., 2005). This is often the result of a mismatch between the selectivity properties of the gear and the specific characteristics of flatfish morphology. For example, flatfish bycatch often occurs in fisheries targeting roundfish species (Wienbeck et al., 2014; Milliken and DeAlteris, 2004). Attempts to improve the selectivity in these fisheries often involve codend modifications in order to improve the size selectivity of the target species. These modifications include strategies like increasing codend mesh size or using meshes with square geometry (Guijarro and Massutí, 2006; Ordines et al., 2006; Fonteyne and M'Rabet 1992). Square mesh geometry facilitates escapement for roundfish species, while the effect on flatfish selectivity is unclear or negative (Guijarro and Massutí, 2006; Fonteyne and M'Rabet, 1992; Robertson and Stewart, 1988). These obser-

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vations indicate that alternative technological methods should be applied to reduce flatfish bycatch in roundfish fisheries.

This paper introduces a new concept for a selection device specifically developed for flatfish species. The FRESWIND (Flatfish Rigid EScape WINDows) uses the special morphology of flatfish to optimize selectivity (i.e., to largely avoid flatfish catches) without compromising the catchability of marketable sizes of the roundfish target species. FRESWIND is designed to be mounted ahead of the codend, to create a sequential selection process in which flatfish selection is achieved mainly by FRESWIND and roundfish size selection is achieved in the codend.

FRESWIND was tested for the first time in the western-Baltic-cod-directed trawl fishery, with catches composed primarily of the target species (*Gadus morhua*), with a mix of flatfish species taken as bycatch. To date, most research efforts in Baltic Sea trawl fisheries have concentrated on improving the size selectivity of cod through codend modifications (Madsen, 2007). As a result, two cod-selective codends are mandatory in the area (T90 and BACOMA; EU 686/2010). Although these codends present good size-selective properties for cod, flatfish selectivity is an increasing concern in the fishery, because species with limited quotas, such as plaice (*Pleuronectes platessa*), can disrupt normal fishing strategies due to the landing obligation rules stated in the new European policy (STECF, 2014; Wienbeck et al., 2014).

This study assesses the performance of a FRESWIND design, developed specifically for the Baltic cod-directed fishery, on the targeted cod and two common flatfish species in the area, plaice and flounder (*Platichthys flesus*). Plaice is the most valuable flatfish bycatch, regulated by total allowable catches (TACs) and a minimum landing size (MLS) of 25 cm. Estimates from the German catch sampling program in commercial fisheries yielded discard ratios ranging from10% to 100% between trips, with mean values from 10% to 40% in the cod directed-trawl fishery. Flounder is the most widely distributed flatfish species in the Baltic Sea, regulated by a MLS of 23 cm (ICES Subdivisions 22–25). It is mainly a bycatch species (ICES, 2012), and the German catch sampling program estimates discard ratios with high variation between trips (0–100%) and mean discard values between 5 and 40%.

This paper will investigate the performance of FRESWIND in the Baltic cod-directed trawl fishery. Further, we predict the consequences of the commercial fishery adopting FRESWIND.

2. Material and methods

2.1. The FRESWIND concept

The FRESWIND concept relies on the differences in flatfish and roundfish species morphology to optimize species selectivity. It was proposed originally by Swedish fisherman Vilnis Ulups, and further developed into the device presented here. The experimental gear design consists of rigid windows mounted on each side of a four-panel extension piece connected forward to the codend. The windows are constructed as grid-like sections with horizontal bars of steel to ensure well defined escape outlets, allowing the body shape of flatfish to pass in natural swimming orientation (Fig. 1). The windows were made of bars 10 mm in diameter with 38 mm barspacing. For this barspacing, the FISHSELECT method (Herrmann et al., 2009) predicted escapement possibilities for a wide range of flatfish sizes, while enabling only escapements for undersized cods (below Minimum Landing Size, MLS = 38 cm). The extension piece where the FRESWIND was mounted was cut in a way that induced ∼45° angle of attack of the windows in relation to the towing direction. By using this specific design, it is intended to produce a tapering zone, which should enhance the probability for a fish to come into contact (attempt made by the fish to escape (Sistiaga et al., 2010)) with the side windows when swimming or drifting towards the codend. The extension piece was made with four net panels of 4 mm double twine and diamond mesh netting. The mesh size was 120 mm, and the number of meshes around was 4 × 25. A V-shape guiding device 860 mm high and 200 mm wing length, was mounted in the centerline of the extension piece ahead of the windows, with the aim of directing fish from the central path of the extension towards the windows. Wires were inserted into the vertical edges of the guiding device to increase its stiffness.

The codend used after the extension piece was the mandatory BACOMA codend (EU 686/2010) provided by the fishers. With this combination of FRESWIND and the codend, a stepwise selection process along the gear is intended, in which flatfish selection is achieved mainly by FRESWIND and cod size selectivity is achieved by the codend.

2.2. Sea trials

Sea trials were carried out on the German commercial twin trawler FV “Crampas” (18 m, 219 kW) during daytime. The cruise was conducted in the western Baltic, west of the island of Bornholm (ICES Subdivision 24), 15–25 March 2013, during the major cod fishing period. The skipper chose the fishing ground and fishing tracks based on his normal fishing strategies, to ensure the fish populations available for the gears were representative of the commercial trips. Two trawls model *ballontrawl 260*, constructed with 120 mm diamond mesh size netting, and with 260–144 meshes in circumference (from the square to the last section of the belly) were provided by the vessel. The groundrope of the trawls were equipped with rubber discs, and the doors used were Thyborön Type 11, weighting 451 kg. The trawls were equipped with the mandatory BACOMA codend and extension pieces. The extension pieces were identical, except that one included the FRESWIND device. The combination of the FRESWIND device and the BACOMA codend is denoted hereafter as the *test* selection system; the setup with the simpler extension piece (without FRESWIND) and the BACOMA codend is denoted as the *reference* selection system. The trials were conducted as a catch comparison experiment (Krag et al., 2014). The test and reference gear were twin trawled for each haul, and the position of each gear were swapped after completing half of the planned experimental hauls, to remove effects from side. Catches from each experimental haul were weighted by species, and the total length of all fish was measured with electronic measuring boards (0.5 cm below).

2.3. Data analysis

2.3.1. Estimation of catch comparison (CC) curves

The number of individuals of each length class caught in each of the trawls was used to evaluate the length-dependent relative catching efficiency of the two trawls for each species separately. For each of the species considered, the proportion of catches in the test system to the total in a haul i was given as:

$$CC_{il} = \frac{nt_{il}}{nt_{il} + nr_{il}} \tag{1}$$

where, nt_{il} is the number of fish of length class l caught by the test system in haul i, and nr_{il} represents the same number for the reference system. The experimental CC_{il} data are commonly used in catch-comparison analyses to estimate the gain/loss of catchability of the test gear, assuming that the observed trend is caused by the introduction of a selection device in the reference gear (Krag et al., 2014). In catch comparison studies, it is of main interest to assess any potential length dependency on the observed catch proportions. This assessment is carried out by estimating the most likely functional form of the catch comparison curve $CC(l)$.

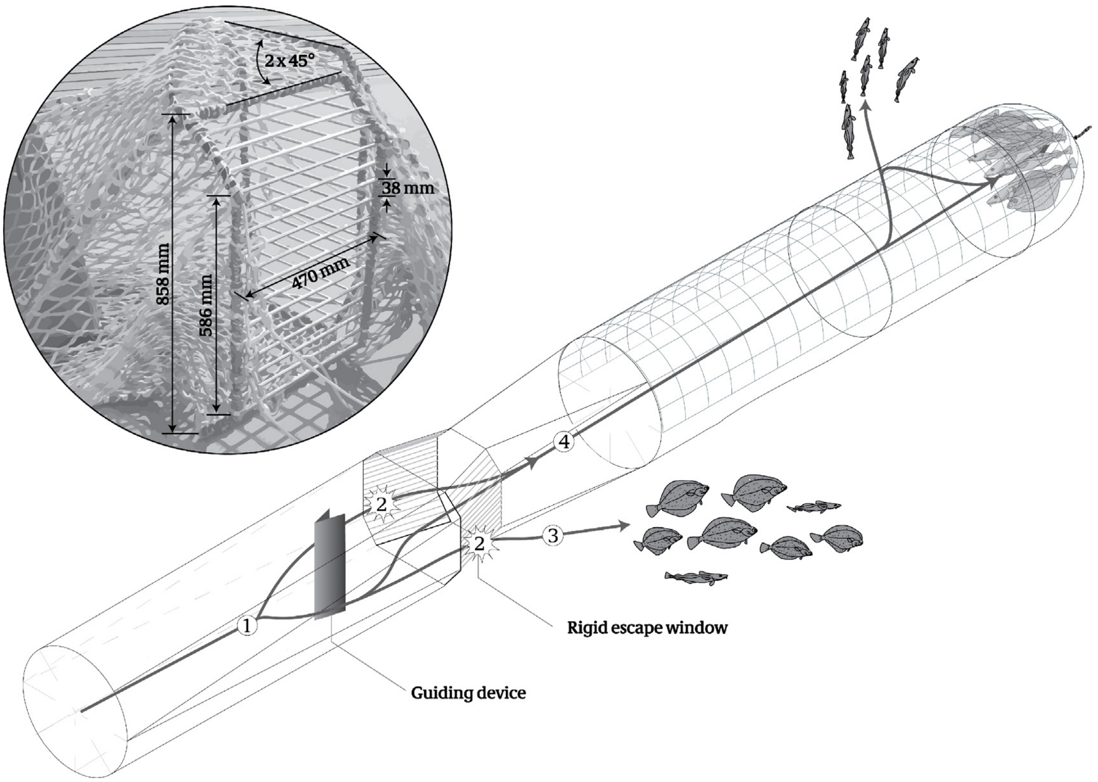

Fig. 1. Sequential selection system with FRESWIND mounted in front of the BACOMA codend. The numbers represent the different events occurring when fish swim into the FRESWIND enclosure. Fish entering the extension piece are guided sideways by the V-shaped canvas device (1). Fish escapements (3) after contacting the windows (2) depend on FRESWIND size selection, which is defined by the bar spacing. Fish not contacting the windows, or not able to escape through the rigid windows because of inefficient contact or size selection, retake the path towards the codend (4), where a successive, cod-directed selection process takes place. Steps 2 and 3 are parametrized in the alternative structural equation model (see Eqs. (3) and (4)). Topleft: FRESWIND picture showing design details of the windows.

Assuming that the performance of the tested device over the hauls conducted during the experiment, is a representative sample of how it would perform under commercial fishery, estimation of the averaged *CC(l)* curve would provide information on the consequences for the catching efficiency by adopting the device in the fishery (Millar, 1993; Sistiaga et al., 2010). The averaged catch comparison of hauls is estimated by pooling the data from the different hauls. A parametric model for *CC(l)* is defined by *CC(l,v)*, where v is a vector consisting of the parameters of the model. The catch-comparison analysis is therefore reduced to a regression problem to estimate the values of the parameters v, which make the observed experimental data averaged over hauls most likely, assuming that the model is able to describe the data sufficiently well. Thus, the maximum likelihood function for binomial data (Eq. (2)) is minimized with respect to v, which is equivalent to maximizing the probability for the observed data.

$$-\Sigma\Sigma\{nt_{il} \times \ln(CC(l,v)) + nr_{il} \times \ln(1.0 - CC(l,v))\} \tag{2}$$

where the sums are for hauls i and length classes l. Evaluation of a model's ability to describe the data sufficiently well using Eq. (2) was based on the calculation of the corresponding p-value together with the visual inspection of residuals distribution. See Wileman et al. (1996) for details on how to apply these fit statistics.

It is necessary to identify the appropriate models for *CC(l,v)* to be able to apply Eq. (2) to the evaluation of the catch-comparison rate for the gear with FRESWIND compared with the reference gear. The two models considered are described in the following subsections.

2.3.1.1. Polynomial model. In catch comparison analysis, the *CC(l,v)* is often modelled using the following equation:

$$CC(l,v) = \frac{\exp(f(l, q_0, \ldots, q_j))}{1 + \exp(\mathrm{f}(l, q_0, \ldots, q_j))} \tag{3}$$

where, *CC*(*l*,*v*)) expresses the probability of finding a fish length class *l* in the codend of the test gear, given that it was found in one of the two codends. A value of $CC = 0.5$ would mean a balanced probability of finding the fish in one of the two codends, implying no FRESWIND effect on catch efficiency. The term *f* in Eq. (3) refers to a polynomial of order *j* with coefficients q_0–q_j, such that $v = (q_0,\ldots,q_j)$. We considered *f* up to an order of 4 with parameters q_0, q_1, q_2, q_3, and q_4. Leaving out one or more of the parameters $q_0q_0,\ldots,q_jq_4$ led to 31 additional models that were also considered potential candidates for the catch-comparison function *CC(l,v)*. Selection of the best model for *CC(l,v)* among the 32 competing models was based on a comparison of their respective Akaike information criterion (AIC) values (Akaike, 1974). The model with the lowest AIC value was selected as the best model used to describe the experimental catch-proportion data.

2.3.1.2. Structural model. The structural model had the following form:

$$CC(l, \mathrm{C}, \mathrm{L50}, \mathrm{SR}, \mathrm{SP}) = \frac{\mathrm{SP} \times C\mathrm{Logit}(\mathrm{C}, \mathrm{L50}, \mathrm{SR})}{\mathrm{SP} \times C\mathrm{Logit}(\mathrm{C}, \mathrm{L50}, \mathrm{SR}) + 1 - \mathrm{SP}} \tag{4}$$

With:

$$C\mathrm{Logit}(l, C, \mathrm{L50}, \mathrm{SR}) = 1 - C \times \left(1 - \frac{\exp\left(\ln(9) \times \frac{(\mathrm{l}-\mathrm{L50})}{\mathrm{SR}}\right)}{1 + \exp\left(\ln(9) \times \frac{(\mathrm{l}-\mathrm{L50})}{\mathrm{SR}}\right)}\right) \tag{5}$$

Table 1
Length class range and catch abundance by minimum landing size (MLS; N_-= numbers below MLS; N_+= numbers equal to or above MLS) and haul observed in test and reference gears for the three species under study (length classes pooled to the centimeter below).

		Cod			Plaice			Flounder		
Haul no.	Gear	Length range (cm)	N_-	N_+	Length range (cm)	N_-	N_+	Length range (cm)	N_-	N_+
1	Ref	40–40	0	1	24–37	1	6	12–42	230	135
	Test	42–57	0	2	36–36	0	1	15–27	69	34
2	Ref	40–50	0	4	24–25	1	1	15–28	203	96
	Test	–	0	0	33–33	0	1	17–26	55	29
3	Ref	28–65	27	266	20–42	79	301	17–42	57	742
	Test	28–68	8	210	20–42	24	109	18–40	15	275
4	Ref	26–62	20	63	21–45	18	251	20–37	14	97
	Test	27–52	8	37	22–38	7	50	21–37	3	67
5	Ref	27–56	41	177	22–43	53	204	20–41	33	236
	Test	26–57	50	176	23–37	15	89	19–40	17	96
6	Ref	27–59	8	66	22–42	30	115	18–37	25	277
	Test	27–62	29	77	22–43	14	54	20–37	14	103
7	Ref	25–62	65	238	22–38	27	102	18–44	37	186
	Test	25–64	77	222	22–38	6	50	21–39	4	72
8	Ref	24–57	67	83	20–37	53	234	18–40	91	419
	Test	24–58	36	59	22–46	15	170	19–35	39	196
9	Ref	21–70	22	51	22–39	39	276	18–38	25	149
	Test	29–56	8	68	21–46	11	103	20–37	5	74
10	Ref	26–66	18	69	21–46	15	176	21–42	8	112
	Test	31–56	5	42	22–40	12	98	22–40	1	63
11	Ref	26–100	78	309	22–38	30	206	18–38	23	134
	Test	27–74	28	361	22–39	15	111	20–47	10	64
12	Ref	25–56	31	120	22–37	14	122	19–42	14	94
	Test	35–70	6	93	22–40	5	73	20–32	5	23
Pooled	Ref	21–100	377	1447	20–46.5	360	1994	12.5–44.5	760	2677
	Test	24–74	255	1347	20–42	124	909	15–47.5	237	1073

where *SP* is the assumed length independent split parameter, which quantifies the probability of a fish entering the extension piece of the test gear, given that it enters one of the two extension pieces. Because the two trawls are identical in design and rigging, except in the section just ahead of the codend, an average *SP* of ≈0.5 is expected, implying equal probability for a fish to enter one of the extension pieces. Therefore, for the analysis, *SP* is assumed to be a constant with a value of 0.5. The justification for considering Eq. (4) with Eq. (5) as a candidate to model the catch comparison performed in this study is that the *C*Logit given by Eq. (5) could account for the reduced probability for fish entering the codend with FRESWIND installed in the extension piece. The parameter *C* can be interpreted as the fraction of fish entering the FRESWIND zone that actually make contact with the FRESWIND windows on their way toward the codend. *L50* (fish length with 50% retention probability) and SR (Selection Range: range between lengths with expected 25 and 75% retention probability) can be interpreted as the selection parameters for fish making contact with the FRESWIND windows (see Herrmann et al., 2013 for further details on model (5)). To validate the use of this modelling alternative on the current experimental data, it is necessary to compare its performance with that of the polynomial-based model (3). The diagnosis of the usability of model (5) is done by (i) plotting together the curves estimated by both methods to inspect if model (4)–(5) provides a description of the experimental catch-proportion data similar to the polynomial model (3), and (ii) checking and comparing the pattern of Pearson residuals from both models (Wileman et al., 1996). In case it is concluded that Eqs. (4) with (5) can be applied equally as well to the experimental data as Eq. (3), the structural model will be used for further analysis. This type of model allows better extrapolations outside the range of available length classes from the experimental dataset than the empirically based type given by Eq. (3), because it is bounded in the nature of the Eqs. (4) and (5) (Fryer and Shepherd, 1996). The catch comparison analyses described above were performed using the statistical analysis software SELNET (Herrmann et al., 2012).

2.3.2. *Estimation of catch ratio curves*

Catch comparison curves cannot directly express the rate of fish of length *l* that would be retained in the codend when using the FRESWIND, relative to the standard gear. Experimentally, such a question can be answered by the catch ratio (*CR*):

$$CR_l = \frac{nt_l}{nr_l} \tag{6}$$

where, data were pooled for hauls, therefore skipping the subscript for individuals. Combining Eq. (1) for the experimental catch-comparison rate with Eq. (6) leads to:

$$CR_l = \frac{CC_l}{1 - CC_l} \tag{7}$$

Thus, if the catch comparison curve *CC(l,v)* has been estimated at a specific length, the catch ratio derived in Eq. (7) can also be estimated. If a functional description of the catch-comparison rate is established, based on the procedure described in the preceding sections, the functional form for the catch ratio *CR(l,v)* can be estimated by:

$$CR(l, v) = \frac{CC(l, v)}{1 - CC(l, v)} \tag{8}$$

Eq. (8) is used to assess the length-specific benefit of using the test selective system (FRESWIND + BACOMA) compared with the reference selective system (BACOMA codend alone). For the marketable sizes of target species (sizes above MLS), the value of *CR(l,v)* should preferably be close to 1.0. In contrast, *CR(l,v)* values closer to 0 are desirable for length classes below MLS and for non-target species. For example, a value of *CR(l,v)* = 0.4 implies that the test gear presents a catch efficiency of 40% for length class *l*, compared with the reference gear, which represents a reduction in the catch by 60%.

2.3.3. *Estimation of usability indicators*

To evaluate the usability of FRESWIND in conjunction with the size-selective codend for the specific fishery, three different indicators were estimated each for cod, plaice, and flounder separately.

Contrary to the catch ratio curve, the indicators defined in this section consider the size structure of the population caught. The following indicators are used:

$$\begin{aligned} nP_- &= 100 \times \frac{\sum_i \left\{ \sum_{l<MLS} nt_{il} \right\}}{\sum_i \left\{ \sum_{l<MLS} nr_{il} \right\}} \\ nP_+ &= 100 \times \frac{\sum_i \left\{ \sum_{l\geq MLS} nt_{il} \right\}}{\sum_i \left\{ \sum_{l\geq MLS} nr_{il} \right\}} \\ nP &= 100 \times \frac{\sum_i \left\{ \sum_{l} nt_{il} \right\}}{\sum_i \left\{ \sum_{l} nr_{il} \right\}} \end{aligned} \tag{9}$$

where, the sum of i is for hauls and l is for length classes. nP_- and nP_+ estimate the ratio of catches below and above MLS, for the test selection system to the reference system, while considering the size structure of the population caught in the reference gear. nP_- and nP_+ are specifically useful for species under discard practices highly conditioned to MLS, allowing a combined assessment on how much and in what sense the catches from the reference system is altered by the effect of FRESWIND. For a good performance for species on which MLS has a strong influence on discard patterns, nP_- should be low whereas nP_+ values should be kept high (close to 100), i.e., that the use of FRESWIND does not lead to considerable loss of individuals greater than MLS, compared with the codend alone. The indicator denoted as nP provides the ratio of catches in the test gear to the catches in the reference gear greater than the available length range; nP represents an indicator of the global change in catch profile resulting from the FRESWIND effect. This indicator is particularly noteworthy for bycatch species, such as flounder in the Baltic Sea, where MLS is not the main factor affecting discard behavior.

2.3.4. *Assessment of confidence intervals*

The confidence intervals (CI) for the averaged catch comparison curve *CC(l,v)* based on Eq. (2), were estimated using a double bootstrap approach, accounting both for uncertainty at haul level and between haul variation. 2000 bootstrap iterations were applied to estimate the Efron percentile 95% confidence limits (Efron, 1982) for all relevant length classes. This approach, which avoided underestimating confidence limits when averaging over hauls, is identical with the one described in Sistiaga et al. (2010) and Herrmann et al. (2012). Traditionally, the CI for a curve and for the parameter values describing this curve are estimated without accounting for potentially increased uncertainty resulting from uncertainty in the selection of the model used to describe the curve (Katsanevakis, 2006). In this study, we accounted for this additional uncertainty of the catch comparison curve, when this was based on the polynomial model (3) (see Section 2.3.1.1) by incorporating an automatic model selection based on which of the 32 models produced the lowest AIC for each of the 2000 bootstrap iterations. It was not necessary to account for such increased uncertainty in the structural-based model (4) and (5) because this has a fixed functional form (see Section 2.3.1.2).

The uncertainty of *CR(l,v)*, nP_-, nP_+, and nP was also assessed by including these parameters estimations into the same bootstrap scheme used for *CC(l,v)*.

2.4. *Predicting the effect of adopting FRESWIND in the commercial fishery*

The effect of adopting the FRESWIND device in the commercial fishery can be predicted based on applying the estimated catch ratio curves to catch data from the target fishery (fishing with the BACOMA codend without FRESWIND). The catch data was collected by German observers sampling the target fishery in 2012, within the scope of the EU data collection framework. To ensure that the datasets remained representative of the experimental conditions, only trawl datasets from ICES Subdivision 24, with cod as target species and BACOMA codends, were used. The use of species length-class structure from the fishery catch data, and the species *CR(l,v)* estimated in (8) (Section 2.3.2), allow prediction of the effect on the fishery catch profile if the FRESWIND were installed ahead of the codend. The usability indicators described in Section 2.3.3 were also estimated for the commercial catch data. This simulation used the parametric simulation facilities in the software tool SELNET.

3. Results

3.1. *Description of sea trial conditions and catches*

In all, 12 hauls were carried out during the commercial cruise in the Arkona basin at depths ranging from ~15 to ~48 m. Haul duration was between 2 and 3 h, and the towing speed ranged from 2.8 to 3.4 knots. The FRESWIND design did not cause any extra handling effort on the test gear, and the crew reported no problems when storing the test gear on the net drum. The catches obtained during the cruise were considered by the crew as representative of commercial catch sizes. Cod, flounder, and plaice accounted for 98.7% of the total catch in weight (test + reference gears). Hereafter, the catches from these three species are denoted as major catch. Cod, flounder, and plaice contributed 61.2, 17.5, and 21.2%, respectively, to the major catch weight. In particular, the major catch observed in the test gear was 1740.2 kg, 30.8% lower than in the reference gear (2514.5 kg). The difference in catch weights was mainly the result of fewer plaice (57.8%) and flounder (56.4%) in the test codend; cod catch was only reduced 9.5%. The total number of cod caught in test gear was 1602 individuals, ~12.2% less than in the reference gear (1824 individuals; Table 1). Greater differences in catches were observed for the flatfish species. A total of 1033 plaice and 1310 flounder were caught in the test gear, ~56.1% (2354 individuals) and ~61.9% (3437 individuals) less than in the reference gear respectively (Table 1).

3.2. *Experimental catch data*

All hauls and observed length classes were used in the catch-comparison analysis (Sections 2.3.1.1 and 2.3.1.2). The Pearson residual distributions of the polynomial and structural models demonstrated that both models described the experimental catch-comparison rates equally well, without any systematic trends in the deviations for any of the three species. The mean curves estimated by the two models overlapped along the most abundant length classes, but differences arose for cod and flounder on the tails (Fig. 2), where shortest and longest lengths were not well represented because of their scarcity in catches (Table 1). The predictions for the polynomial-based model (3) for the longest cod and flounder lengths tended to *CC(l,v)* = 0, whereas for the same species and lengths, the structural model exhibited a non-decreasing tendency reaching equal catch probability (*CC(l,v)* = 0.5). The differences in model predictions were not significant, however, because their CIs overlapped. The CIs for the polynomial-based model were exceptionally wide in the tails, resulting in an overall hourglass shape, in contrast with the narrow band observed for the structural model. The narrower CIs for the structural model suggested a gain in inference power in the tails, resulting in greater length ranges where the differences in catch proportions were significant between the test and reference systems (Fig. 2).

For cod, the equal catch efficiency reference line (0.5) fell within the polynomial-based model CI, i.e., there was no significant difference in catchability between the reference and test gear, whereas

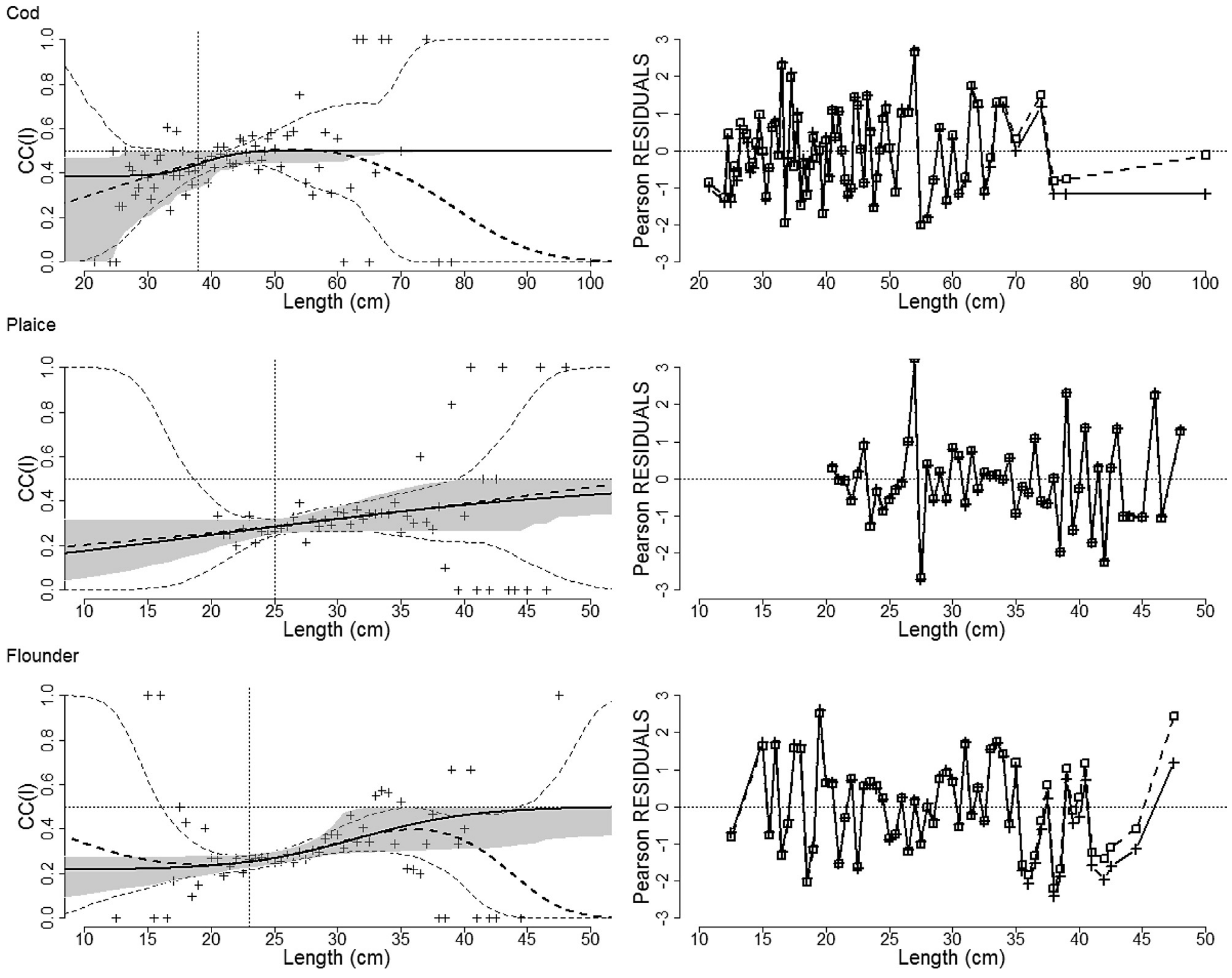

Fig. 2. Catch comparison curves with confidence intervals estimated for the polynomial model (dashed lines) and the structural model (solid line, shaded CI), horizontal dotted baselines at $CC(l) = 0.5$ represent equal catch efficiency, vertical dotted lines represent species MLS (left). Pearson residuals of the two models (right).

the structural modelling demonstrated a significant catch reduction in the test gear for length classes shorter than 27 cm (Fig. 2). For plaice, both models found a significant catch reduction for length classes shorter than ~39 cm, although the polynomial-based model estimated equal catchability for length shorter than ~19 cm, an unexpected result not supported by the structural model. Similar results were found for flounder: a significantly lower catch proportion was found by the polynomial-based model for the length range 16–35 cm, whereas the structural model curve extended the significant area to the length range shorter than ~33 cm.

For cod, the structural model estimated a contact probability of $C = 0.4$ (0.1–1.0). This value can be interpreted as ~40% of cod entering the test gear contacted the rigid windows, although it must be noted that the CI of this parameter covered nearly the full range of probabilities (Table 2). Cod *L50* was, with 38.9 cm (20.4–62.5), estimated to be 1 cm above the MLS, and *SR* was 6.7 (0.1–29.2). Higher contact probability was estimated for flatfish species. For plaice, a value of $C = 1.0$ (0.5–1.0) was achieved, and $C = 0.7$ (0.8–1.0) was estimated for flounder. The CIs from both estimates were narrower than for cod, but they overlapped each other. The estimated *L50* were also similar to both flatfish species (plaice *L50* = 32.1 (26.7–55.8); flounder *L50* = 33.6 (28.2–46.3)), but *SR* differed considerably (but not significantly), with *SR* of 36.8 (0.1–94.6) for plaice and *SR* = 9.9 (0.1–65.2) for flounder (Table 2). As an equal split at 0.5 was assumed (see Section 2.3.1.2), this parameter is presented with no uncertainty (Table 2).

Table 2
Parameter values and fit statistics for the structural model and the values for the usability indicators from the experimental fishing. 95% confidence intervals are in brackets.

Parameter	Cod	Plaice	Flounder
C	0.4 (0.1–1.0)	1.0 (0.5–1.0)	0.7 (0.6–1.0)
L50	38.9 (20.4–62.5)	32.1 (26.7–55.8)	33.6 (28.2–46.3)
SR	6.7 (0.1–29.2)	36.8 (0.1–94.6)	9.9 (0.1–65.2)
SP	0.5	0.5	0.5
p-value	0.1503	0.0827	0.0068
Deviance	86.6	63.3	84.3
d.o.f	74	49	55
nP_-	67.6 (36.9–104.7)	34.4 (25.9–46.9)	31.9 (24.4–39.6)
nP_+	93.3 (77.6–107.6)	45.6 (35.5–57.0)	39.8 (35.0–45.7)
nP	87.8 (71.8–101.1)	43.9 (36.0–53.0)	38.8 (33.7–44.1)

The value of the usability indicators (9) obtained from the experimental sea trials (Table 2) suggests that using FRESWIND reduced the catches of juvenile cod compared to the reference gear by 32.4% ($nP_- = 67.6\%$) on average, although the wide CI associated with the estimate (crossing the 100% boundary) indicated no statistical significance. On the other hand, a significant reduction of 65.6% and 68.1% was found for the number of plaice and flounder, respectively. The estimation of cod nP_+ indicated a small, non-significant catch reduction of 6.7% caused by FRESWIND, whereas the nP_+ values for plaice and flounder indicated significant catch reductions of 54.4% and 60.2%, respectively. Considering the species full length range,

Table 3
Estimated values for the usability indicators from adapting FRESWIND to the commercial fishery. 95% confidence limits based on the confidence limits for the catch ratio curves are in brackets.

Parameter	Cod	Plaice	Flounder
nP_-	70.5 (40.9–100.0)	36.1 (27.8–47.2)	31.8 (26.4–39.6)
nP_+	91.9 (70.6–100.0)	44.4 (35.1–57.5)	44.5 (34.9–59.4)
nP	90.5 (68.4–100.0)	42.3 (33.3–54.9)	41.8 (33.0–55.1)

the catch reductions caused by FRESWIND were 56.1 for plaice and 61.2% for flounder.

The assessment of the catch ratio curves (*CR(l,v)*) was based on the catch comparison curves from the structural model (Fig. 3). The estimated *CR(l,v)* for cod indicates that catch efficiency on lengths shorter than 35 cm was reduced by ∼30–38% as a result of FRESWIND, whereas equal catch efficiency was reached for length classes longer than 52 cm. Considering the upper confidence limit of the estimate, the loss of catch efficiency for cod would only be significant for length classes shorter than 27 cm, with values not lower than ∼10% from the reference gear efficiency. Plaice *CR(l,v)* exhibited a reduction in catch efficiency over the available length classes as a result of FRESWIND. The loss in catch efficiency was ∼60% at 25 cm MLS, reaching values of ∼75% for length classes of ∼15 cm. The upper confidence limit demonstrated that the reduction could only be considered significant for length classes shorter than ∼39 cm, and the loss of catch efficiency on MLS length class was at least 52%. The flounder *CR(l,v)* curve was steeper than the plaice *CR(l,v)* curve. The estimated loss in catch efficiency for the species at MLS was ∼67%, reaching the same catch efficiency as the reference gear on length classes ∼50 cm. The upper confidence limit demonstrated that the reduction can only be considered significant for length classes of flounder shorter than 33 cm, and the loss of catch efficiency on MLS length class was at least 60%.

3.3. Adopting FRESWIND in the commercial fishery

In all, 21 hauls sampled during 14 commercial fishing trips were selected from the German catch sampling program. The total catch abundances by length class for cod, plaice, and flounder were pooled over the selected hauls and used as input data for the assessment of adopting FRESWIND in the commercial fishery (Table 3). The expected flatfish catches considering FRESWIND adoption is substantially lower compared to the observed catch profile, while differences in cod catches are less evident (Fig. 4). The values of the usability indicators obtained from the commercial fishery data were similar to those estimated for the experimental fishing data. For cod, the mean value for nP_- was 70.5%, i.e., a 29.5% catch reduction for cod below MLS as a result of the FRESWIND, whereas marketable cod losses were estimated to be 8.1% ($nP_+ = 91.9$), and the CI reached the 100% boundary. Therefore, catch reductions were considered non-significant for cod. For plaice, the effect of introducing FRESWIND in the commercial fishery would imply a significant reduction in undersized plaice and flounder catches of ∼63.9% and ∼68.2%, respectively, whereas ∼55% significant reduction was estimated for the catch fractions above MLS for both flatfish species (Table 3; Fig. 4). Considering the full length range for the species in the area, the estimated FRESWIND-induced catch reduction in the fishery would be 57.7% for plaice and 58.2% for flounder.

4. Discussion

This paper introduces a new concept for a species selection device—FRESWIND—designed to reduce flatfish bycatch in roundfish-directed fisheries. In general, species-selection devices intend to reduce unwanted catches by exploiting differences in behavior or morphology between the targeted species and the species taken as bycatch (Glass, 2000). The FRESWIND concept exploits the differences in body shape between roundfish and flatfish. The strategy is exemplified by the design of the rigid windows and the horizontal bars with spacing that matches the cross-sectional shape of flatfish. At the same time, the FRESWIND concept improves the probability that fish will interact with the escape windows. A simple guiding device made of canvas directs the natural swimming path sideways, and its effect is enhanced by the angle at which the windows are mounted in the net.

The new concept was adapted and tested for the first time in the Baltic cod-directed trawl fishery, and the results demonstrate that fishing with FRESWIND mounted ahead of the codend significantly reduced flatfish catches over the available length range. The reduction in catch of undersized plaice was 65.6% ($nP_- = 34.4\%$), whereas the reduction in catch above MLS was 54.4% ($nP_+ = 45.6\%$). Although it is desirable for a new selection device to improve the escape rates of undersized individuals, the loss of fish above MLS may compromise its adoption by the industry. This is not the case for plaice in Baltic cod directed fishery, since ∼90% of the discarded plaice are above species MLS (Anon, 2013). In fact, partially low national TACs for plaice may limit the use of the cod quota and choke the trawl fisheries on cod, if the catchability of flatfish is not reduced in coming years. The estimated catch reduction for flounder was similar to the reduction achieved for plaice. Both species have similar morphology, and their populations have similar length-class structure in the fishery, but it is unknown if these species have similar swimming behavior and vertical preference when drifting toward the codend. The similarity in the performance of FRESWIND for these flatfish species supports the use of fish morphology as a sorting strategy over other strategies, and also indicates that the concept can be adapted and used for other flatfish species, considering their morphological characteristics. FRESWIND also induced a substantial but not significant 32.4% reduction in undersized cod catches. These results indicate that, in addition to the reduction in flatfish catches, FRESWIND also supplemented cod size selection occurring in the codend. On the other hand, only a small and not significant loss of 6.7% marketable cod was estimated.

The usability indicators estimated using the experimental catch information can only be extrapolated to the specific experimental conditions. By using commercial fishing data from the German catch sampling program and simulations, we predicted the effect of introducing FRESWIND into the commercial fishery in Baltic Sea. The simulations predicted flatfish catch-reduction rates similar to those estimated in the experimental fishery, demonstrating at the same time that FRESWIND can reduce undersized cod catches in the fishery, but with an estimated loss in marketable cod at ∼9%.

Wienbeck et al. (2014) addressed the problem of flatfish bycatch in the Baltic cod fishery by proposing and testing three different modifications of the mandatory BACOMA codend. However, none of the new codends was found to improve the selectivity for plaice below MLS, compared with the mandatory T90 codend. As a result, lower catches of marketable cod were observed for the alternative codends, compared with the catches in the standard BACOMA, implying potential economic losses and thus rendering its use in the commercial fishery unlikely. The results obtained by Wienbeck et al. (2014) demonstrate the challenge of using codend modifications to reduce flatfish bycatch while maintaining roundfish catchability. Milliken and DeAlteris (2004) attempted to reduce flatfish bycatch in the New England silver hake fishery by placing large mesh panels in the lower part of the belly. Four different panels were investigated, and the best setup achieved significant flatfish bycatch reduction with non-significant, ∼25% target species losses. The concept relies on exploiting behavioral differences between flatfish and roundfish while in the fishing gear, assuming that roundfish tend to rise upon entering the mouth of

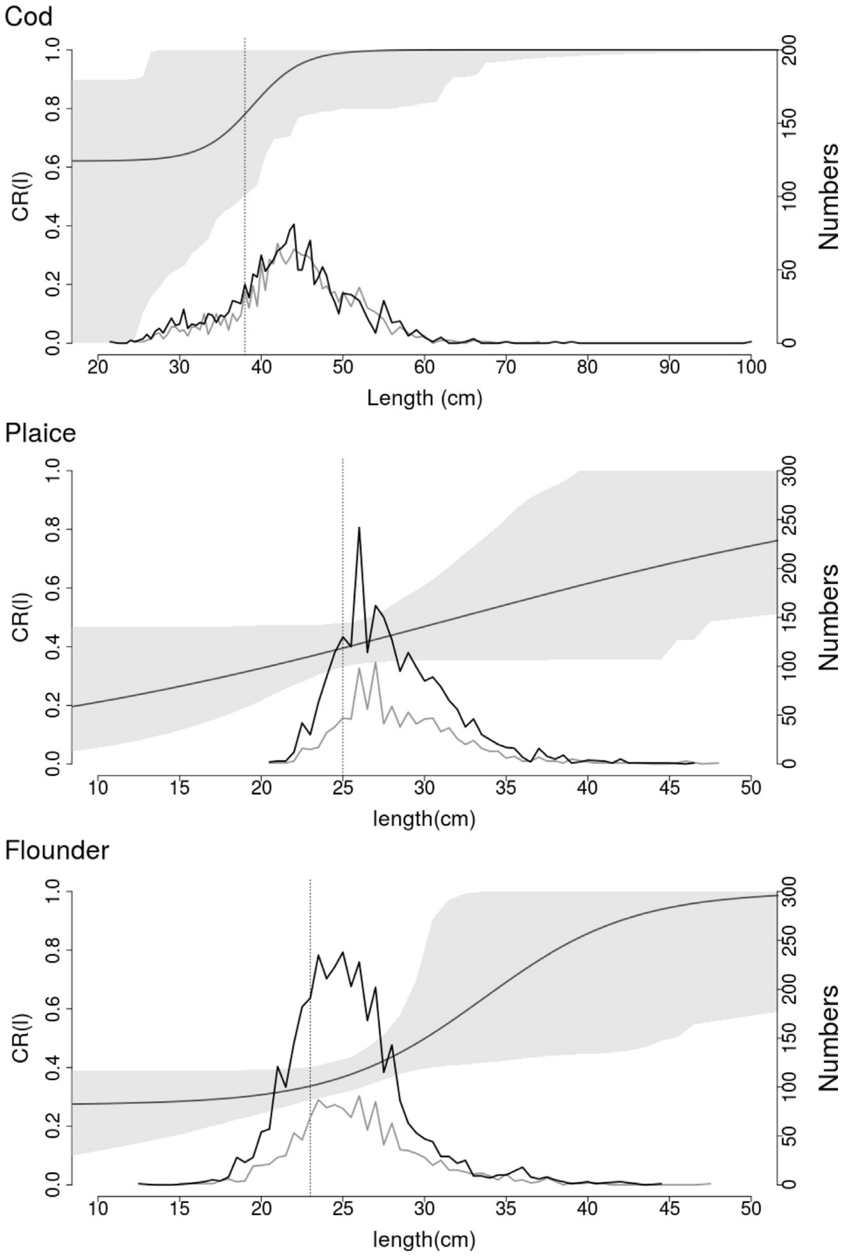

Fig. 3. Estimated catch ratio curves with confidence intervals for cod, plaice, and flounder. Bottom lines represent the length class distribution obtained by the reference (black line) and test (grey line) selection systems (numbers pooled over hauls). Vertical dotted lines represent species MLS.

the gear, whereas flatfish tend to remain close to the seabed. This species separation criteria can be generalized but it may not be applicable within specific fisheries and/or conditions. For example, it is known that cod also tend to stay near the bottom at the first stage of the fishing process (Beutel et al., 2008) in a way similar to the natural response of flatfish (Bublitz, 1996). In contrast, we consider the FRESWIND concept to have a wider application, because it uses inherent differences in morphology that define both groups of species to be separated.

Our sea trial was based on a direct catch comparison between the test and reference selective systems fished simultaneously. The advantage of using such an experimental setup is the easy and practical implementation on commercial twin trawlers, because it does not require extra rigging or the use of small mesh covers that might alter normal fishing behavior. By testing the new system on a commercial vessel, it was possible to collect valuable feedback from the fishermen about operational differences between gears. According to the fishermen involved in the experimental cruise, the FRESWIND did not alter significantly the normal shooting/haulback manoeuvres, and the test gear was stored on the drum without difficulties. In addition, with the lateral position of the FRESWIND windows, no clogging of the escapement outlets were observed even for hauls with high catches, and no blocking events were experienced in the extension piece, a common problem when large objects collide with grids in fishing gears (Catchpole and Revill, 2008).

With the structural model used in this study, we were able to estimate the FRESWIND selection parameters for cod, plaice, and flounder. This facilitates a better understanding of the selection process occurring in the FRESWIND compared to what can be obtained from the polynomial model. The structural model estimated a high contact probability for the flatfish species with the FRESWIND rigid windows, whereas less than half of the cod was estimated to do so. Further investigation based on underwa-

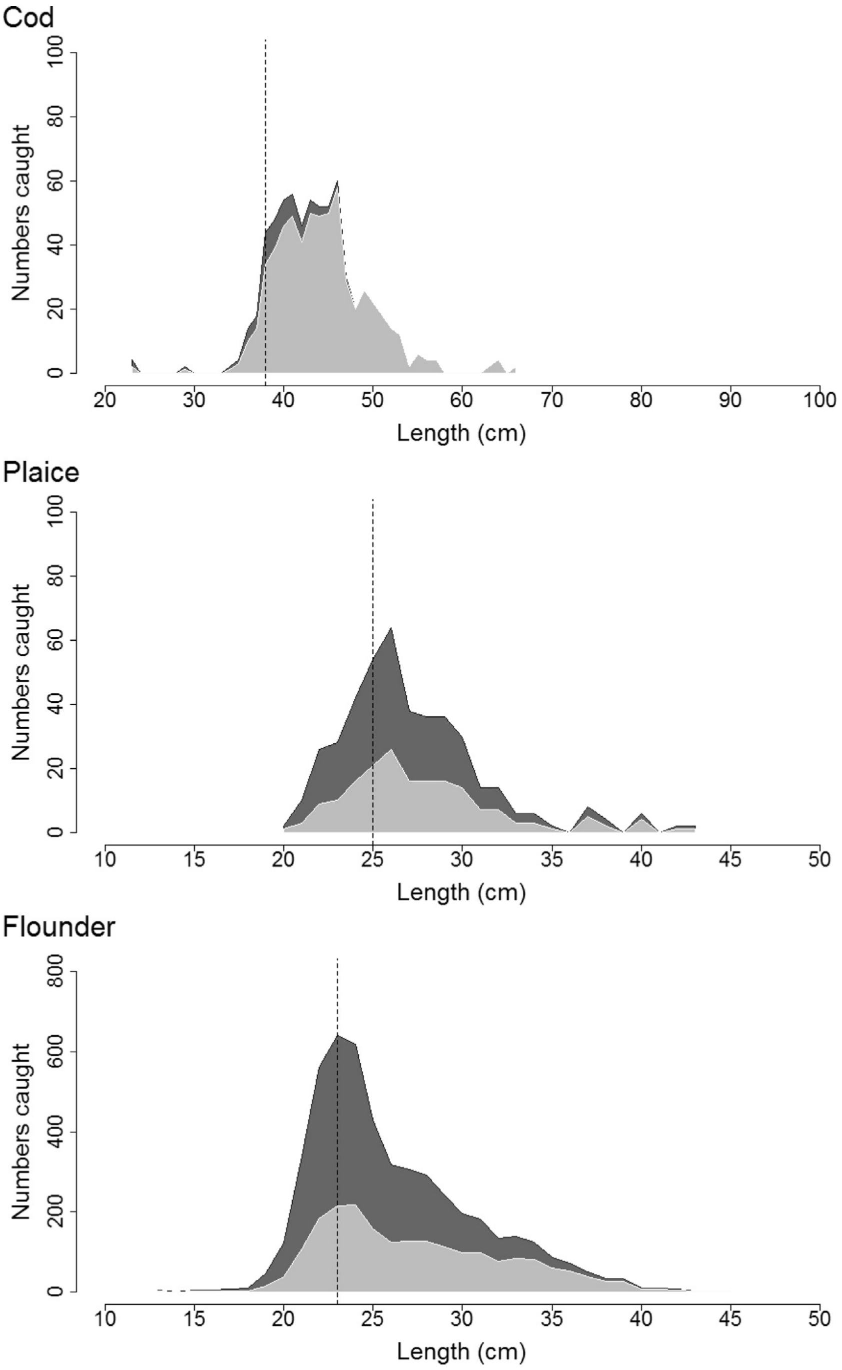

Fig. 4. Catch profile obtained from the German commercial catch sampling program in the same fishing ground as the experimental sea trials (SD24) in 2012, and the same reference selection system (BACOMA; dark grey polygon); expected catch profile after adding the effect of FRESWIND (test system: FRESWIND + BACOMA) to the catch sampling data (light grey polygon).

ter observations would be of interest, clarifying how flatfish and roundfish interact with the guiding device and when they approach the FRESWIND windows.

For size selection, cod *L50* was only 1 cm greater than MLS, whereas for flounder and plaice, the estimated *L50* was far greater than their respective MLSs. Such results comply with the objectives. However, a better understanding of the rigid windows' mechanical sorting would be useful in adapting the bar spacing to specific requirements of the commercial fishery.

The positive results obtained in the case study demonstrate the potential of the FRESWIND to reduce flatfish bycatch in the commercial fishery. Based on these results, it is likely that the concept can also be adapted to other roundfish fisheries with similar flatfish bycatch problems.

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