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Escape of hake (*Merluccius merluccius*), horse mackerel (*Trachurus trachurus*) and blue whiting (*Micromesistius poutassou*) in codends with shortened lastridge ropes

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Abstract

Diamond meshes in trawl codends have limited openness, which reduces escape opportunities for roundfish. Shortening the lastridge ropes (LR) attached to codend selvedges can increase the availability of open meshes resulting in higher chances of escape. However, this availability does not imply optimal mesh openness, nor does it guarantee use. We estimate the escape probability of hake, horse mackerel and blue whiting through a 20% shortened LR codend and a standard codend, and quantify the contribution of different mesh opening angles (OAs) to their size selectivity. The results confirm that high OAs increase escape opportunities for all species. However, shortened LR only improved size selectivity significantly for horse mackerel and blue whiting. This difference between species may be related to behavioural differences. The mesh openness achieved with 20% shortened LR was below that necessary to obtain optimal escape opportunities for these species. The study highlights the relevance of considering fish morphology and behaviour to optimally exploit size selectivity when designing shortened LR codends.

Keywords: lastridge ropes; mesh opening angle; escape opportunities; fish morphology; size selectivity.

Introduction

Trawls with diamond mesh codends are widely used in commercial fisheries (EU, 2019; Kennelly & Broadhurst, 2021). However, the use of this type of codends can entail limitations regarding size selectivity (Halliday & Cooper, 2000; Sala *et al*., 2008; Tokaç *et al*., 2016; Petetta *et al*., 2020). Diamond mesh codend size selectivity depends on mesh opening angle (OA), which can vary depending on the characteristics of the netting used (e.g., twine thickness) (Herrmann *et al*., 2013a), codend construction (e.g., number of meshes in circumference) (Sala & Lucchetti, 2011), or its use (e.g., catch size) (O'Neill & Kynoch, 1996; Herrmann, 2005a). The forces acting on the codend produced by the catch building up causes most meshes in the codend, except for some rows just ahead of the catch accumulation zone (Herrmann, 2005a, b), to be longitudinally stretched (Herrmann *et al*., 2007). Therefore, the probability of a fish of a given length to escape through the codend meshes varies during the fishing operation.

In a codend, lastridge ropes (LR) attached to the selvedges withstand the load otherwise exerted on the codend meshes. These ropes are usually of similar length or slightly shorter (normally ca. 5%) than the codend netting itself and remove the strain on the trawl from the netting to the ropes (Isaksen & Valdemarsen, 1990). When LR are shortened, the length of the netting is fixed in a shorter length and the force created by the drag in the codend as the catch builds up is carried by the ropes earlier. Therefore, regardless of the catch size, the meshes cannot be completely stretched and consequently, they remain more open (Isaksen & Valdemarsen, 1990; Fishing Technology Unit Report No. 02/93 1993; Lök *et al*., 1997; Ingólfsson & Brinkhof, 2020).

In recent decades, several studies have tested the effect of shortening codend LR on the size selectivity of different species (Brothers & Boulos, 1994; Hickey *et al*., 1995; Lök *et al*., 1997; Ingólfsson & Brinkhof, 2020; Einarsson *et al*., 2021; Jacques *et al*., 2021). In general, all studies show that size selectivity for roundfish species was improved because significantly more undersized individuals were released when shortened LR were used compared to equivalent non-shortened LR codends. Further, a recent study demonstrated that higher OAs are available in shortened LR codends compared to the standard ones and that size selection curves of different species can be explained by higher OAs (Sistiaga *et al*., 2021). Specifically, diamond meshes in non-shortened LR codends can include meshes with OAs in between 15 and 60º (Herrmann *et al*., 2009), whereas codends with 15% shortened LR can include mesh OAs between 40-90º and slack meshes (Sistiaga *et al*., 2021).

In principle, higher availability of meshes with high OAs would lead to greater chances of escape for roundfish. However, this higher availability does not necessarily mean that fish utilize them to escape. Sistiaga *et al.* (2021), for example, showed that mesh OAs contributing to the explanation of the size selection curves of different species could differ, meaning that although some specific OAs were available, these would not contribute to the size selectivity of all species. Shortened LR has greater influence in meshes further from the catch accumulation zone, which are often the ones less opened as the catch builds up. This could favor the chances of escape of those species trying to escape along the entire codend, and not those that mainly attempt to escape in the aft. Higher availability of more open meshes may also provide higher chances for fish of getting optimal mesh OAs in the codend, which would facilitate the escape of undersized and non-desired individuals.

The bottom trawl fishery in the Bay of Biscay uses, by regulation, a codend with a minimum diamond mesh size of 70 mm together with a 100 mm square mesh panel in the upper panel of the extension piece. However, the capture of undersized and non-desired individual fish of commercially relevant species represents a problem (Cuende *et al.,* 2020a; b) that has more serious consequences for fishermen with the introduction of the Landing Obligation (EU, 2013). Cuende *et al.* (2022) concluded that although different square mesh panel designs could increase the escape probability of undesired sizes of hake (*Merluccius merluccius*) and blue whiting (*Micromesistius poutassou*) (e.g., square mesh panels with increased size and/or changed position), efforts to optimize the size selectivity in this fishery should focus on the codend meshes. Therefore, in this study we aimed at estimating the chances of fish escaping through a standard diamond mesh codend design and the same codend with 20% shortened LR for hake, horse mackerel (*Trachurus trachurus*) and blue whiting, which are species of global commercial relevance (FAO, 2020). Further, morphology data was used to investigate whether the differences in size selectivity between these three species can be explained based on fish morphology and behavior. Finally, we set out to find out to what extent shortened LR codend meshes offer optimal openness for the different species to pass through. To do so, the Basque bottom trawl fishery was used as a case fishery, where the average fishing effort of the vessels involved in the fishery between 2014 - 2020 was 80,441 Kw/day. In this fishery, hake is one of the main target species, and horse mackerel and blue whiting can be bycatch species, depending on quota and market preferences.

Materials and Methods

Experimental sea trials

Sea trials were carried out on board the oceanographic vessel Emma Bardan (29 m length overall; 900 Kw) from 4 to 22 June 2021. The fishing was carried out in a specific area within ICES divisions 8c and 8b, which are Spanish and French waters (43.27ºN - 44.34ºN and 1.77ºW - 2.07ºW), at depths that varied between 124 and 142 m.

The gear used in the experiments was a four-panel bottom trawl type GOC73 (Bertrand *et al*., 1997). This trawl is built according to the standard bottom trawl survey manual for the Mediterranean (MEDITS Working Group, 2016). The headline, sideline, and fishing line were 35.7, 7.4, and 40.0 m long, respectively. The trawl was rigged with a set of Morgère doors (Morgère WH S8 type, 2.6 m2; 350 Kg), 100 m sweeps, and a light rockhopper ground gear (with 3 × 40 Kg chains + 15 Kg chains on the bosom). While fishing, the trawl had a horizontal opening of 16 m and a vertical opening between of 2.7 - 3.2 m. The towing speed was 3.0 - 3.3 knots.

A single experimental codend was used during the trials. It consisted of two diamond mesh panels made of double braided polysteel twine (Ø4 mm each), had 54 free meshes in circumference and a total length of 7 m. The mesh size was 79.41 ± 1.98 mm, measured with an electronic OMEGA mesh gauge (Fonteyne *et al*., 2007) following the procedure described in Wileman *et al.* (1996). The commercial Basque bottom trawl fleet commonly uses slightly longer LR than the stretched length of the codend; i.e., the aim of the LR is to prevent the codend from breaking at large catches. Since experimental trials in scientific vessels usually tow shorter and get smaller catches, LRs were not needed for that purpose. Thus, the two configurations tested during the trials were the codend with no LR on the selvedges (hereafter No LR codend), and the same codend with 20% shortened LRs (hereafter shortened LR codend) (Fig. 1). The ropes used for the purpose were made of polyethylene and had a diameter of 25 mm.

A cover was installed over the codend to catch codend escapees. It was 9 m long and constructed of 26.50 ± 0.41 mm mesh size (Ø1.3 mm PA twine) (Fig. 1). To ensure that the cover stayed clear of the codend netting we used nine pairs of floats (N-25/5 type; 100 mm diameter; 0.30 Kg buoyancy each), eight kites (four per panel), and four chains (1 Kg each) in the lower panel. To observe gear performance, an underwater camera was placed at the beginning of the codend pointing backwards. No artificial light was added to prevent species' behavioral responses from being affected. The validity of hauls was determined according to the underwater images during shooting and haul-back processes, and the skippers' expertise.

Each haul was carried out with one configuration at a time. The species captured in sufficient numbers to be in-

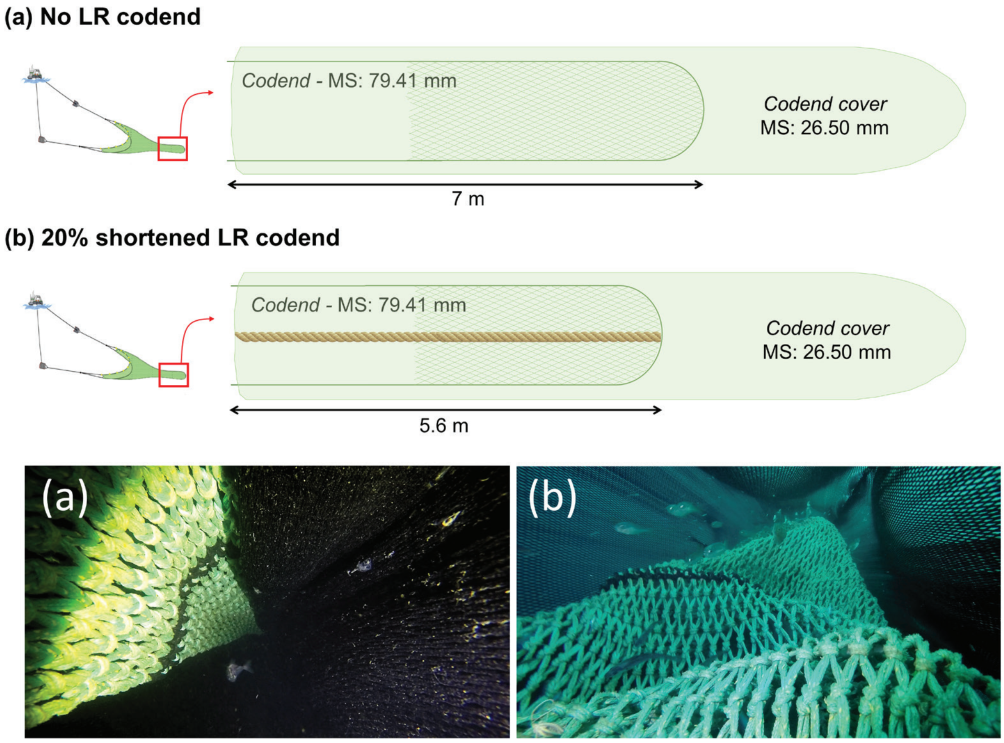

Fig. 1: (a) No LR codend length and mesh size (MS) specifications and underwater image of it; and (b) 20% shortened LR codend specifications and underwater image of it. Both underwater images were taken from a camera positioned between the codend and the codend cover.

cluded in the data analysis were hake, horse mackerel and blue whiting. After each haul, the length for these three species was measured to the centimeter below. When the catch of a specific species exceeded approximately 600 individuals, randomly selected subsamples of the catch were length measured for this species, and the subsample ratio was calculated. Hauls with < 10 measured individuals were excluded from further analyses following Krag *et al*. (2014). Minimum Conservation Reference Size (MCRS) for hake and horse mackerel are 27 and 15 cm, respectively, and minimum marketable size for blue whiting is 18 cm.

Modelling and estimation of the experimental size selection in the codends

The numbers of individuals per length class, retained either by the codend cover or by the codend itself, were used to estimate codend retention probability (i.e., length-dependent retention probability). To do so, the fraction of fish measured in the codend was compared to the fraction of fish measured in the codend cover, species by species. The experimental design applied (Fig. 1) to test codend size selectivity enabled analysis of the collected catch data as binomial data, where individuals, either retained in the codend cover or in the codend itself, were used to estimate the size selection in the codend. In a codend, size selectivity is expected to vary between hauls (Fryer, 1991). However, in this study, we were only interested in the combined size selection overall hauls because this would inform about the overall consequences for the size selection process when applying the specific codend in the fishery. Six different models were chosen as basic candidates to individually describe for each codend and species: *Logit*, *DLogit* and *DSLogit*, *Probit*, *Gompertz*, and *Richard*. Details on the models and the size selection estimation procedure can be found in Appendix A.

Evaluating the ability of a model to sufficiently describe the data was based on estimating the corresponding p-value, which expresses the likelihood of obtaining at least as big a discrepancy between the fitted model and the observed experimental data by coincidence. Therefore, for the fitted model to be a candidate to model the size selection data, this p-value should be > 0.05 (Wileman *et al*., 1996), which means that the difference between the experimental points and the model used in every case could be coincidental. In the case of a poor fit statistic (p-value < 0.05), the residuals were inspected to determine whether the poor result was due to structural problems when modeling the experimental data with the different selection curves or if it was due to overdispersion in the data (Wileman *et al*., 1996). The best model among the six considered was selected by comparing their Akaike information criterion (AIC) values (Akaike, 1974). The model with the lowest AIC value was selected.

Once the specific size selection model was identified for each species and codend configuration, bootstrapping was applied to estimate the confidence limits for the average size selection. We used the SELNET software tool (Herrmann *et al*., 2012) for the size selection analysis, and the double bootstrap method was implemented to obtain the confidence limits for the size selection curve and the corresponding parameters (details in Appendix A).

Estimation of difference in size selectivity between codends

To investigate to what extent shortened LR modify the selection properties of diamond mesh codends, we quantified changes in retention probability when using shortened LR codend with respect to no LR codend configuration, and the 95% confidence intervals (CI) were also estimated as detailed in Larsen *et al*. (2018).

Understanding codend size selection based on fish morphology and mesh geometry and contribution of different mesh OAs to size selectivity

Using fish morphology, we predicted size selection for hake, horse mackerel and blue whiting in codends with different mesh geometries. For this purpose, FISHSELECT methodology was used; a framework of methods, tools, and software developed to determine if a fish can penetrate a certain mesh shape and size in a fishing gear (Herrmann *et al*., 2009). The FISHSELECT methodology is thoroughly described in Herrmann et al. (2009), and has been applied to investigate size selectivity for numerous species in various fisheries (e.g., Frandsen *et al.*, 2010; Herrmann *et al.*, 2012, 2013b, 2016; Krag *et al.*, 2014, Sistiaga *et al.*, 2011, 2020; Tokaç *et al.*, 2016). Both the FISHSELECT software and specific measuring tools are needed to study the size selectivity of a species with this method. Through computer simulation, the method estimates the risk of escape by comparing the morphological characteristics of a particular fish species and the shape and size of the selection devices of interest. The following subsections briefly describe the different steps needed to use FISHSELECT. The FISHSELECT models used for blue whiting were those established by Cuende *et al*. (2020c) whereas those for hake and horse mackerel were developed within this study by following the same procedure as Cuende *et al*. (2020c) and are detailed in Appendix B.

Once FISHSELECT models (cross-section and penetration models) of hake and horse mackerel were developed, we simulated the size selection of these two species for a number of mesh OAs. We used a mesh size identical to the codend used in the experimental fishing (79.41 mm mesh size) and OAs from 5 to 90 degrees in 5-degree increments were simulated to establish the potential size selection in the codend and its dependency on the mesh OA. In addition, we simulated the potential size selection for stiff diamond meshes, assumed not to be deformed by fish trying to escape through it, and slack meshes, meshes that can potentially be fully deformed by the effort of the fish while trying to escape. The procedure followed is described in Cuende *et al*. (2020c).

Then, the OAs selected for the estimation of their potential contribution to the experimental size selection curve were those that were at least partially between the CIs of the experimental curve. Once the relevant OAs were identified, we tried to reproduce the experimental size selection curve based on different combinations of contributions from the different OAs by simulation in FISHSELECT. This procedure is identical to the one applied by Herrmann *et al*. (2013b; 2016) and Cuende *et al*. (2020c), who provide detailed information on the technical aspects of the method.

Prediction of size selectivity for different codend configurations

Predictions to explore the potential of codend design changes were carried out in FISHSELECT. Using the penetration model and virtual population (see Appendix B), the codend size selectivity for no LR and shortened LR configurations were estimated for all three species. Predictions were made for mesh sizes ranging from 50 to 130 mm with 10 mm intervals and only considering the OAs that contribute to the reproduction of the experimental size selection curve. The procedure followed is described in Cuende *et al*. (2020c). Additionally, design guides were created, which summarize for each species the L50 values obtained with different combinations of mesh size and OA (Herrmann *et al*., 2009).

Results

Experimental size selection

During the sea trials, 21 valid hauls were carried out, 10 with shortened LR and 11 with no LR. In total, 1,254 hake, 8,711 horse mackerel and 11,438 blue whiting (Table 1) were length-measured. For each species, those hauls with sufficient individuals were selected for data analysis (Table 1).

The size selectivity analysis results showed overall that the models used to represent the experimental data were adequate. In all cases, the p-value for the model with the lowest AIC value among the models considered was > 0.05 (Table 1). This result was corroborated by the selectivity curves, which in general, fitted the experimental data well in every case (Fig. 2).

The L50 values estimated for the 20% shortened LR codend were significantly higher than for the no LR codend for horse mackerel and blue whiting. For hake, the estimated value was also higher but not statistically significant (Table 1). Additionally, SR were estimated higher when the shortened LR were used, although these results were only significant for blue whiting. The higher L50 and SR values for shortened LR configurations can also been observed in Figure 2 since these curves are further positioned to the right and they are less steep than the standard configuration for all three species. Additionally, the selection curve for hake clearly shows the dual process, where the L50 for the first process is 17.23 cm (12.65 cm - 18.80 cm), and for the second is 35.46 cm (19.48 cm - 38.78 cm). However, although the model applied for this configuration fits the data well enough (p-value > 0.05), we observe wider confidence bands for the length range 20 – 35 cm, caused by overdispersion in

Table 1. Raised number of individuals retained in the codend (*nCD*) and cover (*nCC*) for the two codend configurations (number of fish measured in brackets). Selection model, model parameters (L50, SR), and fit statistics (p-value, Deviance, DOF) for each of the configurations tested and the three species sampled during the sea trials. Ranges in brackets represent 95% confidence intervals. $L50_1$ and SR_1 or $L50_2$ and SR_2 describe the selectivity of the sub-processes assumed by the double logistic models, and L50, SR the overall parameters for these models (see Appendix A). Dash symbol (-) means that the specific parameters do not correspond to the selected model.

	Hake		**Horse mackerel**		**Blue whiting**	
	No LR	**20% shortened LR**	**No LR**	**20% shortened LR**	**No LR**	**20% shortened LR**
n. of hauls	11	9	11	8	10	7
nCD	365 (365)	411 (411)	5221 (4071)	114 (114)	938 (938)	1256 (1256)
nCC	162 (162)	316 (316)	10103 (4028)	498 (498)	2675 (2675)	33115 (6569)
Model	*DSLogit*	*Richard*	*DLogit*	*Probit*	*DLogit*	*Logit*
L50 (cm)	17.58 (16.43–19.17)	18.57 (16.62–19.97)	14.56 (13.16–15.76)	20.74 (17.31–23.92)	22.23 (20.28–22.97)	24.30 (23.05–25.91)
SR (cm)	3.95 (1.76–9.06)	5.96 (4.23–10.18)	4.10 (2.54–14.41)	4.67 (1.05–6.26)	1.70 (1.18–2.80)	5.33 (4.20–6.55)
δ	-	0.43 (0.01–2.27)	-	-	-	-
C_1	0.10 (0.00–0.77)	-	0.79 (0.06–1.00)	-	1.00 (0.86–1.00)	-
$L50_1$ (cm)	35.46 (19.48–38.78)	-	15.10 (1.13–18.05)	-	18.21 (0.00–317.85)	-
SR_1 (cm)	1.00 (0.46–29.63)	-	2.58 (1.52–3.89)	-	8.79 (5.60–34.16)	-
$L50_2$ (cm)	17.23 (12.65–18.80)	-	1.00 (0.00–10.45)	-	21.88 (19.99–22.71)	-
SR_2 (cm)	3.38 (1.39–29.94)	-	9.01 (5.33–17.48)	-	1.00 (0.87–2.38)	-
p-value	0.9851	0.9616	0.9808	0.9987	0.9997	0.1269
Deviance	25.38	29.71	11.22	9.5	5.99	29.66
DOF	43	45	23	26	22	22

the data. For these lengths few individuals were captured, both in the codend and the cover (Fig. 2).

A comparison of the retention probability curves for both configurations also illustrated the differences in the size selectivity for each species among configurations (Fig. 3). The retention probability of hake was not significantly different when shortened LR were used. However, the retention probability for horse mackerel was significantly lower for individuals both below and above the MCRS (15 cm), whereas for blue whiting these differences were only found for individuals above the minimum marketable size (18 cm). Specifically, horse mackerel between 9 and 18 cm and blue whiting between 22 – 27 cm were significantly less retained when shortened LR were used (Fig. 3).

Simulation of the experimental selectivity curves and contribution of different meshes to size selectivity

Simulation of the experimental size selectivity curves was carried out according to the FISHSELECT results for the morphological description of hake and horse mackerel, which can be found in Appendix C. Results for the morphologic modeling of blue whiting can be found in Cuende *et al*. (2020c).

The simulated size selection curves of the different codend mesh OAs were plotted together with the experimental size selection curves (Fig. 4). In general, for the shortened LR configuration, the range of potential OAs contributing to the selectivity curve explanation is wider, due to that size selection curves are less steep than for no LR codend. For horse mackerel, the contribution of OAs when LR are shortened include, not only a wider range, but also higher OAs than when no LR are used (Fig. 4). Slack meshes seem not to contribute to the explanation of the experimental size selection curves for any of the species.

In every case, the simulated selectivity curve resulting from combining the different contributions (derived by the FISHSELECT models - Appendices B & C) was within the CIs of the experimental selectivity curves (yellow curve in Fig. 4). The simulation results showed that for both codend configurations and the three species included in the study, the experimental selectivity curves could well be explained by a combination of contributions from different mesh sizes and opening angles (Fig. 4).

Based on the cumulative contribution of the different OAs, a higher relevance of lower OAs was evident when the non-shortened configuration is used compared to the shortened LR configuration (Fig. 5). In general, OAs below 30º have greater weight explaining the experimental size selectivity. This is especially true for horse mackerel, for which OAs below 25º explain > 90% of the standard LR configuration selectivity curve, whereas for the 20% shortened LR codend this happens in between OAs of 20

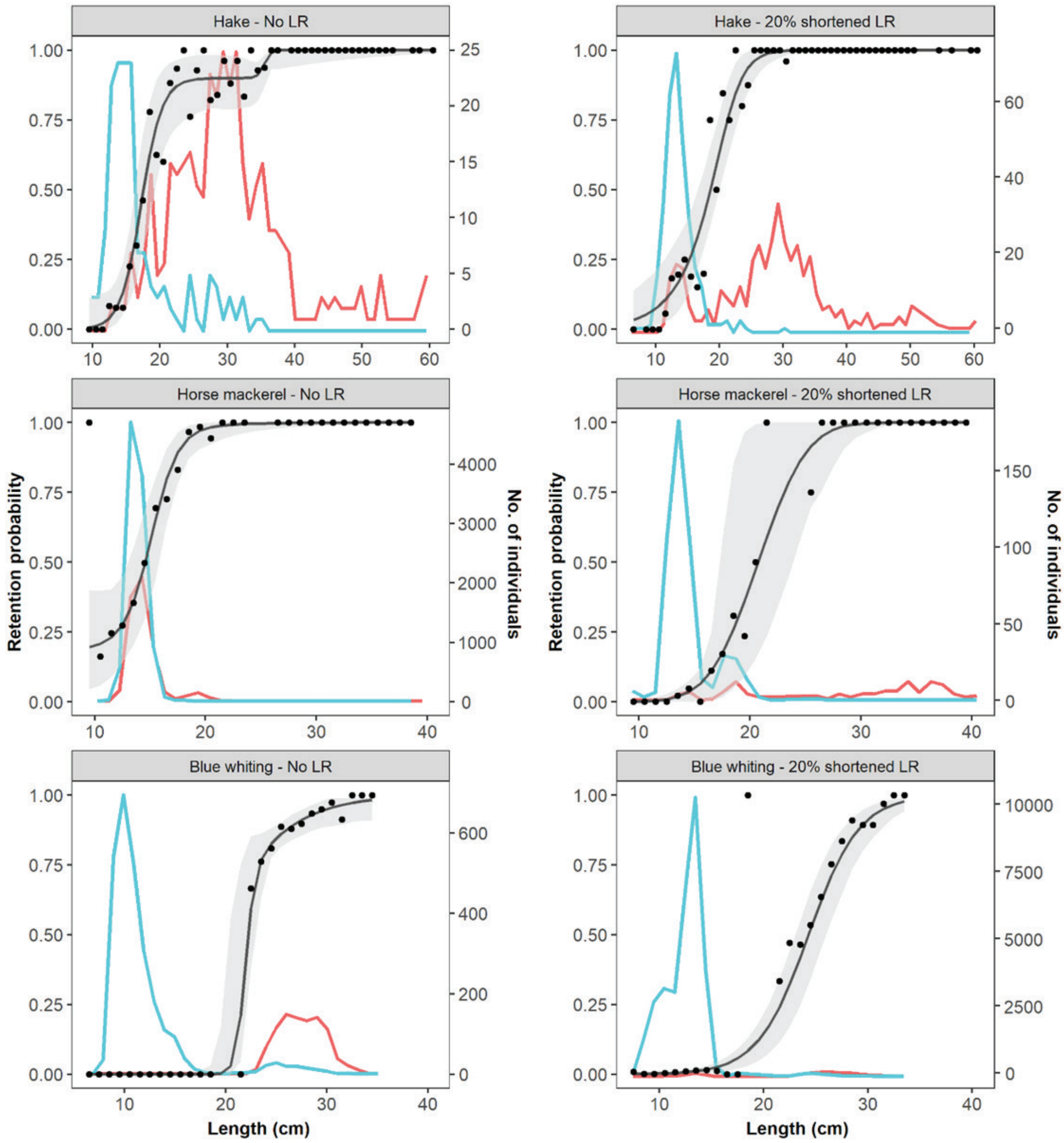

Fig. 2: Experimental size selection curves (black line) for hake, horse mackerel and blue whiting, the corresponding 95% CIs and the experimental retention rates (black dots). Red lines represent the population retained in the codend and blue lines represent the population retained in the codend cover.

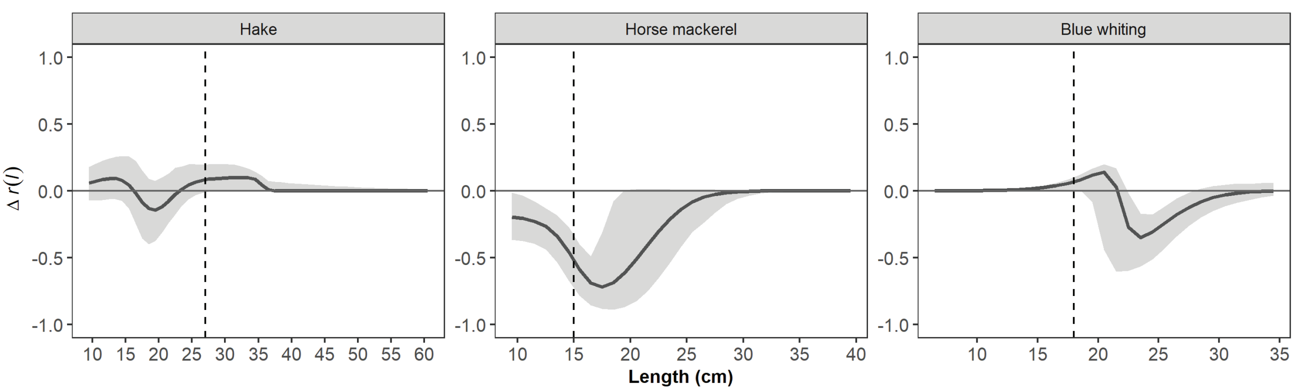

Fig. 3: Changes in retention probability between the 20% shortened LR codend configuration and the no LR codend configuration. The horizontal line at 0.0 represents equal retention probability for both designs. Mean curve and CIs above or below horizontal line mean a significantly higher or lower retention probability for the shortened LR configuration. Vertical dashed lines show the MCRS for hake and horse mackerel and minimum marketable size for blue whiting.

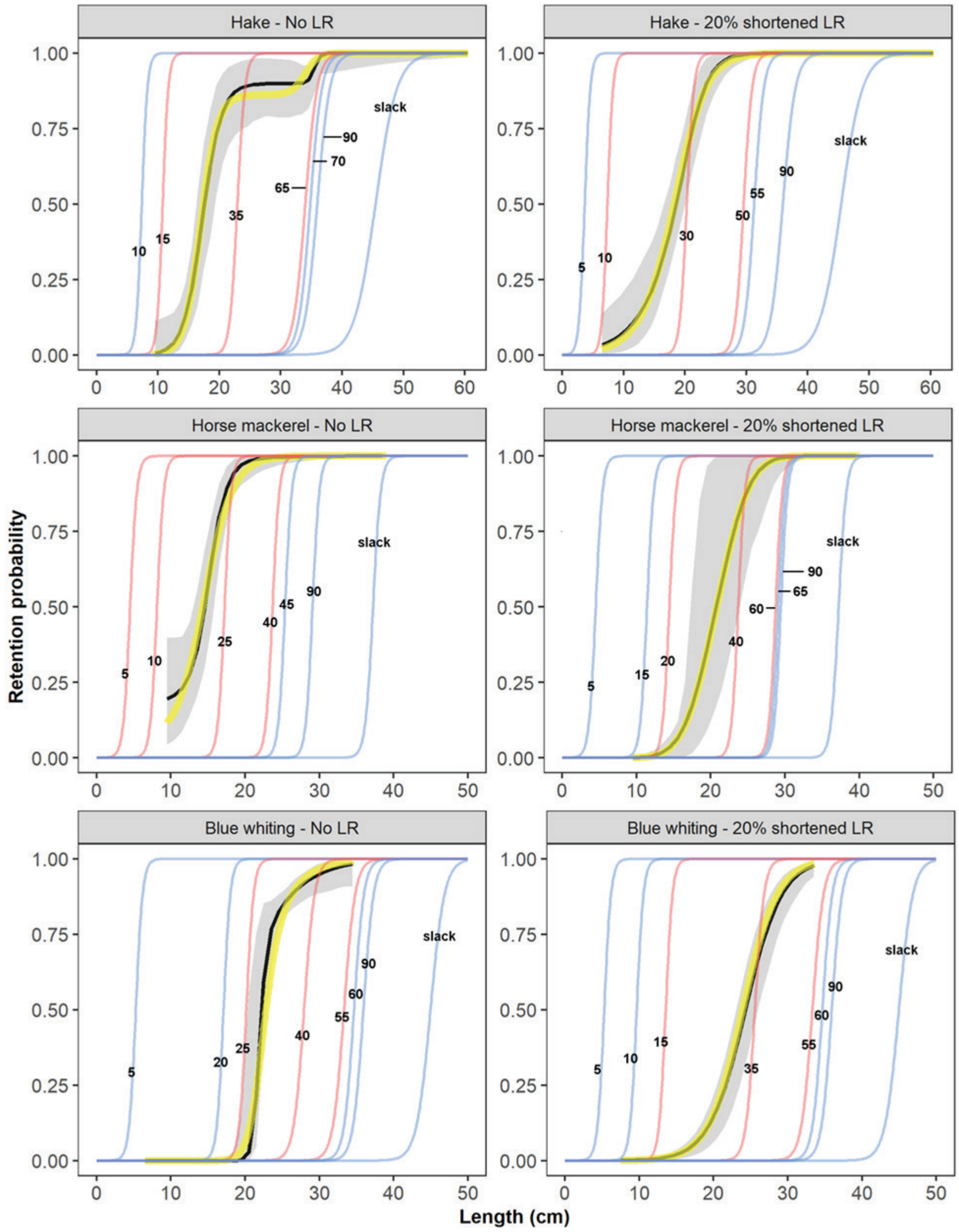

Fig. 4: Black curves show experimental codend size selection curve with corresponding CIs. Blue and red curves show size selection curves simulated for the OAs indicated. The curves with potential contribution (red) were included in the analysis, whereas the remaining were not (blue). Yellow curves represent the simulated size selection curves based on different combinations of OA contributions.

and 45º (Fig. 5). Similarly, the size selection curve of no LR for blue whiting is mainly explained by a mesh OA of 30º, and OAs below 30º explain 85% of the standard LR selectivity curve (Fig.5).

For blue whiting, the cumulative curve of contributions is less steep for the shortened codend than for the non-shortened one, meaning that the size selectivity curves for these species are explained by a broader range of OAs (Fig. 5). Still, the broader range reaches bigger OAs when the codend is shortened (Fig. 5). In the case of hake, the mesh range involved in the explanation of the experimental curve is wider because meshes open at 65º also make a considerable contribution, which corresponds to the second logistic process of the size selection curve for this configuration (Fig. 2).

Prediction of size selectivity for different codend configurations

Predictions of size selectivity show that in the case of hake, the 70 mm mesh size established by the regulation in force has high retention probability of individuals below MCRS, especially with the shortened LR configuration. Increasing the mesh size to the maximum here estimated (130 mm) could reduce the probability of retaining individuals of 27 cm length to 39 and 37% for each configuration, respectively (Fig. 6). For horse mackerel, increasing the mesh size to 130 mm in the no LR configuration would be equivalent to shortening the 70 mm mesh size codend by 20%, because both measures would diminish retention probability for individuals of 15 cm

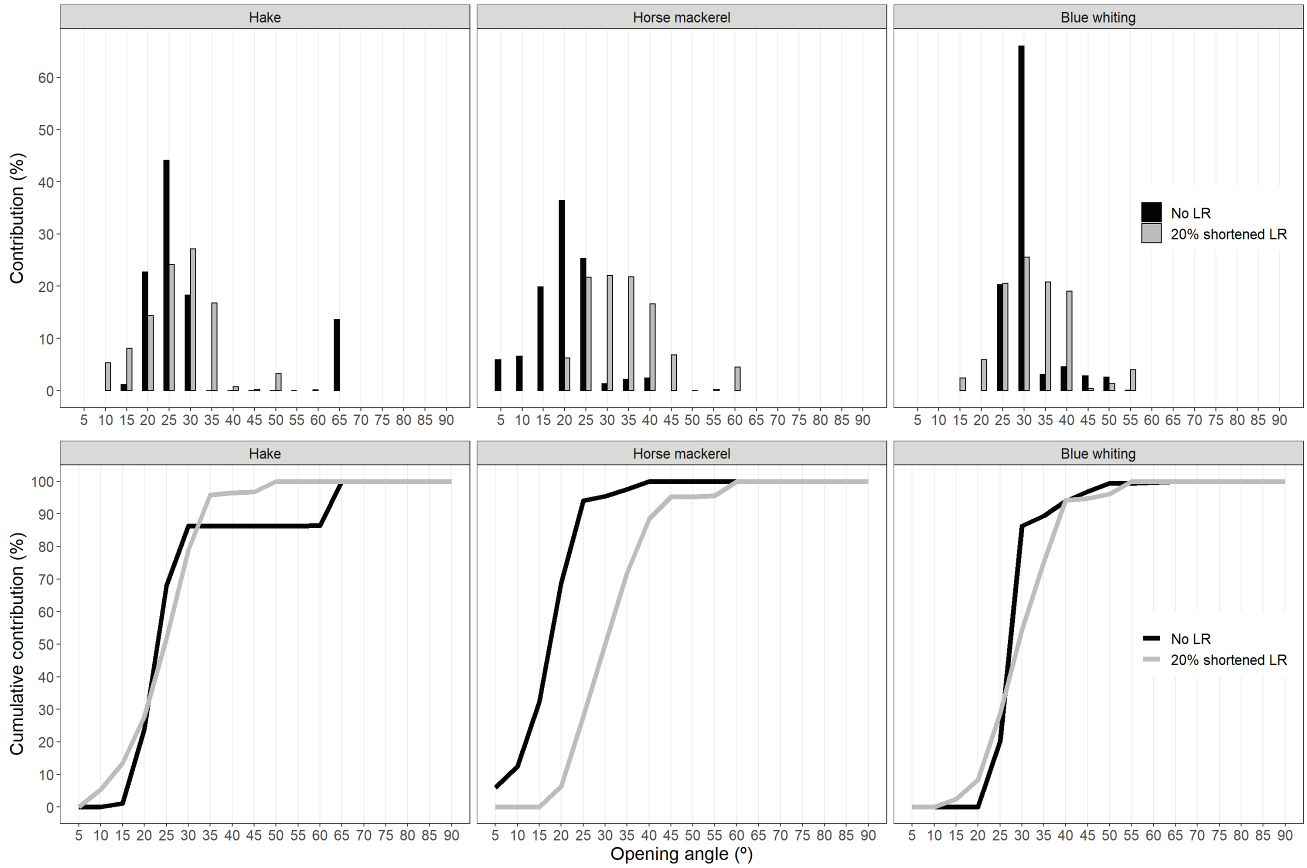

Fig. 5: Percentage of contribution (above) and percentage of cumulative contribution (below) of the different codend mesh OAs that explain the experimental codend size selection curves of hake, horse mackerel and blue whiting. Black bars and lines represent no LR codend and grey bars and lines 20% shortened LR codend.

(MCRS) up to a 12% (Fig. 6). For the smallest mesh size (50 – 60 mm mesh size), horse mackerel would never reach 0% retention for any length class when no LR are used (Fig. 6). Finally, the higher SR for mesh sizes above 70 mm leads to a lower retention probability of blue whiting for the shortened LR configuration (Fig. 6).

The design guides (Fig. 7abc) show that for a given mesh size, L50 of codend diamond meshes greatly depended on the OA when these are in between 5 and 50º, approximately. In general, once the OA reaches 70º, the influence of the angle on the L50 diminished. Still, this dependency varies for the different species. For horse mackerel for example, from 30º on, the OA has less influence on the L50 since the slope turns flatter (Fig. 7d). Opposite, for hake and blue whiting, the curve continues till 50-55º before it turns nearly flat (Fig. 7d). The three species reach optimal OAs for escaping through meshes on high OAs. Specifically, hake reach optimal OAs for being released at 85º, horse mackerel at 75º and blue whiting at 80º (Fig. 7abc).

Discussion

One of the main findings in this study was that the codend used by the Basque fleet with 20% shortened LR increases the escape probability of horse mackerel and blue whiting in the length range of 9 - 18 cm and 22 - 27 cm, respectively. Although these results show that the shortened LR codend releases commercial-sized individuals and could be seen as poor capture efficiency, catches of these two species are often non-desired in this fishery due to low market value (Rochet *et al.*, 2014). Therefore, the effect of the shortened LR can be considered positive for the sustainability of this fishery. On the other hand, hake did not show any significant difference in the retention probability between the codend configurations tested and therefore this configuration does not prevent the capture of a high proportion of undersized hake.

Although several studies have previously demonstrated that, in general terms, shortened LR codends release a higher number of undersized individuals of many roundfish species (Brothers & Boulos, 1994; Hickey *et al.*, 1995; Lök *et al.*, 1997; Ingólfsson & Brinkhof, 2020; Einarsson *et al.*, 2021; Jacques *et al.*, 2021; Sistiaga *et al.*, 2021), the results presented for hake here do not comply. Sistiaga *et al.* (2021) found that the retention probability of small-sized cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) did not significantly change when shortening LR by 15% in a 128 mm mesh size codend. However, they also showed that the retention probability of redfish (*Sebastes* spp.) was significantly lower for the same length range. They speculated that the origin of these differences could be both morphological and behavioral. Redfish is a fish that usually tries hard to squeeze itself through meshes (Sistiaga *et al.*, 2018), whereas cod tries less to escape (Sistiaga *et al.*, 2021). In the case of hake, its morphology (big head) together with

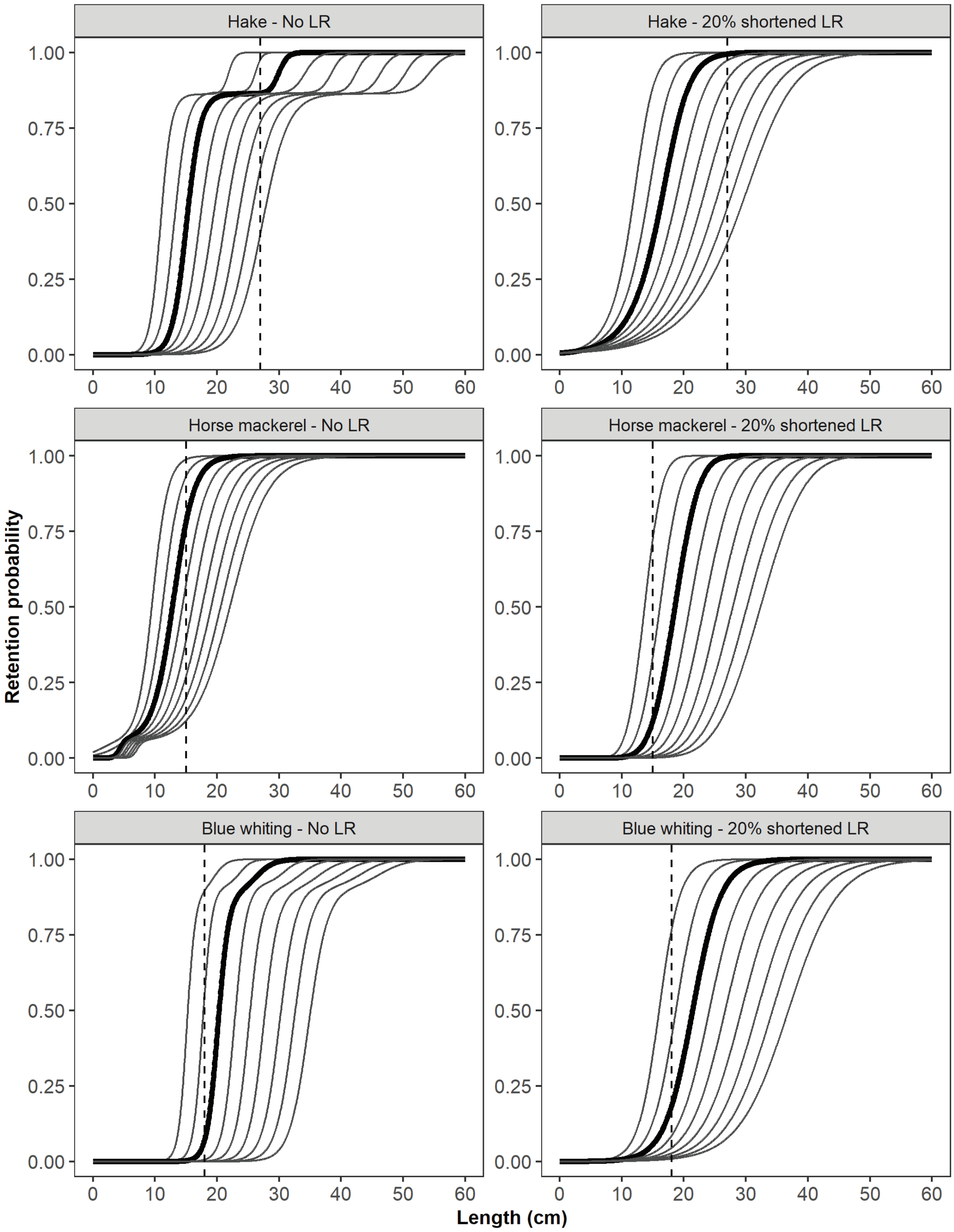

Fig. 6: Predicted size selectivity for hake, horse mackerel and blue whiting and the two codend configurations. The curves in each of the plots show the predictions for the mesh size range of 50 – 130 mm with 10 mm increments from left to right. Thick black curves correspond to the current codend mesh size used by the fleet (70 mm). Vertical dashed lines show the MCRS for hake and horse mackerel and minimum marketable size for blue whiting.

its behavior (known to be less active than horse mackerel and blue whiting (Cuende *et al*., 2020a; b) may explain the low escape probability through the shortened LR codend compared to the other two species.

Size selectivity of hake through shortened LR codend is explained by a wider mesh OAs (mainly from 10 to 35º) compared to no LR configuration, for which 86% of the size selection process is driven by OAs in between 20 and 30º. It is unclear why the remaining 14% seem to be contributed by meshes with an OA of 65º. In a standard diamond mesh codend (non-shortened LR codend), higher mesh OAs are just in front of the catch accumulation zone (Herrmann & O'Neill, 2005; Herrmann, 2005b). Based on previous studies, the OA of the meshes in that area can reach 60º as the catch builds up (Herrmann *et al*., 2009). However, when the force created by the drag in the codend as the catch builds up is carried by the ropes, it may be that openness in this area is reduced due to the effect of the LR. Based on previous knowledge on hake behaviour inside the trawl, this species passively drifts backwards

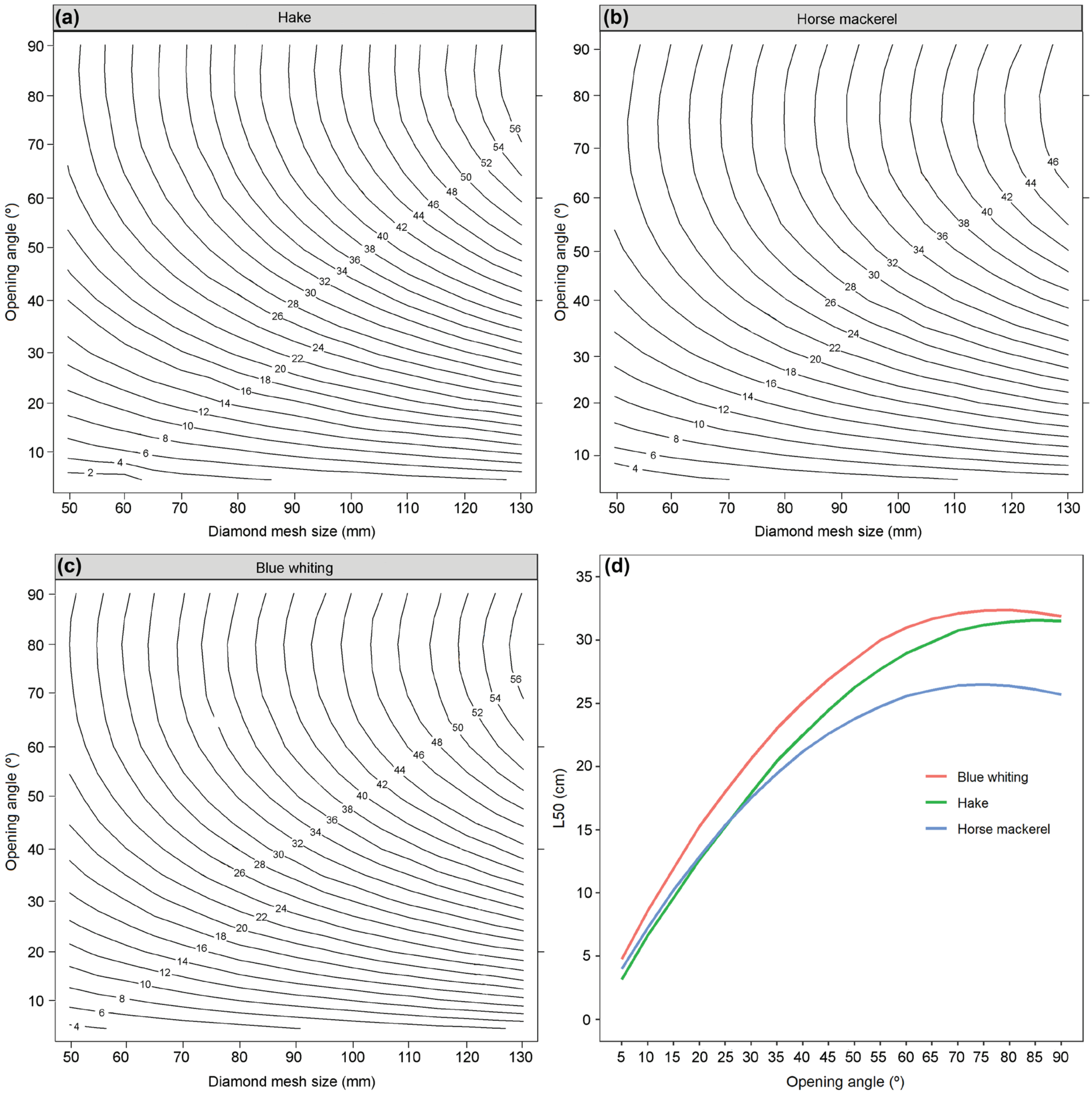

Fig. 7: Design guides for diamond meshes showing L50 isocurves for (a) hake, (b) horse mackerel and (c) blue whiting as a function of mesh size (mm), for sizes between 50 and 130 mm, and mesh OA between 10º and 90º, respectively. (d) Predicted L50 values for a 70 mm diamond mesh codend for mesh OAs between 5 and 90 degrees, with 5º increments, for hake horse mackerel and blue whiting.

towards the codend (Cuende *et al.*, 2020a), which implies that the escape attempts may be limited through meshes along the codend. However, if we assume that once at the catch accumulation zone (where they cannot fall further back) they seek an escape route, the contribution of mesh OAs of 65º for the no LR configuration could be explained. If that is the case, we could conclude that shortened LR codend have a limited effect on this species because LR may not increase openness in the area where this species attempts to escape (i.e., the catch accumulation zone) and increase availability of open meshes at the area where it does not (i.e., along the codend).

As for more active species, which are expected to seek a way to escape along the entire codend, shortened LR codend can have a greater effect on their size selectivity, as it is the case of horse mackerel and blue whiting. The analysis of the mesh OA contribution to explain the selectivity results showed that with the shortened LR codend, the availability of meshes with high OAs can be expected to be larger. The largest contributions were for mesh opening angles of 20-45º for horse mackerel and 20-40º for blue whiting. However, when the available mesh OAs are smaller, as is the case when LR are not used, horse mackerel appear to be more able to use meshes with smaller OAs for escaping than blue whiting, taking more advantage of escape opportunities. Specifically, horse mackerel use meshes with OAs in between 5-25º whereas blue whiting mainly uses OAs of 25-30º. The CS shape (laterally compressed) may be a major factor in favoring their passage through more closed meshes compared to blue whiting and hake. It can be argued that these two species could be better at squeezing themselves through meshes due to a more compressible body than horse mackerel, based on the penetration models developed in this study (Appendix C). As for blue whiting, although their more fusiform body shape could favor passage through meshes better than hake, the reasons why the selection curves for hake have a higher contribution of lower mesh OAs for both codend configurations remain unclear.

In any case, the results in this study show that the mesh openness achieved with a shortened LR codend was well below the one necessary to optimize escape chances for any species. According to the design guides, mesh OAs that would optimize fish escape based on their CS morphology and compressibility are around 75º and 85º for the three species tested. Based on the explanation provided, hake would not have shown relevant changes in the size selectivity even if the mesh OAs were optimal for escape because they do not attempt to escape where there is availability of these meshes (along the codend). However, if meshes with optimal OAs for horse mackerel and blue whiting were available (75º and 80º, respectively), their L50 value could have increased from 20.74 to 30.06 cm and from 24.30 to 36.89 cm, respectively. Several studies have shown that a slack mesh let larger fish escape than a stiff mesh of the same size did (Herrmann *et al*., 2016; Sistiaga *et al*., 2020; Vincent *et al*., 2022). However, in the light of these results, a codend made of meshes with constant optimal OAs that maximizes the size selection potential of the codend could be worth testing (e.g., Bak-Jensen *et al*., 2022).

The predictions show that a codend with shortened LR can reduce retention probability of all species to the same extent as when a considerable increase in mesh size is made. For example, the retention probability of a 70 mm mesh size codend with 20% shortened LR for 15 cm length horse mackerel is 12%. However, for our predictions, the mesh size of a codend without LR would need to be increased to 130 mm to get a 12% retention probability for the same individuals. In this situation, the retention probability of a 27 cm length hake would be reduced to 40%, whereas maintaining the 70 mm mesh size but shortening LR by 20% would keep the retention probability of these individuals at 99%. Additionally, fishermen are often reluctant to increase codend mesh size. Therefore, increasing mesh OAs by means of shortened LR may be a way to improve gear selectivity, minimize losses, with the added bonus acceptance by the fishing sector. They are simple to handle and cheap to implement.

In conclusion, according to the findings in this study, we were able to understand fish escape chances by estimating the contribution of mesh OAs to the size selection curves. We found out that the availability of different mesh OAs does not necessarily imply that fish use those meshes to escape. The results showed that shortened LR codend may provide more open meshes along the codend, although the spatial distribution of them could be different to the no LR codend. This, together with fish morphology, body compressibility and behavior, are major factors affecting fish escape chances since our results indicate that different species have different abilities at utilizing open meshes located at different places. For each species and design, we were able to identify the mesh OAs that they potentially use to pass through, and the mesh OAs that would optimize the release of non-desired individuals. We believe that the outputs of the present study provide new knowledge to understand size selectivity of these three globally relevant species when LR are used.

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Appendix A
Size selection estimation and modeling

A short description of the procedure followed to estimate codend size selectivity and the models used is shown here.

Model estimation

To estimate codend retention probability *r(l)*, we assumed that the retention likelihood could be modeled using a binomial distribution with length-dependent probabilities for being retained in the codend, specifically by a parametric model of the form *r(l,* ***v****)*, where is a vector consisting of the parameters in the model. The purpose of the analysis was to estimate the values of the parameters in ***v*** that maximized the likelihood for the experimental data (averaged over hauls) to be obtained. For this purpose, the following expression was minimized, which corresponds to maximizing the likelihood for obtaining the observed experimental data:

$$-\sum_l \sum_{j=1}^{m} \left\{ \frac{nC_{lj}}{qC_j} \times \ ln\big(r(l,\boldsymbol{v})\big) + \frac{nCC_{lj}}{qCC_j} \times ln\big(1.0 - r(l,\boldsymbol{v})\big) \right\} \qquad \text{(A1)}$$

where nC_{lj} and nCC_{lj} are the numbers of fish in the codend and cover for length class *l* in haul *j*, respectively, and qCC_{lj} and qC_{lj} are the sampling factors for the fraction of the species length measured in the codend and the cover in haul *j*, respectively. The outer summation in expression (A1) is over the length classes *l* in the data, and the inner summation is over the hauls *j* (from 1 to m).

Size selection models

To describe the experimental size selection *r(l,* ***v****)* six different models were considered: *Logit*, *DLogit* and *DSLogit*, *Probit*, *Gompertz*, and *Richard*. The description is given below:

$$r(l,\boldsymbol{v}) = \begin{cases} Logit(l, \mathrm{L50}, SR) = \dfrac{exp\left(\dfrac{ln(9.0)}{SR} \times \ (l - \mathrm{L50}\ )\right)}{1.0 + \ exp\left(\dfrac{ln(9.0)}{SR} \ \times \ (l - \mathrm{L50})\right)} \\ DLogit(l, \mathrm{C}_1, L50_1, SR_1, L50_2, SR_2) = \mathrm{C}_1 \times Logit(l, L50_1, SR_1) + (1.0 - \mathrm{C}_1) \times Logit(l, L50_2, SR_2) \\ DSLogit(l, \mathrm{C}_1, L50_1, SR_1, L50_2, SR_2) = \big(1.0 - \mathrm{C}_1 + \mathrm{C}_1 \times Logit(l, L50_1, SR_1)\big) \times Logit(l, L50_2, SR_2) \\ Probit(l, \mathrm{L50}, SR) \approx \Phi\left(\dfrac{1.349}{SR} \times (l - \mathrm{L50})\right) \\ Gompertz(l, \mathrm{L50}, SR) \approx \ \exp\left(-\exp\left(-\left(0.3665 + \dfrac{1.573}{SR} \times (l - \mathrm{L50})\right)\right)\right) \\ Richards(l, \mathrm{L50}, SR, \delta) = \left(\dfrac{exp\left(ln\left(\dfrac{0.5^{\delta}}{1.0 - 0.5^{\delta}}\right) + \left(\dfrac{ln\left(\dfrac{0.75^{\delta}}{1.0 - 0.75^{\delta}}\right) - \ ln\left(\dfrac{0.25^{\delta}}{1.0 - 0.25^{\delta}}\right)}{SR} \right)(l - \ \mathrm{L50}) \right)}{1.0 + exp\left(ln\left(\dfrac{0.5^{\delta}}{1.0 - 0.5^{\delta}}\right) + \left(\dfrac{ln\left(\dfrac{0.75^{\delta}}{1.0 - 0.75^{\delta}}\right) - \ ln\left(\dfrac{0.25^{\delta}}{1.0 - 0.25^{\delta}}\right)}{SR} \right)(l - \ \mathrm{L50}) \right)} \right)^{1/\delta} \end{cases}$$

The first three models are fully described by the selection parameters L50 (length of fish with 50% probability of being retained) and SR (difference in length between fish with 75% and 25% probability of being retained, respectively), whereas the *Richard* model requires an additional parameter *(δ)* that describes the asymmetry of the curve (Wileman *et al*., 1996). The term Φ in the probit function refers to the cumulative distribution function of a standard normal distribution. The *DLogit* and *DSLogit* (dual and dual sequential logistic models, respectively) combine two *Logit* models, assuming that all fish entering the codend are not subject to the same size selection process, and therefore some fish will be subjected to one logistic size selection process while the remaining fraction will be subjected to another logistic size selection process (Herrmann *et al*., 2016). The *DLogit* considers the contact ratio parameter C_1, which indicates the probability for an individual to have its selectivity determined by the first process, i.e. the chance of each individual to get in contact with the selective area within the first process (Herrmann *et al*., 2013c). Consequently, the probability to have its selectivity determined by the second process is $1.0–C_1$. Thus, C_1 is a number between 0.0 and 1.0. $L50_1$ and SR_1 or $L50_2$ and SR_2 describe the selectivity of the according "sub-process". The *DSLogit* model is similar to the double logit model, but it is a sequential function. This means that the proportion of individuals that try to escape in the second process is assumed to consist of those that did not attempt to escape in the first process plus those that attempted to but were retained (see Herrmann *et al*. (2016) and Noack *et al*. (2017)). For the *DLogit* and *DSLogit* models, the overall L50 and SR parameters are estimated based on the numerical approach described in Sistiaga *et al*. (2010).

Estimation of confidence intervals

Bootstrapping was applied to estimate the confidence limits for the average size selection. This approach is identical to the one described in (Millar, 1993) and takes into consideration both within-haul and between-haul variations. The hauls for each codend configuration were treated as a group of hauls. To account for between-haul variations, an outer bootstrap resample with replacement from the group of hauls was included in the procedure. Within each re-sampled haul, the data for each length class were bootstrapped in an inner bootstrap with replacement to account for within-haul variation. For each species analyzed, 1,000 bootstrap repetitions were carried out. Each bootstrap run resulted in a set of data that was pooled and then analyzed using the identified selection model. Thus, each bootstrap run resulted in an average selection curve. The Efron percentile 95% confidence limits for the average selection curve were obtained based on the same 1000 bootstrap repetitions (Efron, 1982; Herrmann *et al*., 2012).

Appendix B
FISHSELECT data and modeling

A short description of the standard FISHSELECT methodology applied for collecting morphology and mesh penetrability data and for compressibility modeling of hake and horse mackerel is shown here. Equivalent information for blue whiting as well as the procedure to apply FISHSELECT methodology can be found in Cuende *et al*. (2020c).

Data collection

In October 2016, species' individuals were collected onboard the pair-trawler "Aketxe-Gaztelugatxe" (26m length overall; 270 HP) in the Bay of Biscay (ICES subdivision VIIIc) between 43º24'N–43º30'N and 1º48'W–2º21'W. A total of 57 hake in between 14-50 cm length and 35 horse mackerel in between 14 and 32 cm length were selected with all length classes being represented randomly with one to five individuals.

Cross-section modeling

For each fish, we first measured fish length (mm), and then we measured maximum girth for the head (CS1) and maximum girth for the fish (CS2) using a mechanical sensing tool called a morphometer (Herrmann *et al*., 2009) (Fig. B1). The CS contours were modelled by a variety of different geometrical shapes: Ellipse, Flexdrope, Flexellipse 1, Ship, and Superdrope (Fig. B1) (details on these geometrical models can be found in Frandsen *et al*. (2010) and Tokaç *et al*. (2016). Akaike information criterion (AIC) values (Akaike, 1974) and R^2 values were used to identify which of the shapes defined the contour for each CS best.

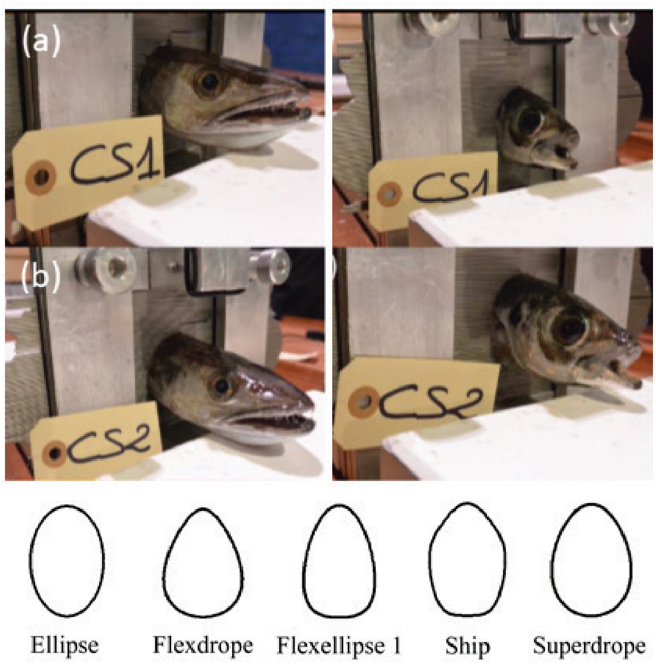


Fig. B1: The two CS measurements collected for each hake (left) and horse mackerel (right) sampled: (a) cross-section 1 (CS1) and (b) cross-section 2 (CS2). The illustrations below show all five geometrical shape models tested for each CS contour.

Fall-through experiments

Fall-through experiments are used to determine whether a fish can physically pass through a certain mesh. The tests are carried out using a series of rigid meshes. We tested 478 different rigid meshes that included diamonds, hexagons, and rectangles. These are identical to those described by (Tokaç *et al*., 2016). Each fish was tested in each mesh under the pull of gravity alone (Herrmann *et al*., 2009), and the results were registered as "yes" (the fish was able to pass through the mesh) or "no" (the fish was not able to pass though the mesh).

Simulation of mesh penetration and selection of a penetration model

For each CS, three-parameter penetration models with symmetrical and asymmetrical compressibility were created and tested. The three parameters represented the dorsal, lateral, and ventral compressibility of both fish species (Herrmann *et al*., 2009). The potential compressibility of the fish at an arbitrary angle around the fish CS was then modelled by linear interpolation between the potential compressibility (dorsally, laterally, and ventrally) of the fish at each CS. Models with compressibility that varied between 0% and 32% compression in steps of 2%, 4%, or 6% at three points in each CS (depending on the precision needed at that point based on the compressibility of the CS) were tested for hake and horse mackerel. This resulted on a total of 216 different model combinations for CS1 and 324 different model combinations for CS2 for each species, respectively. Additionally, the different penetration models for each CS1 were combined with the different penetration models for CS2, for a total of 69,984 combined models (216 x 324).

The CS shape and compressibility of a fish ultimately determine whether it will be able to pass through a mesh. Using a simulation tool in the FISHSELECT software, the modeled shapes representing each CS for each fish were geometrically compared with each of the 478 mesh templates to determine if each fish included in the trials could physically pass through them. The purpose of these simulations was to estimate the precise compressibility potential of each CS and to assess which CS or CS combination models need to be considered when estimating the ability of hake and horse mackerel to pass through meshes of different shapes and sizes. Thus, the experimentally obtained fall-through results were compared to the simulated fall-through results obtained with the different penetration models created in the FISHSELECT software. The best penetration models, which were considered optimal for modeling hake and horse mackerel mesh penetration and were used in further analyses, were established as the ones that showed the highest degree of agreement (DA) with the experimental fall-through results for each species, respectively. The DA value was the percentage of the fall-through results for which the simulated results came up with the same result ("yes" or "no") as the experimentally obtained result.

Creation of a virtual population

The modeled relationship between each of the parameters defining CS1 and CS2 and fish length allowed us to create a virtual population of 5,000 hake and horse mackerel individuals, respectively. A wide range of uniformly distributed lengths and well-defined CSs were simulated (between 5 and 90 cm) to calculate the selectivity for the smallest and largest mesh sizes. This ability to create virtual populations of hake and horse mackerel with defined morphological characteristics was the first important outcome of this first step. The second important outcome was the penetration model with the highest DA obtained, which allowed us to predict whether a fish individual with a specific length and defined CSs can pass through a mesh of specific size and shape. We used these two outcomes, which form the predictive model, in step two to determine whether individuals of different sizes can pass through an array of meshes of different sizes and shapes.

Appendix C
Morphological description of the species tested based on FISHSELECT

Results on morphological modeling of hake and horse mackerel are presented below.

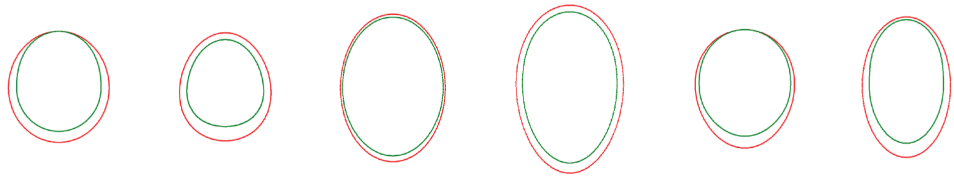
Best CSs shapes models for hake and horse mackerel were the Flexellipse1 for CS1 and CS2 of hake and Flexdrope CS1 and CS2 of horse mackerel, based on R^2 and AIC values (Table C1).

Table C1. AIC values for the different models tested for each species and cross-section; models resulting in the lowest AIC in bold.

Species	Cross-section	Ellipse	Flexdrop	Flexellipse1	Ship	Super drope
Hake	CS1	219.17	195.88	**191.47**	204.01	286.58
	CS2	250.76	217.88	**214.49**	228.55	266.76
Horse mackerel	CS1	292.08	**171.08**	200.05	255.88	392.75
	CS2	231.24	**187.78**	195.99	215.89	328.15

Based on the results from the 33,460 fall-through trials for hake, 26,290 for horse mackerel derived from the 478 meshes, we selected a penetration model to use for simulating size selection of each species. These penetration models consist of both CS1and CS2 and resulted in a DA-value at 97.67% and 98.54% for hake and horse mackerel, respectively. The compression values for the penetration models with highest DA-values are summarized in Table C2.

Table C2. Lateral, dorsal and ventral compression values for the best penetration models for CS1 and CS2 and for each species. The values for blue whiting have been included from Cuende *et al*. (2020c). Green inner curves correspond to fully compressed CSs with the best penetration model and red outer curves correspond to no compressed CSs.

	Hake		**Horse mackerel**		**Blue whiting**	
	CS1	**CS2**	**CS1**	**CS2**	**CS1**	**CS2**
						
Lateral compression	16 %	16 %	4 %	12 %	8%	16%
Dorsal compression	0 %	12 %	4 %	8 %	0%	4%
Ventral compression	20 %	28 %	8 %	12 %	20%	20%