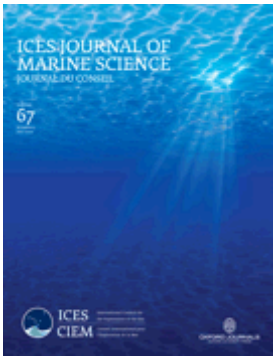

Prediction of square mesh panel and codend size selectivity of blue whiting based on fish morphology

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Complete List of Authors:	Cuende, Elsa; AZTI (BRTA), Marine Research Division Arregi, Luis; AZTI (BRTA), Marine Research Division Herrmann, Bent; SINTEF Fisheries and Aquaculture, Fishing Gear Technology Sistiaga, Manu; Institute of Marine Research, Fisheries Technology Aboitiz, Xabier; AZTI (BRTA), Marine Research Division
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Prediction of square mesh panel and codend size selectivity of blue whiting based on fish morphology

Elsa Cuende[1*◊], Luis Arregi[1◊], Bent Herrmann[2◊], Manu Sistiaga[3◊], Xabier Aboitiz[1]

[1]AZTI, Marine Research, Basque Research and Technology Alliance (BRTA). Txatxarramendi ugartea z/g, 48395 Sukarrieta, Bizkaia.

[2]SINTEF Ocean, Fishing Gear Technology, Willemoesvej 2, 9850, Hirtshals, Denmark; The Arctic University of Norway, UiT, Breivika, N-9037 Tromsø, Norway.

[3]Institute of Marine Research, Postboks 1870 Nordnes, Bergen, 5817, Norway;

Norwegian University of Science and technology, Otto Nielsens veg 10, N-7491 Trondheim, Norway.

[*]**Corresponding author:** AZTI, Marine Research, Basque Research and Technology Alliance (BRTA). Txatxarramendi ugartea z/g, 48395 Sukarrieta- Bizkaia. ecuende@azti.es

[◊]**Equal authorship**

Abstract

Square mesh panels (SMPs) are selective devices used extensively to supplement codend size selectivity in trawl fisheries. Therefore, predictions of the effect of mesh size in both SMPs and codends on size selectivity are valuable. Here, we established a framework to predict size selection of blue whiting through different SMPs and diamond mesh codends based on the morphological characteristics of this species. We hypothesized that size selection for a SMP is determined by different fish contact angles, whereas different mesh opening angles determine size selection for the codend. Based on these hypotheses, we first developed a model that enabled us to predict which sizes of blue whiting are able to pass through meshes of different sizes and shapes. We then tested whether the selectivity for blue whiting of the SMP, the codend, and the combination of both could be explained by the models. Finally, we predicted size selectivity of multiple combinations of SMPs and diamond mesh codends. The method presented here can potentially be applied to make predictions for species other than blue whiting.

Keywords: Square mesh panel (SMP); contact angle; opening angle; fish behaviour; *Micromesistius poutassou*

Introduction

In many bottom trawl fisheries around the world, codend size selectivity is supplemented with additional devices such as square mesh panels (SMPs) (Özbilgin *et al.,* 2005; Graham, 2010; STECF, 2012). Unlike in the codend, where the shape of the meshes can vary substantially (Robertson and Stewart, 1988; Herrmann, 2005*a*; Herrmann and O'Neill, 2005), SMPs maintain their shape and therefore provide mesh shapes that better support escape for non-targeted fish. SMPs were first introduced into legislation in the Northern European *Nephrops* fishery in 1992, primarily to improve the release of undersized gadoids (*Merlangius merlangus*) (Briggs, 1992). Since then, they have been introduced in some other crustacean (Broadhurst, 2000; Catchpole and Revill, 2007) and fish-directed fisheries (Regulation EU 2019/1241). Today, SMPs are compulsory when targeting specific species in some fishing areas (Regulation EU 2019/1241), and their applicability and efficiency have been broadly studied (O'Neill *et al.,* 2006; Herrmann *et al.,* 2015; Brčić *et al.,* 2016, 2018).

Two conditions must be met for a fish to be able to escape through a SMP: the fish first needs to contact the SMP and then it needs to be able to pass through the meshes in the SMP (Herrmann *et al.,* 2009; Sistiaga *et al.,* 2011). A number of researchers have estimated contact probability and fish release efficiency of SMPs (e.g., Zuur *et al.,* 2001; O'Neill *et al.,* 2006; Herrmann *et al.,* 2015; Santos *et al.,* 2016; Krag *et al.,* 2017; Sistiaga *et al.,* 2017; Brčić *et al.,* 2018), and some have tried to improve this contact probability to increase SMP release efficiency (Cuende *et al.,* 2020*a*; Cuende *et al.,* 2020*b*). In addition to having estimated the contact probability of fish with the SMP, all of these studies investigated the size selectivity of those fish that contacted it. This size selectivity is quantified in terms of L50 (length of fish that has a 50% chance of retention by the SMP assuming that contacts occurs) and selection range (SR) (= L75 – L25) (Wileman *et al.,* 1996; Millar and Fryer, 1999; Sistiaga *et al.,* 2010). However, when the experimentally obtained L50 and SR results are compared with the expected values based on fish morphology and SMP mesh size, the experimental L50s often are much smaller and the SRs much larger than the expected values (Alzorriz *et al.,* 2016). No study to date has investigated in detail the reasons for this difference between the expected and obtained selectivity results.

The overall size selectivity of the gear is determined not only by the properties of the SMP but also by the size selectivity of the codend used. The factors affecting diamond mesh codend size selectivity have been widely investigated, both theoretically and experimentally. Factors such as catch size (O'Neill and Kynoch,

1996; Herrmann, 2005*b*), netting orientation and twine thickness (Herrmann *et al.,* 2013*a*), or the number of meshes in the circumference (Sala and Lucchetti, 2011) can affect codend size selectivity because they can alter codend shape and thereby mesh shape and opening angles (OAs) (e.g., O'Neill and Herrmann, 2007; Herrmann *et al.,* 2009; Sistiaga *et al.,* 2011; Herrmann *et al.,* 2012; Herrmann *et al.,* 2013*b*; Tokaç *et al.,* 2016, 2018). Several studies investigated the influence of fish morphology on codend size selectivity. However, no study has investigated the influence of fish morphology and mesh size on the overall size selectivity of a gear composed of a SMP together with a size selective codend.

Blue whiting (*Micromesistius poutassou*) is a globally important commercial fish species (FAO, 2018), with catches that, for example, exceeded 1.7 million tons in the Northeast Atlantic in 2018. However, little is known about its size selection in the commercial fishing gear. This species is mostly harvested with pelagic trawls, but its size selectivity is also relevant for bottom trawls, where it is discarded both in crustacean (e.g., Monteiro *et al.,* 2001) and fish-directed mixed bottom trawl fisheries (Rochet *et al.,* 2014). In the Basque bottom trawl fishery, mostly targeting anglerfish (*Lophius* spp.), megrim (*Lepidorhombus* spp.) and hake (*Merluccius merluccius*), blue whiting constitutes one of the main discarded species. In 2006, a gear composed of a 100 mm SMP inserted in the upper panel of the extension piece of the trawl and a 70 mm diamond mesh codend was introduced as a regulation in this fishery (Regulation EC 51/2006) to increase the release efficiency of undersized fish. However, Rochet *et al.* (2014) estimated that during the period 2011-2013 ~98% of the blue whiting caught in this fishery was discarded. The gear used by the fleet today is still the same and despite the Landing Obligation (Regulation EU 1380/2013) discards of blue whiting are still likely. More recently, Cuende *et al.* (2020*a*) showed that a considerable percentage of the blue whiting entering the gear was able to contact the SMP, meaning that a properly designed SMP would substantially affect the overall trawl size selection. For these reasons, blue whiting is a relevant species to investigate the size selectivity of a trawl equipped with a SMP and a diamond mesh codend.

The goals of this study were to investigate size selection of blue whiting through SMPs and diamond mesh codends and to predict the effect of SMP and codend mesh size and shape on the overall size selective properties of the gear for this species.

Materials and methods

In the past, size selectivity studies of towed fishing gears have mainly been carried out at sea following a trial and error procedure (Kvamme and Isaksen, 2004; Jørgensen *et al.,* 2006). However, as sea trials are

costly and time consuming, modelling, and predictive work have become more common in this field to supplement and assist experimental methods (Herrmann, 2005*b*; Herrmann *et al.,* 2009).

In this study, we applied a three-step approach to predict size selection of blue whiting for different combinations of SMP and codend mesh sizes:

1. We developed a model that enabled us to predict which sizes of blue whiting are able to pass through meshes of different sizes and shapes. To do this, we used FISHSELECT, which is a framework of tools, methods, and software developed to determine whether or not a fish is able to penetrate a certain mesh by comparing the morphology of the fish and the geometry of the mesh. The methodology was previously used to investigate size selectivity for numerous species in various fisheries (Frandsen *et al.,* 2010; Sistiaga *et al.,* 2011; Krag *et al.,* 2011; Herrmann *et al.,* 2012, Herrmann *et al.,* 2013*b*; Krag *et al.,* 2014; Herrmann *et al.,* 2016; Tokaç *et al.,* 2016). It was applied to blue whiting for the first time in our study.
2. Based on selectivity results obtained from sea trials carried out with a gear configuration composed of a SMP and a diamond mesh codend (Cuende *et al.,* 2020*a*), we tested whether the selectivity for blue whiting of the SMP, the codend, and the combination of both could be explained by the models obtained from the application of FISHSELECT.
3. Provided that the experimental results obtained at sea (Cuende *et al.,* 2020*a*) could be explained by the models obtained from the application of FISHSELECT, we predicted the size selectivity of multiple combinations of SMPs and diamond mesh codends.

Collection of morphology and mesh penetrability data of blue whiting using FISHSELECT

In October 2016, blue whiting individuals were collected onboard the pair-trawler "Aketxe-Gaztelugatxe" (26 m 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 55 blue whiting ranging from 14 to 32 cm in length were selected with all length classes being represented randomly with one to five individuals. FISHSELECT requires precise measuring of fish morphology, and it is important that the shape of the fish measured is not affected by dehydration, depressurization, rigor mortis, or any other factor that could alter the original shape of the fish. Therefore, the fish included in the experiment were selected from the last haul of the trip, when the transit time to port was ~1 hour. During transit, the fish were kept in seawater with ice to avoid damage or

deformation. FISHSELECT measurements of blue whiting were carried out on land at the harbor immediately after the fish were unloaded from the vessel. Details on the application of the standard FISHSELECT methodology to blue whiting are given in Supplementary Material.

Understanding SMP and diamond mesh codend size selection for blue whiting

Simulation of square mesh and diamond mesh selectivity

The virtual population and the compression model obtained (see Supplementary Material) were used to simulate SMP and diamond mesh codend size selectivity. Specifically, size selection for blue whiting was simulated for meshes of varying sizes and shapes in FISHSELECT.

In trawl codends, water flow decreases as fish approach the catch-accumulation zone (Jones *et al.,* 2008). The decreased water flow and the more open meshes in this zone favors the active escape of fish swimming here (O'Neill *et al.,* 2003). Therefore, fish are expected to have several chances to attempt escape through the codend meshes. Multiple attempts result in a higher probability that a fish will have at least one attempt with optimal orientation towards the mesh to escape through it. Thus, size selectivity in codends can be simulated considering only optimal fish contact angle (CA) towards the mesh (Herrmann and O'Neill, 2005; Herrmann and O'Neill, 2006; Sistiaga *et al.,* 2011; Tokaç *et al.,* 2016). However, mesh openness is not constant in diamond mesh codends, and therefore it must be considered when simulating size selectivity (Herrmann, 2005*a*; O'Neill and Herrmann, 2007; Herrmann *et al.,* 2009). For diamond meshes, mesh openness can be described by the OA (Herrmann *et al.,* 2009).

Using the penetration model and virtual population (see Supplementary Material), we simulated the size selectivity of blue whiting through individual diamond meshes of sizes between 50 and 150 mm in steps of 5 mm and OAs between 10 and 90º in steps of 5º. These simulations resulted in artificial "covered-codend" size selectivity datasets with fish size distributions for the fish "retained" and the fish that "escaped" through each mesh (Wileman *et al.,* 1996). Each dataset was subsequently analyzed by fitting a logit size selection model defined by the parameters L50 and SR (Wileman *et al.,* 1996) to the data. The results of this process consist of associated mesh size and OA and L50 values summarized in a design guide (Herrmann *et al.,* 2009) showing L50 isocurves (lines with equal L50) dependent on mesh size and OA.

In contrast to diamond mesh codends, the mechanisms involved in the size selection through SMPs are not well understood. SMPs are usually installed at the upper panel of the extension piece of the trawl (Krag *et al.,* 2008; Wienbeck *et al.,* 2014; Nikolic *et al.,* 2015) where they maintain an open mesh shape independent

of the tension in the netting (Graham *et al.,* 2003). Therefore, SMP size selectivity can be simulated assuming fully open square meshes. However, at this position in the trawl, SMP meshes are not located in the natural swimming path of the fish (Briggs, 1992; Briggs and Robertson, 1993). Thus, in order to have a chance of escaping through the SMP meshes, most of fish need to actively change swimming direction and seek the SMP meshes (Briggs, 1992; Briggs and Robertson, 1993). Strong water flow relative to the gear in this area of the trawl makes it unlikely that every fish has multiple chances of having an optimal CA to escape through the SMP. For many blue whiting, it is likely that none of the few attempts would have an optimal CA (Fig. 1a) (i.e., perpendicular to the square mesh). For a specific mesh size, the closer the CA gets to 90º, the larger the projection of the mesh from the fish's perspective and, consequently, the higher probability that a larger fish can pass/squeeze itself through the mesh (Fig. 1a). However, at low CAs, the projection of the mesh becomes narrower, meaning that the size of fish that can pass through it is smaller (Fig. 1a). Therefore, when simulating SMP contact size selection, we assumed that the CA needed to be considered (size selection of the fish that actually contact the SMP and are size-selected by the meshes in it (Sistiaga *et al.,* 2010)). Specifically, we hypothesized that changes in the size and shape of the projected SMP meshes could be a major factor explaining the differences observed between simulated and experimentally obtained size selection results. This hypothesis is supported by underwater recordings from earlier sea trials (Cuende *et al.,* 2020*a*), which revealed that blue whiting attempt escape through SMPs with different CAs (Fig. 1b).

FIGURE 1

Fig. 1. (a) Different contact angles (CAs) (ranging from 10 to 90º) for blue whiting attempting to escape through SMP meshes. The column to the right for each of the angles shows the shape of the projected mesh for the different CAs (green rectangle) and the cross-section of the largest blue whiting that would pass through it (blue circle). (b) Underwater recordings from experimental trials (Cuende *et al.,* 2020*a*) showing fish trajectory (red arrow) for each escape attempt with different CAs through a SMP.

To simulate SMP contact size selectivity dependent on fish CA, we first had to determine the size and shape of the mesh from the perspective of the fish. When the CA is lower than 90º, the projected mesh shape becomes rectangular because the mesh bars that are perpendicular with respect to the orientation of the fish keep their original length, while the bars that are longitudinal with respect to the orientation of the fish shrink (Fig. 2). The length of the mesh bars that are longitudinal regarding fish orientation is given by:

(1) $p = \frac{m}{2} \times \sin(CA)$

where p is the projected length of the longitudinal bars of the mesh with respect to the orientation of the fish, $\frac{m}{2}$ is the mesh bar length (equal to half mesh size), and CA is the contact angle (Fig. 2).

FIGURE 2

Fig. 2. (a) Blue whiting contacting the SMP with a specific contact angle (CA). The rightmost part of the diagram shows how to calculate the mesh size projection according to the CA. $\frac{m}{2}$ is the bar length of the square meshes (half mesh size), and p is the projected length of the longitudinal bars of the mesh with respect to the orientation of the fish. (b) Transformation from an original SMP mesh to the projected mesh based on the specific CA of a fish.

Using the penetration model and virtual population, we simulated the size selectivity of blue whiting through individual projected SMP meshes (rectangular meshes) resulting from CAs between 10 and 90º in steps of 5º. The simulations were carried out for mesh sizes between 50 and 150 mm in steps of 5 mm. As for the diamond meshes, a logit selection model was fitted to the size selection dataset simulated for each mesh. Results for the SMP meshes were summarized in a design guide showing L50 isocurves for different SMP mesh sizes and fish CAs.

Comparison of simulated and experimental size selection

To investigate whether the experimentally obtained size selection curves for blue whiting (Cuende *et al.,* 2020*a*) could be explained by the simulated results obtained with FISHSELECT, experimental SMP and codend size selection results were compared with results simulated for different CAs and OAs, respectively. The mesh sizes for the experimental SMP and diamond mesh codend were 82.70 mm and 72.80 mm, respectively (Cuende *et al.,* 2020*a*). Therefore, the size selectivity for blue whiting through SMP and codend meshes of these sizes was simulated first. The size selection of a SMP with square meshes of 82.70 mm was simulated for CAs ranging from 10º to 90º in steps of 5º. Likewise, the size selection of a diamond mesh codend with meshes of 72.80 mm was simulated for OAs ranging between 10º and 90º in steps of 5º. Following the same procedure as that used in previous section, logit size selection curves were fitted to each of the simulated datasets derived from the 17 different square meshes considered and from the 17 different diamond meshes considered.

The experimental SMP size selection curve from Cuende *et al.* (2020*a*) was plotted together with the size selection curves simulated for the square meshes derived from each CA and with the size selection curves simulated for the diamond meshes with different OAs. All fish entering the codend were assumed to have contacted the codend meshes and to have been subjected to a size-dependent escape probability through them. Therefore, we could directly compare the experimental curve for the diamond mesh codend from Cuende *et al.* (2020*a*) with the curves simulated in the present study for the meshes with different OAs. However, this direct comparison was not possible for the SMP, as experimental selection curves for the SMP in Cuende *et al.* (2020*a*) showed that only 27% of the blue whiting entering the gear in the sea trials contacted the SMP (Fig. 3a).

For a SMP, the size selectivity curve estimated based on the entire population of fish entering the gear (those that contact the device and those that do not) is known as the available SMP selectivity curve (ra_{SMP}) (Fig. 3a), whereas the selectivity curve estimated based only on the fish that actually contact the device is known as the contact selectivity curve (rc_{SMP}) (Millar and Fryer, 1999; Sistiaga *et al.,* 2010) (Fig. 3b). The relationship between ra_{SMP} and rc_{SMP} is described by Cuende *et al.* (2020*b*) as:

$$ra_{SMP}(l) = 1 - C_{SMP} + C_{SMP} \times rc_{SMP}(l) \quad (2)$$

FIGURE 3

Fig. 3. (a) Experimental available SMP retention probability curve (ra_{SMP}) (black line) with corresponding confidence intervals (dashed lines) and experimental rate (crosses). (b) Contact SMP retention probability (rc_{SMP}) (black line) with corresponding confidence intervals (dashed lines).

As CAs are only relevant for the fish that actually contact the SMP, it is the experimental rc_{SMP} selection curve (Fig. 3b) that needs to be explained by means of different CAs.

The experimental rc_{SMP} and codend size selectivity curves, with their corresponding confidence intervals (CIs) (Cuende *et al.,* 2020*a*), were plotted together with the selection curves obtained from the FISHSELECT simulations for the different rectangular meshes representing the projected square meshes and the different diamond meshes, respectively. The purpose of the comparison between the experimental and simulated curves was to determine which range of CAs and OAs could contribute to explain the size selection curves experimentally obtained for the SMP and the diamond mesh codend, respectively. The ranges selected included all simulated selection curves corresponding to the different CAs and OAs that, at

least partially, were in between the CIs of the experimental rc_{SMP} curve and experimental diamond codend size selection curve, respectively.

Once the relevant ranges of CAs and OAs were identified, we estimated the contribution of each of the CAs and each of the OAs to the observed experimental SMP and codend size selection curves. The most likely combination of CAs for the SMP and OAs for the codend that could best reproduce the entire experimental selection curves were investigated for each of the cases. For this purpose, we first represented the entire experimental SMP and codend size selection by calculating L05 to L95 (length of fish with retention likelihood between 5% and 95%) in steps of 5% for each of the curves. These values were calculated as reference points in the curves and obtained by numerical methods implemented in SELNET (Herrmann *et al.,* 2013*b*). Once the experimental L05,…, L95 were obtained for SMP and codend selection curves, we tried to reproduce them based on different combinations of contributions from the different CAs and OAs by simulation in FISHSELECT. Specifically, the contributions were expressed in terms of weight factors that summed up to 100%. The values of the weight factors were estimated by minimizing a penalty function. The penalty function quantified the difference in sum of squares between the experimental L05,…, L95 and the obtained one based on the FISHSELECT simulations. This method was applied using the approach described by Herrmann *et al.* (2013*b*, 2016). Application of this method resulted in a list of relative contributions of the different CAs and OAs that most accurately reproduced the experimental SMP and codend size selection curves, respectively. CAs and OAs with contributions < 0.001% were considered negligible and not included further in the analyses.

The contributions of the different CAs and OAs were used to create size selection curves for the SMP, diamond mesh codend, and combination of the two. The curves obtained were then plotted and compared with results from the sea trials reported in Cuende *et al.* (2020*a*). For SMP size selection, rc_{SMP} was converted to ra_{SMP} by means of Equation 2 using the C_{SMP} estimated from the sea trials. The models used to create the SMP and codend size selection curves based on the different CA and OA contributions were the ones used to represent the experimental curves in each case: *CGompertz* for the SMP and *Richard* for the codend (Wileman *et al.,* 1996). Equation (3) was used to create a combined retention probability curve for blue whiting based on the contributions of different CAs for the SMP selectivity and different OAs for the codend selectivity:

$$r_{comb}(l) = ra_{SMP}(l) \times r_{codend}(l) \quad (3)$$

Prediction of size selectivity for different mesh size combinations of the SMP and diamond-mesh codend

Provided that the experimental results obtained at sea could be explained by the approach presented in the previous section, predictions to explore the potential of making gear design changes were carried out in FISHSELECT. Using the penetration model and virtual population (see Supplementary Material), the available SMP size selection of blue whiting was simulated for mesh sizes ranging from 50 to 150 mm with 10 mm intervals and only considering CAs that contributed to reproduction of the experimental SMP size selection curve. Likewise, codend size selection was simulated for mesh sizes ranging from 50 to 150 mm with 10 mm intervals and only considering the OAs that contributed to reproduction of the experimental curve. These simulations resulted in a "covered-codend" (Wileman *et al.,* 1996) size selectivity dataset for each mesh size and CA or OA combination. We assumed that the contribution of the different CAs and OAs for all mesh sizes would be the same as the contributions previously estimated for the experimental SMP and codend size selection. Thus, we predicted the size selection for different SMP and codend mesh sizes by applying the contributions of the different CAs and OAs to all the SMP and codend mesh sizes simulated. The output of this procedure was a "covered-codend" dataset for each SMP and codend mesh size that considered the contribution of the different CAs and OAs, respectively. A logit size selection model was fitted to each of the resulting datasets.

Predictions of the combined size selection for blue whiting were also made for different combinations of SMP and codend mesh sizes. To explore the consequences of potential mesh size modifications in the SMP or the codend for blue whiting selectivity, we investigated how mesh size modifications would alter the selective properties of the SMP + diamond mesh codend gear used in the Basque bottom trawl fishery. Using Equation 3 and the available predicted SMP and codend size selection results, the combined size selectivity of different SMP and codend mesh sizes relevant to the Basque bottom trawl fishery were predicted. Because the regulation for the fishery requires compulsory use of a 100 mm SMP and a 70 mm diamond mesh size codend, we first varied the SMP mesh size from 50 to 150 mm in steps of 10 mm while keeping the codend mesh size constant at 70 mm. We then varied the codend mesh size from 50 to 150 mm in 10 mm increments while keeping the SMP mesh size constant at 100 mm. Blue whiting does not have a minimum conservation reference size (MCRS), but it has a minimum marketable size of 30 individuals/Kg (Regulation EC 2406/1996), which is equivalent to 18 cm in length on average according to the weight-

length ratio for this species (Dorel, 1986). This size was also taken into consideration when assessing the risk for catching or losing non-marketable and marketable blue whiting.

We then produced a series of five design guides showing L05, L25, L50, L75, and L95 for combined SMP and diamond mesh codend results; these represent sizes of blue whiting with 5%, 25%, 50%, 75%, and 95% probability of being retained, respectively. Each design guide covered mesh sizes in the range of 50 to 150 mm. The aim of the design guides was to show how the retention for blue whiting changes depending on the SMP and codend mesh sizes combined. These design guides provide a global picture of the selective potential of the gear and are a useful tool for identifying the best mesh size combinations for the gear.

Given that the experimental C_{SMP} for blue whiting was estimated to be 0.27 (Cuende *et al.,* 2020*a*), we then explored the extent to which the ra_{SMP} size selectivity and combined size selectivity could be affected by increasing the C_{SMP} value. We evaluated the selectivity of a 100 mm SMP and combined size selection of a 100 mm SMP and 70 mm codend for C_{SMP} values of 0.40, 0.60, 0.80, and 1.00.

Results

Morphological description of blue whiting based on FISHSELECT

Description of cross-section shapes

The cross-section shapes of 55 blue whiting ranging from 14 to 32 cm in length were measured during the experimental data collection period. The analysis carried out in FISHSELECT for each of the two cross-sections extracted from each individual showed that, based on R^2 and AIC values, the Flexdrope and Flexellipse 1 models best fitted blue whiting cross-section 1 and 2, respectively (Table 1).

Table 1. AIC values for the different models tested for each cross-section; the model that resulted in the lowest AIC value (best model) is in bold.

TABLE 1

Fall-through results and penetration model

We obtained 26,290 experimental fall-through results for blue whiting. Based on comparisons of the fall-through results with the different compression models tested for cross-section 1 and 2, the best agreement was found for a model that considered both cross-section 1 and cross-section 2. For cross-section 1, this model had 8% mean lateral compression, 0% dorsal compression, and 20% ventral compression (Fig. 4).

For cross-section 2, this model had 16% lateral compression, 4% dorsal compression, and 20% ventral compression (Fig. 4). The model resulted in a 97.39% degree of agreement.

FIGURE 4

Fig. 4. Compression models for cross-section 1 (left) and cross-section 2 (right). Green inner curves correspond to the best compression model and red outer curves correspond to no compression for each cross-section of blue whiting.

Square and diamond mesh selectivity based on fish CA and mesh OA

Design guides for square and diamond meshes

With the optimal penetration model defined for each species and with the ability to produce virtual populations with defined cross-sections, we produced design guides for square and diamond meshes ranging from 50 to 150 mm size and from 5 to 90º CA and OA, respectively (Fig. 5). The square mesh design guide demonstrated that, for a given mesh size, the size selectivity of blue whiting depended greatly on the CA of the fish towards the SMP (Fig. 5a). This was especially true for the range of CAs between 10º and 40º, where L50 increased rapidly with increasing CA. For all mesh sizes with CA > 40º, L50 isocurves changed into nearly vertical lines, thus L50 rose much slower with increasing CA. L50 of codend diamond meshes depended greatly on the OA, especially when OAs were between 10 and 50º (Fig. 5b). For larger OAs, the influence of the angle on the L50 diminished, especially at smaller mesh sizes.

FIGURE 5

Fig. 5. Design guide for (a) square and (b) diamond meshes showing L50 isocurves as a function of mesh size (mm), for sizes between 50 mm and 150 mm, and mesh CA and OA between 10º and 90º, respectively.

Explanation and validation of the size selection curve for blue whiting based on simulations

The size selection curves simulated for SMPs and diamond mesh codends for blue whiting based on different CAs and OAs were plotted together with the experimental rc_{SMP} and codend size selection curves (Fig. 6). The results show that for both the SMP and codend, respectively, a range of CAs and OAs may contribute to the experimental size selection curves for blue whiting. Specifically, the CAs and OAs potentially involved in the selectivity process corresponded to 15º to 90º CAs for the SMP (Fig. 6a) and 15º to 50º OAs for the codend (Fig. 6b).

FIGURE 6

Fig. 6. Grey curves show (a) the simulated SMP selectivity for different CAs and (b) codend selectivity for different OAs from 10º to 90º in steps of 10º. Black curves depict (a) experimental rc_{SMP} and (b) experimental codend size selection curve with corresponding CIs (dashed lines).

Table 2 shows the average contribution of the different CAs and OAs considered to be potentially involved in reproducing the experimental rc_{SMP} and diamond mesh codend curves. Among the CAs, the relative contributions of the angles between 55º and 75º were below 0.001% and therefore were not considered relevant to the results for the experimental rc_{SMP}. In contrast, all OAs that could potentially contribute to the experimental codend selectivity curve contributed more than 0.001% and were considered relevant.

Table 2. Contribution (%) of the considered SMP CAs and codend mesh OAs as potentially involved in reproducing experimental rc_{SMP} and codend size selection curves. *: could not contribute due to no overlap with experimental selectivity curve.

TABLE 2

Using the CAs and OAs with contributions > 0.001% from Table 2, SMP, codend, and combined size selection curves were simulated. A comparison between the experimental and simulated size selectivity curves showed that the simulated SMP, codend, and combined size selection curves reproduced the experimental ra_{SMP}, codend, and combined size selection curves accurately (Fig. 7). These results demonstrated that SMP, diamond mesh codend, and combined size selection can be understood by the contribution of the different CAs and OAs.

FIGURE 7

Fig. 7. Experimental (black line) and simulated (yellow line) size selection curves are shown for (a) SMP, (b) codend, and (c) combined SMP and codend. Experimental 95% CIs are shown (dashed lines).

Prediction of size selectivity for different SMP and codend mesh size combinations

Because the contributions of the CAs and OAs in Table 2 could explain the experimental SMP, codend, and combined size selection, we predicted size selection for different SMP and codend mesh combinations (Fig. 8). Results show that given the low contact probability of blue whiting with the SMP (C_{SMP} = 0.27), the retention probability of the SMP was high (i.e., there was low escape probability through it no matter

how much the SMP mesh size is increased) (Fig. 8a). Limited effects of changing SMP mesh size were also evident in the combined selectivity analysis (Fig. 8c), as L50 values were very similar for all mesh sizes (in between 20.15 and 21.20 cm). The low contact probability between the SMP and blue whiting implies that mesh size modifications affected only the upper part of the curve, which led to a low efficiency of increasing SMP mesh size. Nevertheless, individuals of blue whiting below marketable size (18 cm) had high escape probability (81.85–82.20%) through the whole predicted mesh size range (Fig. 8c). In contrast to the SMP, codend mesh size modifications affected the entire selectivity curve (Fig. 8b). Therefore, they may be a useful approach to regulating gear size selectivity, as all blue whiting entering the trawl, except for those few escaping through the SMP, were size selected by the codend meshes (Fig. 8d). However, Figure 8d also shows that for small codend mesh sizes (50 and 60 mm), the 70 mm SMP had the potential to release individuals that would be retained by codend meshes.

FIGURE 8

Fig. 8. (a) Predicted a_{SMP} for the mesh size range of 50 to 150 mm with 10 mm increments. (b) Predicted codend retention probability for the same mesh size range. (c) Predicted combined retention probability of the gear by maintaining codend mesh size mandated by regulation (70 mm) and changing SMP mesh size for the same mesh size range. (d) Predicted combined retention probability of the gear by maintaining SMP mesh size mandated by regulation (100 mm) and changing codend mesh size for the same mesh size range. Thick black lines correspond to the current SMP and codend mesh sizes used by the fleet (100 and 70 mm, respectively). Vertical dashed lines correspond to the minimum marketable size of blue whiting: 18 cm.

Additionally, design guides for different combinations of SMP and codend mesh sizes were created (Fig. 9). Design guides for L05, L25, L50, L75, and L95 showed the length at which blue whiting had 5%, 25%, 50%, 75%, and 95% probability of being retained, respectively. Specifically, the isocurves in each design guide followed different patterns; some were vertical lines with little curvature (Fig. 9a,b,c), whereas those for L75 (Fig. 9d) and L95 (Fig. 9e) showed much more curvature. At low retention probabilities (≤ 50%, Fig. 9a,b,c), gear size selection was mainly governed by codend meshes, whereas the SMP contributed to the gear size selection to a greater extent at higher retention probabilities (≥ 75%) (Fig. 9d,e). The low curvature of the L05, L25, and L50 isocurves was directly related to the low contact probability of blue whiting with the SMP (C_{SMP} = 0.27). Considering this contact factor, changing SMP mesh size will have very little effect on the overall retention probability until L73 is reached, because when retention

probabilities were lower than that the fish did not contact the panel. Therefore, at L75, the contribution of SMP to the gear size selection and the curvature of the isocurves becomes greater due to dependency not only on codend mesh size but also on SMP mesh size. These curves become even more curled at L95 (Fig 9e). At this point, small changes in SMP mesh size create bigger changes in the retention length of fish compared to modifications of codend mesh size.

FIGURE 9

Fig. 9. Design guides showing L05, L25, L50, L75, and L95 isocurves as a function of different combinations of SMP and codend mesh sizes (mm) for blue whiting.

Predictions of a_{SMP} and combined retention probability for different values of C_{SMP} were also made (Fig. 10). As contact probability increased, the SMP retention probability for small fish decreased (Fig. 10a). Likewise, increasing contact probability led to an important improvement of the overall size selection of the gear, which highlights the potential of the SMP as a size selection device (Fig. 10b).

FIGURE 10

Fig. 10. (a) Predicted a_{SMP} retention probability assuming different values of C_{SMP} (0.27, 0.40, 0.65, 0.80, and 1.00). (b) Predicted combined retention curve assuming different values of C_{SMP} (same as (a)). Thick black lines correspond to the current SMP and codend mesh sizes used by the fleet (100 and 70 mm, respectively). Vertical dashed lines correspond to the minimum marketable size of blue whiting: 18 cm.

Discussion

Different studies have reported that for SMPs, the experimental L50s are much smaller and SRs much larger than theoretically expected (e.g. Alzorriz *et al.,* 2016). The results of the present study offer an explanation for the differences observed between the theoretical and practical selective performance of SMPs and show that they are related to the ability of fish to contact SMPs at a more or less optimal CA. Furthermore, the results of this study demonstrate that it is possible to predict size selection processes in gears composed of SMPs and diamond mesh codends based on fish morphology and behaviour.

Previous research identified fish CA and orientation towards the mesh as factors that influence size selection in codends and sorting grids. For example, Herrmann *et al.* (2013*b*) demonstrated how different flatfish orientations towards a sorting grid could create considerable differences in the selective properties

of the gear. Krag *et al.* (2014) showed that krill selectivity could be explained assuming optimal orientation and CA. Regarding SMPs, the results of the present study show that different CAs lead to different size selection for blue whiting. Based on fish and mesh morphology, we identified which CAs led to successful reproduction of the experimental selection curves presented in Cuende *et al.* (201920*a*). The CAs implicated in reproducing the experimental SMP contact size selection were between 15 and 50º and 80 and 90º, whereas CAs between 55 and 75º barely contributed to the contact size selection. Video observations made by Cuende *et al.* (2020*a*) reported that blue whiting exhibit active and erratic behavior towards SMPs, whereby they turn and swim quickly either towards the panel or the codend. Based on this behavior, we speculated that most individuals contact the SMP from less optimal angles (< 50º). This may mean that the low size selection efficiency of SMPs reported in different fisheries may not be due only to low contact rates between fish and SMP meshes (Herrmann *et al.,* 2015; Nikolic *et al.,* 2015; Alzorriz *et al.,* 2016; Santos *et al.,* 2016; Brčić *et al.,* 2018) but also to non-optimal fish CA towards the device. These differences in fish CAs could be caused by many factors, such as towing speed (which allow more or less time for fish to attempt an escape), the swimming ability of fish, or densities of fish entering the SMP section. Many of these factors are not easy to control at sea and can affect the ability of the fish to contact the SMP or to orientate well enough to have a good chance to escape through it.

Regarding codend size selection, our results for blue whiting are in line with those of previous studies in which diamond mesh codend size selection can be explained by means of mesh OAs (Sistiaga *et al.,* 2011; Herrmann *et al.,* 2012, 2013*b*; Tokaç *et al.,* 2016, 2018). Mesh openness is driven by factors such as mesh size (Herrmann *et al.,* 2013*a*), number of meshes in the circumference (Sala and Lucchetti, 2011), and the size of the catch accumulated in the codend (Wileman *et al.,* 1996). Herein, the experimentally obtained codend size selection was entirely reproduced by the mesh OAs between 15 and 50º. This result emphasizes the importance of understanding the mechanisms affecting codend mesh OAs under commercial fishing conditions in order to optimize codend design and make proper size selectivity predictions.

Our results show that codend mesh OAs together with fish-SMP CAs can explain the overall size selection of a gear composed of a SMP and a diamond-mesh codend. Therefore, we were able to predict gear size selection for different combinations of SMP and codend mesh sizes for blue whiting. Even though codend meshes determine the overall size selection of the gear to a great extent due to the limited escape of blue whiting through the SMP (Cuende *et al.,* 201920*a*), the design guides showed that when accounting for the fish that actually contact the SMP, small variations of its mesh size result in big changes for SMP size

selection. This indicates that when SMP contact probability increases, the probability of fish contacting the SMP from an optimal angle increases as well. Thus, modifying SMP mesh size can lead to greater changes in the overall gear selectivity than modifying codend mesh size, which highlights the potential of SMPs as size selection devices. Therefore, in addition to changes in SMP mesh size, we also considered changes in SMP contact probability when making SMP size selection predictions for blue whiting. Our results showed that increasing SMP contact probability without modifying its mesh size may result in great changes in gear selectivity. Additionally, these results suggest that increasing SMP contact probability and favor an optimal CA of fish towards the SMP meshes may be good strategies for improving size selection, especially in multispecies fisheries for which increasing codend mesh size may involve less retention of valuable species. In this context, research in fisheries around the world has focused on designing stimulating devices to increase contact probability between fish and SMPs with different degrees of success (Glass and Wardle, 1995; Kim and Whang, 2010; Herrmann *et al.,* 2015; Grimaldo *et al.,* 2018). Regarding blue whiting, Cuende *et al.* (2020*a*) showed that floating ropes attached to the lower panel beneath the SMP significantly increased contact probability with the SMP and consequently the release efficiency for this species.

Finally, in agreement with results of previous studies reporting on the experimental suitability of SMPs for blue whiting release (Briggs and Robertson, 1993; Campos and Fonseca, 2004), we found that blue whiting is a species with high potential for being released by SMPs in trawl gears. Its active behaviour, which results in more escape attempts, can lead to high contact rates with the SMP (Cuende *et al.,* 2020*a*), thereby increasing the chances of contact with an optimal CA. As blue whiting is a relevant species for fisheries worldwide, both as a target and bycatch species, SMPs may be a useful selection device for the management of this species in fisheries of interest, especially since the creation of the new Common Fisheries Policy (Regulation EU 1380/2013).

Supplementary material

The following supplementary material is available at ICESJMS online. It includes a short description of the standard FISHSELECT methodology applied for collection of morphology and mesh penetrability data of blue whiting.

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Figures

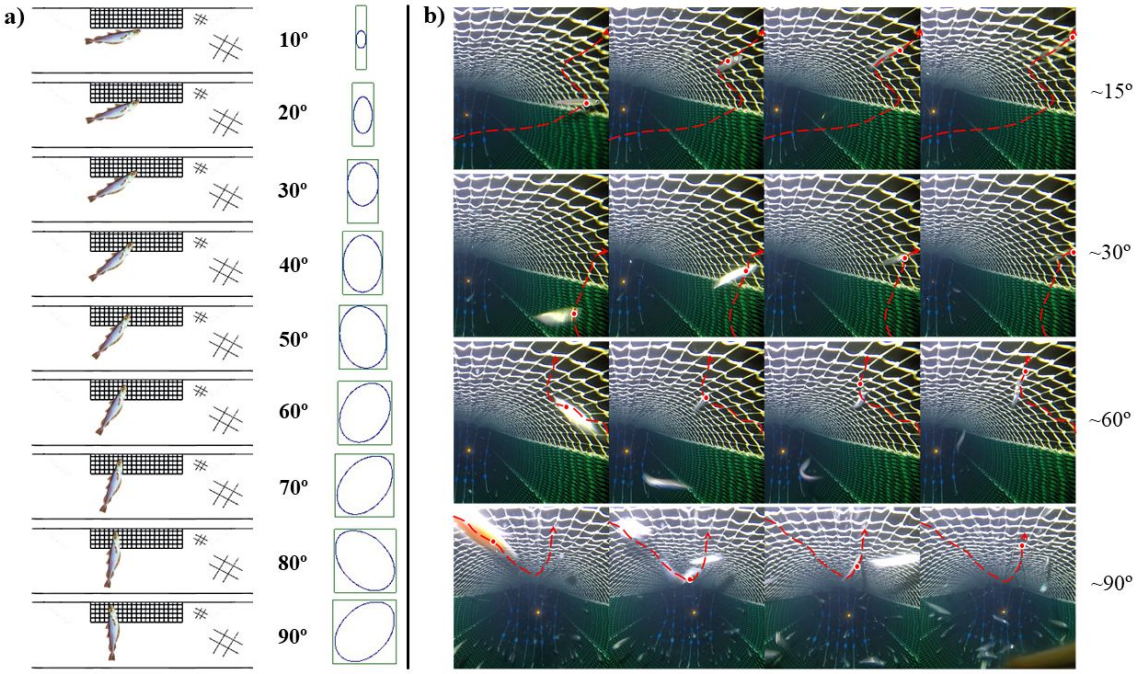

Fig. 1. (a) Different contact angles (CAs) (ranging from 10 to 90º) for blue whiting attempting to escape through SMP meshes. The column to the right of each of the angles shows the shape of the projected mesh for the different CAs (green rectangle) and the cross-section of the largest blue whiting that would pass through it (blue circle). (b) Underwater recordings from experimental trials (Cuende *et al.,* 2020*a*) showing fish trajectory (red arrow) for each escape attempt with different CAs through a SMP.

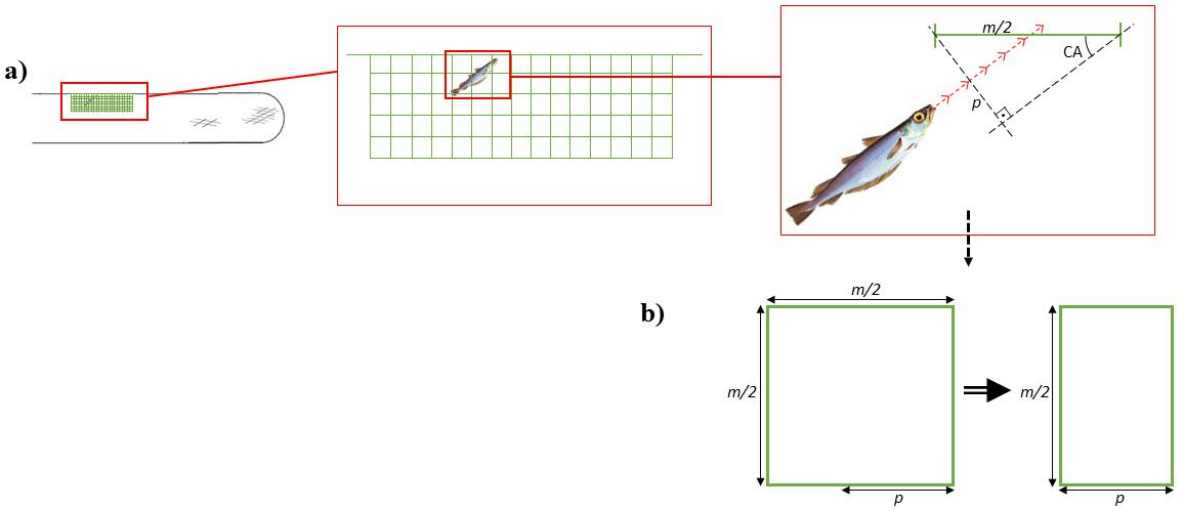

Fig. 2. (a) Blue whiting contacting the SMP with a specific contact angle (CA). The rightmost part of the diagram shows how to calculate the mesh size projection according to the CA. $\frac{m}{2}$ is the bar length of the square meshes (half mesh size), and p is the projected length of the longitudinal bars of the mesh with respect to the orientation of the fish. (b) Transformation from an original SMP mesh to the projected mesh based on the specific CA of a fish.

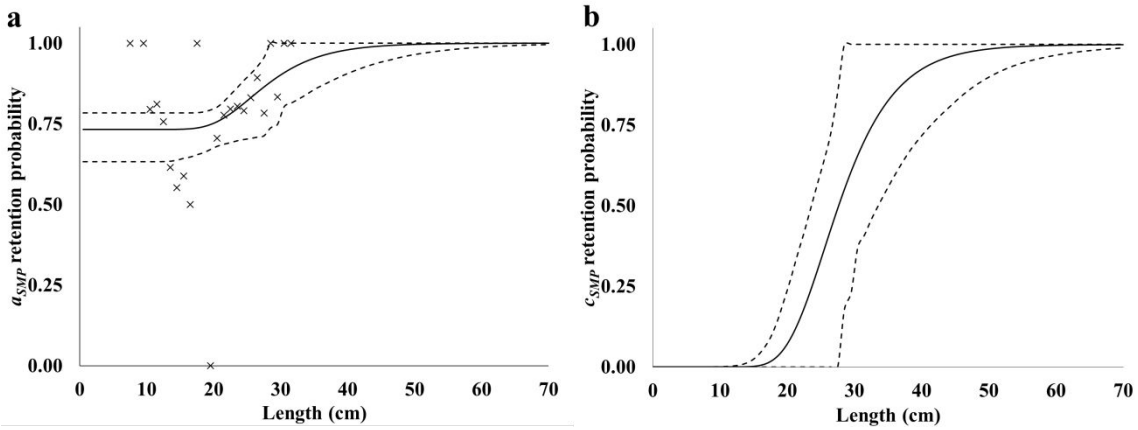

Fig. 3. (a) Experimental available SMP retention probability curve (ra_{SMP}) (black line) with corresponding confidence intervals (dashed lines) and experimental rate (crosses). (b) Contact SMP retention probability (rc_{SMP}) (black line) with corresponding confidence intervals (dashed lines).

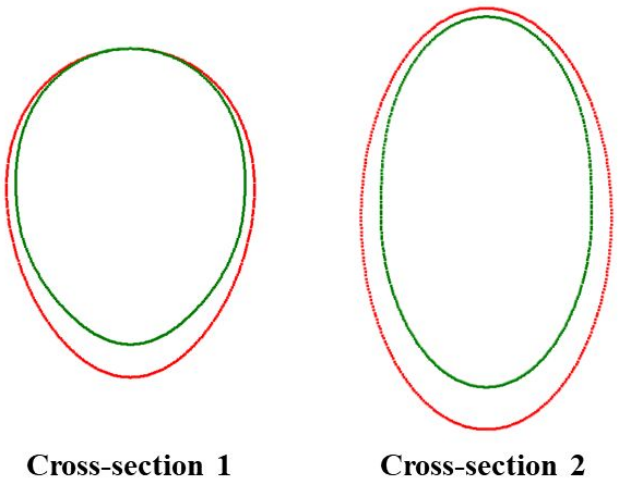

Fig. 4. Compression models for cross-section 1 (left) and cross-section 2 (right). Green inner curves correspond to the best compression model and red outer curves correspond to no compression for each cross-section of blue whiting.

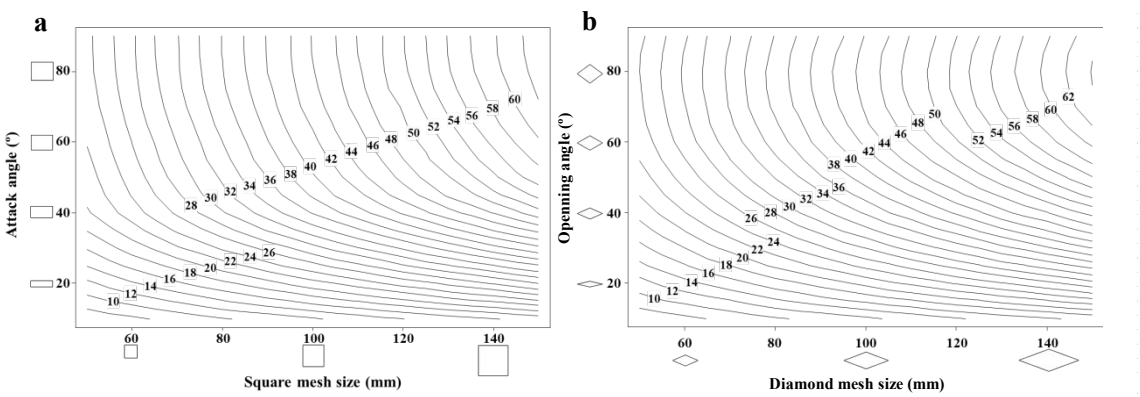

Fig. 5. Design guide for (a) square and (b) diamond meshes showing L50 isocurves as a function of mesh size (mm), for sizes between 50 mm and 150 mm, and mesh CA and OA between 10º and 90º, respectively.

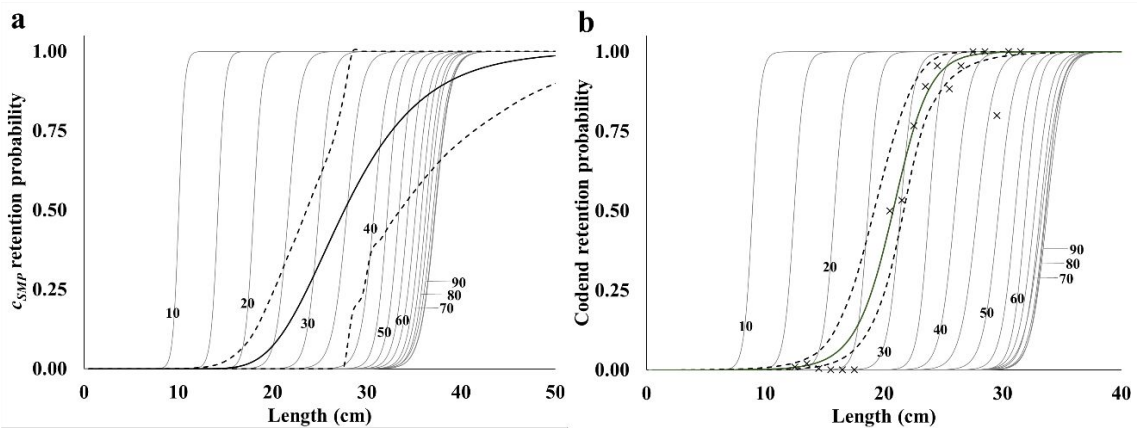

Fig. 6. Grey curves show (a) the simulated SMP selectivity for different CAs and (b) codend selectivity for different OAs from 10º to 90º in steps of 10º. Black curves depict (a) experimental rc_{SMP} and (b) experimental codend size selection curve with corresponding CIs (dashed lines).

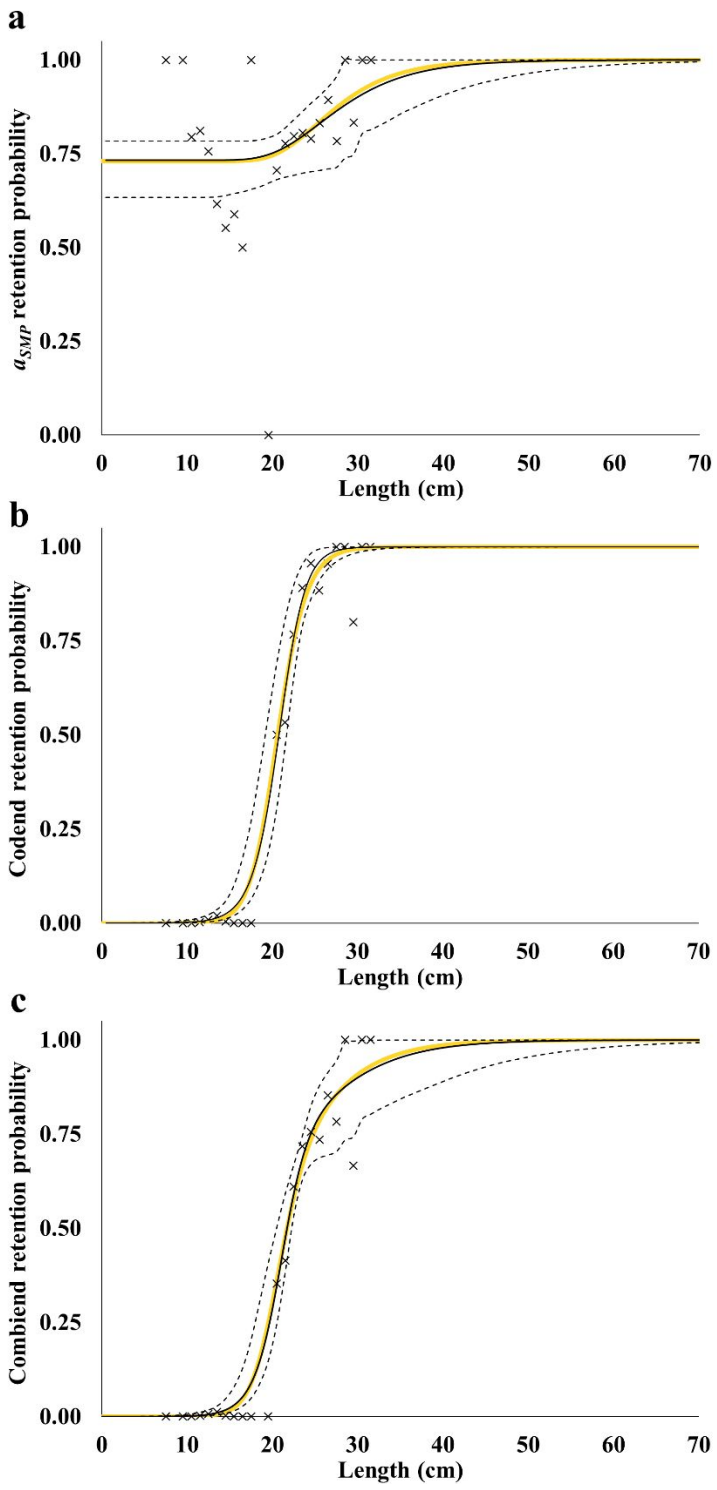

Fig. 7. Experimental (black line) and simulated (yellow line) size selection curves are shown for (a) SMP, (b) codend, and (c) combined SMP and codend. Experimental 95% CIs are shown (dashed lines).

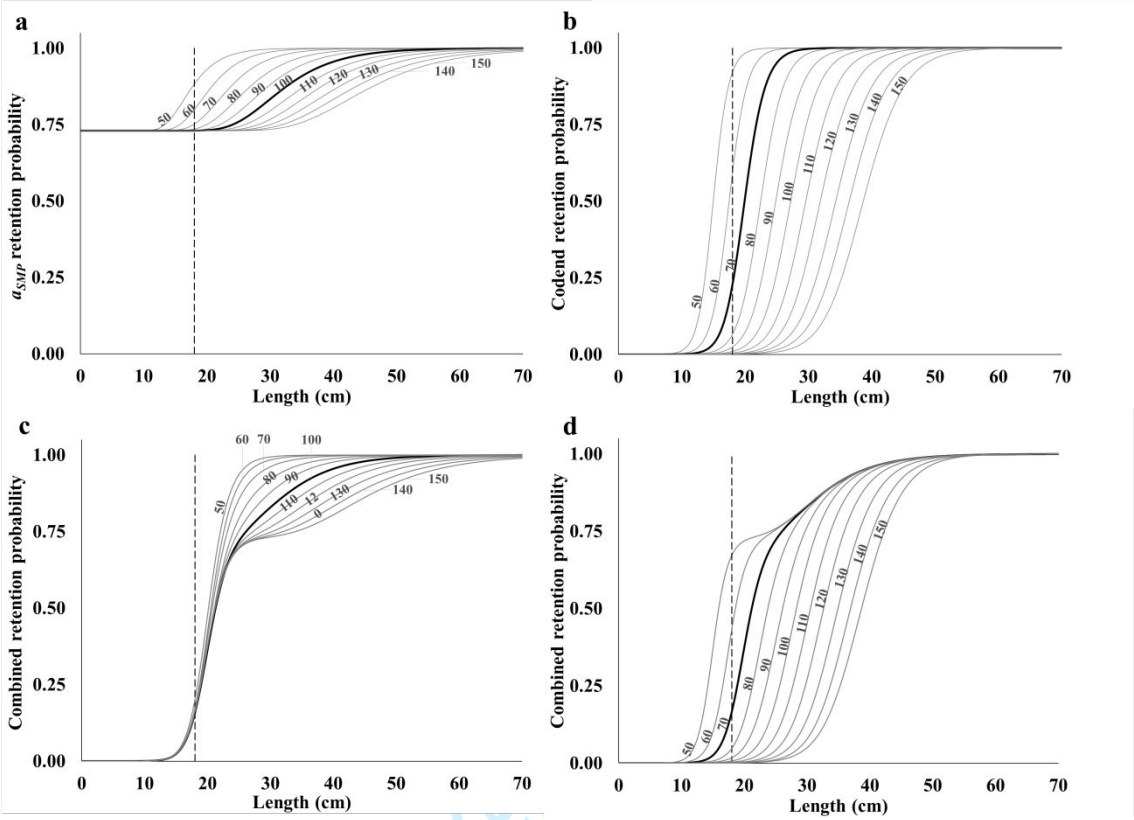

Fig. 8. (a) Predicted a_{SMP} for the mesh size range of 50 to 150 mm with 10 mm increments. (b) Predicted codend retention probability for the same mesh size range. (c) Predicted combined retention probability of the gear by maintaining codend mesh size mandated by regulation (70 mm) and changing SMP mesh size for the same mesh size range. (d) Predicted combined retention probability of the gear by maintaining SMP mesh size mandated by regulation (100 mm) and changing codend mesh size for the same mesh size range. Vertical dashed lines correspond to the minimum marketable size of blue whiting: 18 cm.

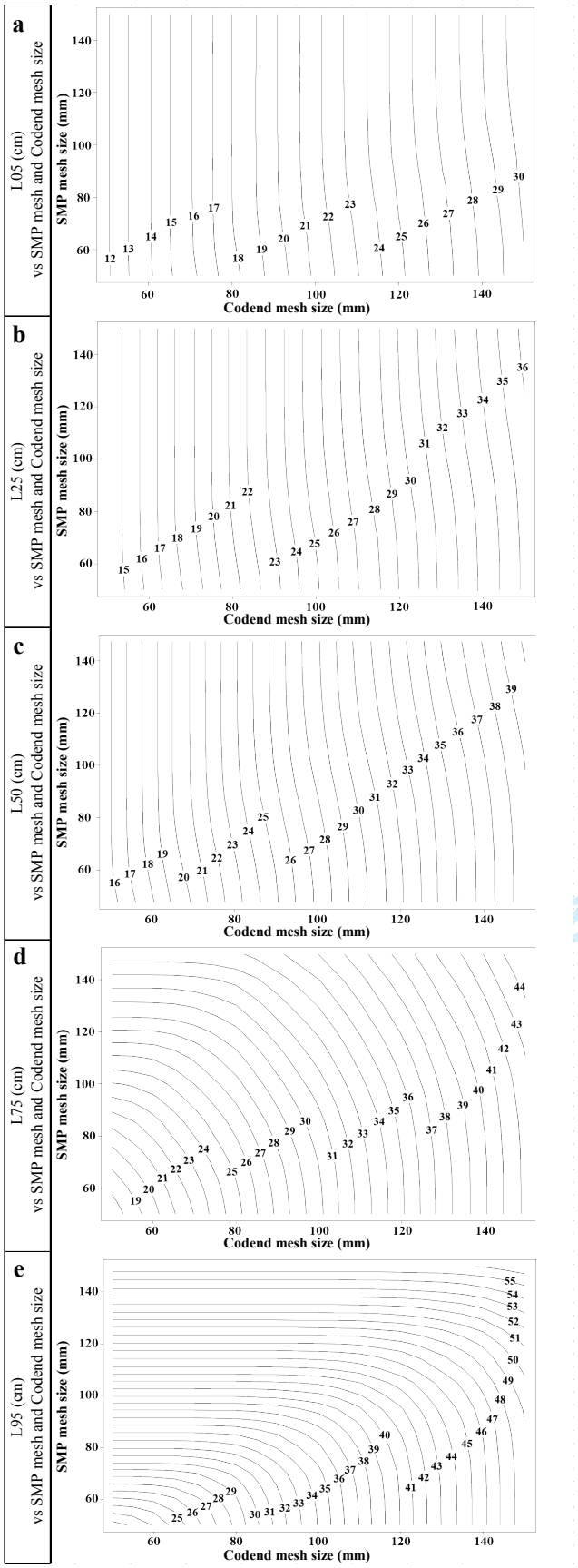

Fig. 9. Design guides showing L05, L25, L50, L75, and L95 isocurves as a function of different combinations of SMP and codend mesh sizes (mm) for blue whiting.

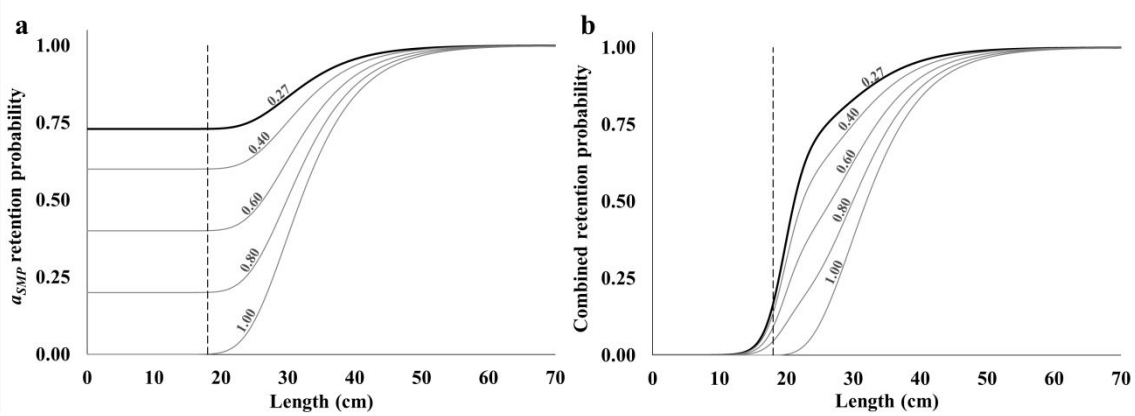

Fig. 10. (a) Predicted a_{SMP} retention probability assuming different values of C_{SMP} (0.27, 0.40, 0.65, 0.80, and 1.00). (b) Predicted combined retention curve assuming different values of C_{SMP} (same as (a)). Thick black lines correspond to the current SMP and codend mesh sizes used by the fleet (100 and 70 mm, respectively). Vertical dashed lines correspond to the minimum marketable size of blue whiting: 18 cm.

Tables

Table 1. AIC values for the different models tested for each cross-section; the model that resulted in the lowest AIC value (best model) is in bold.

		Ellipse	Flexdrope	Flexellipse 1	Ship	Superdrope
Cross-section 1	AIC	173.07	**143.13**	144.53	157.05	235.04
	R^2	0.94	**0.96**	0.96	0.95	0.91
Cross-section 2	AIC	200.90	168.32	**165.44**	183.66	226.89
	R^2	0.93	0.95	**0.95**	0.95	0.93

Table 2. Contribution (%) of the considered SMP CAs and codend mesh OAs as potentially involved in reproducing experimental rc_{SMP} and codend size selection curves. *: could not contribute due to no overlap with experimental selectivity curve.

CA and OA (°)	Contribution (%)	
	SMP	Diamond codend meshes
5	*	*
10	*	*
15	0.419	1.422
20	5.040	7.222
25	18.097	27.599
30	18.508	45.361
35	18.053	14.519
40	14.217	0.400
45	3.968	0.374
50	0.851	3.104
55	0.001	*
60	0.000	*
65	0.000	*
70	0.001	*
75	0.001	*
80	1.821	*
85	9.704	*
90	9.320	*