UiT The Arctic University of Norway

Faculty of Bioscience, Fisheries and Economy

Norwegian College of Fishery Science

Gear modifications for bycatch reduction in the Bay of Biscay demersal trawl fishery

Elsa Cuende de Francisco

A dissertation for the degree of Doctor Philosophiae December 2022

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Acknowledgements

First of all, I want to thank Professor Bent Herrmann and Professor Manu Sistiaga for their support from the very first moment I started my research career in the field of fishing gear technology. I thank you for the conversations, discussions, agreements and especially disagreements that have made me better scientist, with better criteria and higher self-confidence. I owe you that I have challenged my own limits and have found that they are further than I expected. I have really enjoyed working with you, and I hope we can keep our collaboration and friendship in the coming years.

I am also very grateful to Professor Roger B. Larsen for providing the opportunity to submit my Doctor Philosophiae thesis to UiT, welcoming me onboard RV Helmer Hansen, and making me feel the North Pole is home, ESKERRIK ASKO!

Thanks to AZTI for supporting me in the development of this thesis and providing the necessary resources. To Peli (Luis Arregi), thank you so much for the opportunity given, all knowledge shared and helping me finding a place in this field. You have always been ready to answer questions and share your invaluable knowledge. I am thankful to Mikel Basterretxea, for being always ready to answer my infinite questions, you are an awesome colleague, and to Esteban Puente and Gorka Gabiña for your support during all this time. Thanks to Arkaitz Pedrajas for all the time shared at sea, it has always been more enjoyable with you. To Iñigo Onandia, for the very good moments in that first trip where the spark that triggered this thesis was conceived. I also want to make an especial mention to Marina Santurtún, Arnaitz Mugerza, Jose Mari Ferarios, Xabi Aboitiz, Raúl Prellezo, Estanis Mugerza and Lucia Zarauz, for answering my questions any time I show up at your offices.

Thanks to all colleagues I have met during the cruises for sharing the desperation of measuring hundreds of fish! I hope this is the beginning of a friendship and future collaboration. To the Emma Bardan crew, for your help and good disposition always. Thanks to all the co-authors of the studies presented in this thesis; it has been a pleasure to work with you.

I want to thank all the people that during these years has supported me and especially, have made of this journey the funniest: the interns! It has been a pleasure to have you in the day-by-day life. You are the reason for being happy when I go to work, and of course for partying, climbing, skiing, diving, … An especial mention to Maite Erauskin, for transmitting me your extraordinary good will and energy to materialize ideas and make them real.

To my good friends Nerea, Nagore and Dani, for your unconditional support and believing on the good my work can do in this crazy world. To Claudia and Maria because we share the privilege of living the Nature in an especial way, which makes us to deeply understand each other. To Giorgos, thanks for always helping me getting perspective and to Tximi, for always taking care of me onboard.

To Gorka, thanks for showing me so many things, supporting me during so many years and also for teaching me that being in the right place at the right time is not always a matter of good luck.

Finally, I thank to the most important people in my life, my family. Ama, aita, Darío and Daniel, you accompany me, encourage me, you lift me and if necessary, we fall down together. You are the central pillar in my life, and I am most privileged for having you. Thanks for letting me see myself through your eyes, for believing in me, advising, loving, and supporting me every day. Ama, you are my best inspiration; strong and independent, you are home, you are the joy of living, the spirit of achievement, I will never have enough beautiful and gratitude words for you. I love you all.

Diego no conocía la mar. El padre, Santiago Kovadloff, lo llevó a descubrirla.

Viajaron al sur.

Ella, la mar, estaba más allá de los altos médanos, esperando. Cuando el niño y su padre alcanzaron por fin aquellas cumbres de arena, después de mucho caminar, la mar estalló ante sus ojos. Y fue tanta la inmensidad de la mar, y tanto su fulgor, que el niño quedó mudo de hermosura.

Y cuando por fin consiguió hablar, temblando, tartamudeando, pidió a su padre:

–¡Ayúdame a mirar!

Eduardo Galeano – El libro de los abrazos

Summary

Bottom trawl fisheries have great social and economic importance for coastal communities in the Basque Country. However, the activity of the demersal trawl fishery in the Bay of Biscay, which includes the coastline of the Basque country, can be compromised due to its multispecies nature, high proportion of unwanted species in the catch, and the increasingly strict legislation implemented aiming to ensure sustainable fisheries. In this scenario, developing gear modifications to reduce unwanted bycatch is increasingly important. This thesis presents results from six selectivity research papers that address unwanted catch issues in the Bay of Biscay bottom trawl fishery.

Hake (*Merluccius merluccius*), horse mackerel (*Trachurus trachurus*), blue whiting (*Micromesistius poutassou*), and mackerel (*Scomber scombrus*) are some of the most relevant species for the bottom trawl fishery in the Bay of Biscay and constitute the main choke species in the fishery. Papers I and II present selectivity results for different square mesh panel (SMP) designs aimed to improve fish-SMP contact probability and release efficiency for these species. Among the designs tested, the results demonstrate that modifying SMP size and position can increase fish contact probability with the SMP. Paper III investigates the size selection process through SMP and codend meshes for blue whiting based on fish morphology and behavior. The results demonstrate that SMP size selection can be explained by different fish contact angles with SMP meshes, which allows making accurate predictions for fish size selectivity. Paper IV explores the effect of alternative SMP and codend mesh combinations on the size selectivity of hake and blue whiting and on the fishery exploitation pattern for a variety of fish population scenarios. The results demonstrate that changes both in SMP and, especially, codend designs can have a significant effect on the size selectivity and exploitation patterns of hake and blue whiting. This paper also outlines new ways for investigating and illustrating the effect of multiple gear changes on the size selectivity and exploitation pattern indicators by means of diagrams named treatment trees. These may aid in the identification of promising gear designs and help the industry in the pursuit of specific catch goals. In Paper V a trawl configuration for species separation is tested. This new configuration intends to guide those species that hold themselves close to the lower panel of the trawl through a horizontal grid into a lower codend, while the rest of the species are directed to an upper codend. The findings in Paper V demonstrate that, under the conditions in which this fishery operates, the trawl configuration tested is not able to efficiently separate species based on their behavior. Finally, in Paper VI the effect of shortening codend lastridge ropes on codend size selectivity compared to a standard codend is tested, and fish escape chances estimated based on fish morphology. The results show that a codend with shortened lastridge ropes can improve the size selectivity of horse mackerel and blue whiting, while the selectivity of hake was not affected. The results indicate species-dependent variability in the ability to utilize open meshes located at different places.

In general, the work presented in this thesis provides technological advances and knowledge that contributes with guidance on how to reduce unwanted bycatch and generate alternative exploitation patterns in the Bay of Biscay demersal trawl fishery.

Paper I is published in Fisheries Research; Paper II in Scientia Marina; Paper III in the ICES Journal of Marine Science; Paper IV in PLOS One; Paper V in Ocean and Coastal Management; and Paper VI is accepted for publication in Mediterranean Marine Science.

List of papers

Paper I: Cuende, E., Arregi, L., Herrmann, B., Sistiaga, M., & Onandia, I. (2020). Stimulating release of undersized fish through a square mesh panel in the Basque otter trawl fishery. Fisheries Research, 224, 105431. https://doi.org/10.1016/j.fishres.2019.105431

Paper II: Cuende, E., Arregi, L., Herrmann, B., Sistiaga, M., & Basterretxea, M. (2020). Release efficiency and selectivity of four different square mesh panel configurations in the Basque mixed bottom trawl fishery. Scientia Marina, 84(1), 39–47. https://doi.org/10.3989/scimar.04975.17A

Paper III: Cuende, E., Arregi, L., Herrmann, B., Sistiaga, M., & Aboitiz, X. (2020). Prediction of square mesh panel and codend size selectivity of blue whiting based on fish morphology. ICES Journal of Marine Science, 77(7–8), 2857–2869. https://doi.org/10.1093/icesjms/fsaa156

Paper IV: Cuende, E., Sistiaga, M., Herrmann, B., & Arregi, L. (2022). Optimizing size selectivity and catch patterns for hake (*Merluccius merluccius*) and blue whiting (*Micromesistius poutassou*) by combining square mesh panel and codend designs. PLOS ONE, 17(1), e0262602-. https://doi.org/10.1371/journal.pone.0262602

Paper V: Cuende, E., Herrmann, B., Sistiaga, M., Basterretxea, M., Edridge, A., Mackenzie, E. K., Kynoch, R. J., & Diez, G. (2022). Species separation efficiency and effect of artificial lights with a horizonal grid in the Basque bottom trawl fishery. Ocean & Coastal Management, 221, 106105. https://doi.org/10.1016/J.OCECOAMAN.2022.106105

Paper VI: Cuende, E., Sistiaga, M., Herrmann, B., Basterretxea, M., & Arregi, L. (2022). Escape of hake (*Merluccius merluccius*), horse mackerel (*Trachurus trachurus*) and blue whiting (*Micromesistius poutassou*) in codends with shortened lastridge ropes. Accepted for publication in Mediterranean Marine Science.

Thesis structure

The thesis is structured in eight chapters as follows:

Chapter one introduces the specific fishery studied and identifies challenges to be addressed in the thesis.

Chapter two defines the overall objective and sub-objectives of the thesis based on the challenges of the fishery described in the previous chapter.

Chapters three, four and five review the technologies and methodologies currently available that could be adapted and used to address the challenges in the Bay of Biscay demersal trawl fishery.

Chapter six formulates the specific research questions to be addressed by the research conducted in the thesis, based on the thesis objective (Chapter two) and reviews of the currently available technologies and methods (Chapters three, four and five).

Chapters seven presents the scientific papers in the thesis and explains how and to what extent the research conducted in each of them addresses the specific research questions (Chapter six) of the thesis.

Chapter eight discusses the extent the research conducted has fulfilled the overall objective of the thesis.

Chapter 1. The trawl fishery in the Bay of Biscay and related challenges

This section introduces the demersal trawl fishery in the Bay of Biscay and describes challenges that compromise its current and future sustainability.

1.1. Demersal trawl fishery in the Bay of Biscay

A trawl is a cone-shaped body of netting, usually with one codend, that can be towed either through the water column or on the seabed. It is towed by one or two boats and catches fish by herding and subsequent sieving. Bottom trawls, designed to be towed close to, or in contact with the seabed, are a common fishing gear used around the world (Watson et al., 2006). Trawl fishing areas can comprise from very shallow waters (3 m depth) to deep-sea waters (> 1000 m depth), although it is mostly carried out on continental shelves (< 200 m) (Oberle et al., 2016). The continental shelf in the Bay of Biscay (Atlantic Ocean) (Fig. 1) is suitable for bottom trawling. Thus, bottom trawls are the most common gear used in the Bay of Biscay and Iberian Waters ecoregion, which covers the southwestern shelf seas and adjacent deeper eastern Atlantic Ocean waters of the European Union (ICES, 2021a).

The Bay of Biscay is a gulf orientated towards the NW and located in the NE Atlantic Ocean, south of the Celtic Sea. It covers the International Council for the Exploration of the Sea (ICES) subarea 8, which includes mainly French, Spanish, and to a lesser extent, UK's Exclusive Economic Zones (EEZ) (Fig. 1). The abyssal basin of the Bay represents around 50% of the total surface. Bottom trawlers operate on the continental shelf, between 30 and 200 m depth. The continental shelf in the south of the Bay, mostly corresponding to ICES division 8c, is between 6 and 16 nautical miles, and the Spanish regulation does not allow trawl gears fishing shallower than 100 m depth (BOE, 2022a). Therefore, most of the bottom trawlers in this area operate along the French coast, which happens to be much wider, especially in the north, where it can be more than 80 nautical miles wide (Borja et al., 2019) (Fig. 1). This fishing area corresponds to the ICES divisions 8abd (FAO, 2022).

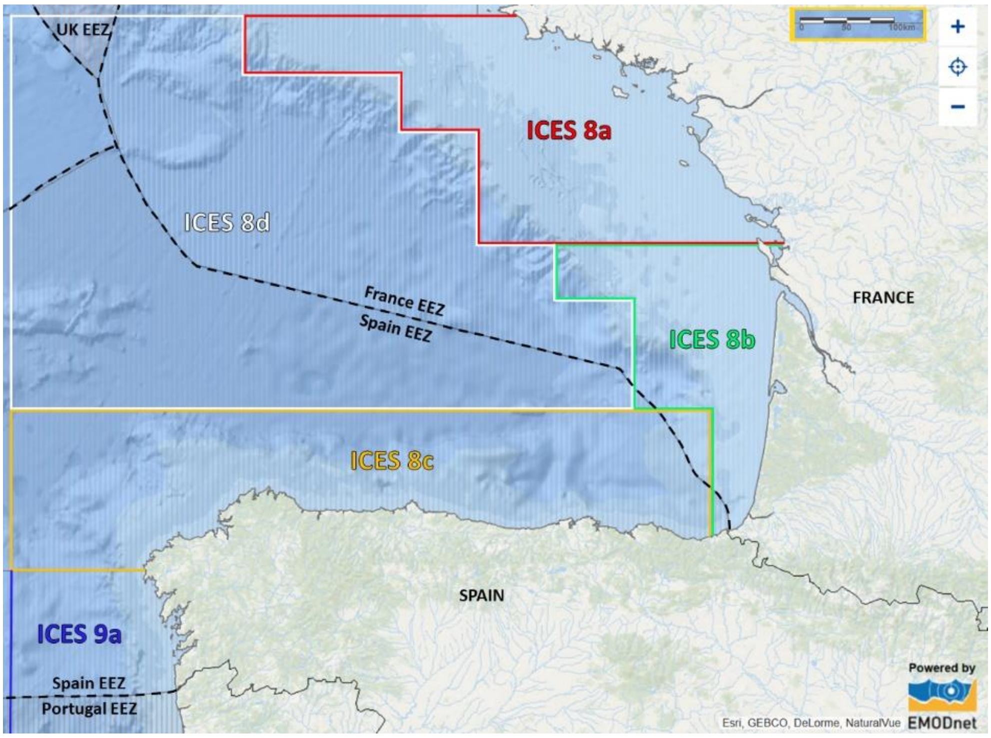


Fig. 1. The Bay of Biscay (ICES area 8abd) and Iberian Waters ecoregion (ICES area 8c and 9a).

The fishing activity in the ICES 8abd area is carried out by vessels from several countries. Most of them are bottom trawlers from Spain and France that include single, pair and twin trawlers (Fig. 2abc). Bottom trawlers like Belgian beam trawlers (Fig. 2d) or Irish single trawlers are also present, although their fishing activity in the area is minor (ICES, 2021b; STECF, Fisheries Dependent Information (FDI) database 2021).

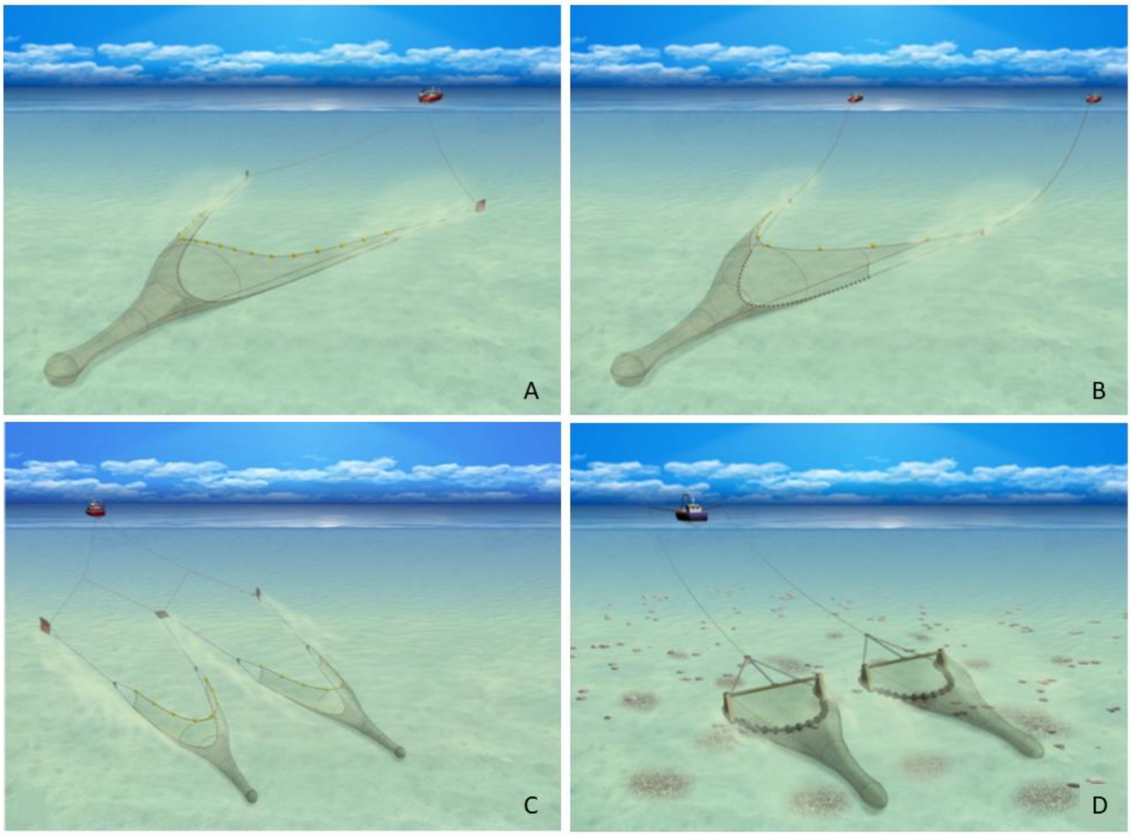


Fig. 2.- (A) Single bottom otter trawl; (B) Pair bottom trawl; (C) Twin trawl; (D) Beam trawl. Source: He et al., (2021).

The 26% of the Spanish fishing vessels operating in the ICES area 8abd consists of bottom trawlers (ICES, 2021b), both pair and single trawlers. All vessels are around 40 m in length and 60% of the fleet belongs to the Basque country, a small region in the north part of the Iberian Peninsula. The Basque fleet has a very homogeneous activity throughout the year, and while single trawlers target European hake (*Merluccius merluccius*), megrim (*Lepidorhombus* spp.) and anglerfish (*Lophius* spp.), pair trawlers target mainly hake. The rest of the Spanish bottom trawlers devote a minor part of their activity to operate in the Bay of Biscay (ICES 8abd).

The French bottom trawl activity is mainly conducted within the 12 nautical mile limit in French territorial waters. Thus, the 71% of all French vessels operating in the ICES area 8abd (ICES, 2021b) is composed of small vessels (< 18 m) (ICES, 2021b) that switch between different fishing gears during the year and target a wide variety of species depending on the fishing gear, time of the year and fishing area. The offshore fisheries consist of bottom trawlers, purse seiners, gillnetters, and a few longliners. However, the fishing effort of bottom trawlers offshore is minor compared to the Spanish fleet. In the period 2014 – 2020 the Spanish average fishing effort in the Bay of Biscay was of 71416 Kw/day, carried out by fishing vessels of 24 – 40 m, whereas the French was 9025 Kw/day (STECF, FDI database 2021) (Fig. 3). Therefore, considering this and given that the Spanish trawl fleet in this area is mainly composed by Basque trawlers, it could be assumed that the Basque fleet is representative of the offshore bottom trawl activity carried out in the Bay of Biscay (ICES 8abd).

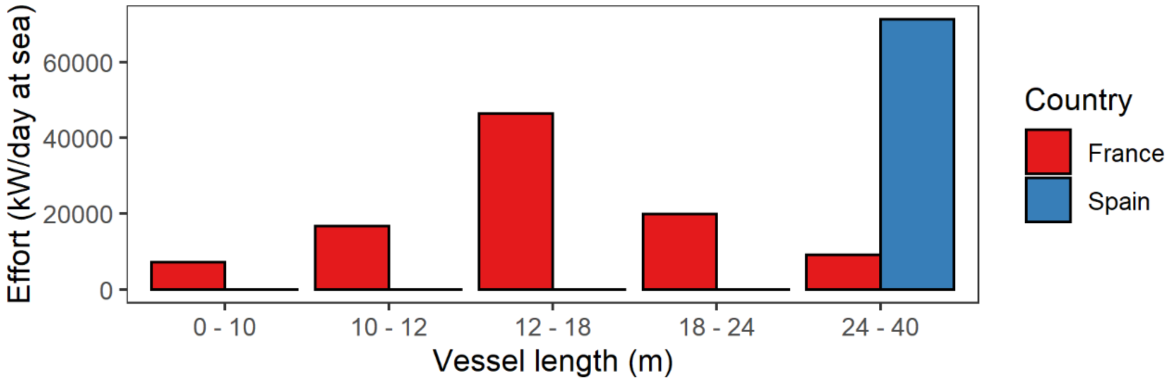


Fig. 3. Fishing effort of French and Spanish bottom trawlers in the Bay of Biscay (ICES area 8abd). Data source: STECF, Fisheries Dependent Information (FDI), 2021.

1.2. Socio-economic relevance of the Basque bottom trawl fishery in the Bay of Biscay

Bottom trawl fisheries have great social and economic importance for coastal communities in the Basque Country (Gobierno Vasco, 2008). The development of industrial fisheries based on trawling began in the early twentieth century (López Losa, 2008), and its productivity peaked in the late 1970s, when 53% of the Spanish trawling fleet fishing in EU community waters (ICES 6ab, 7bcghj, 8abd) was Basque. From 1977 on, the implementation of the principle of jurisdiction by the coastal state concerned over the management of marine resources within its EEZ and the so-called Total Allowable Catches (TACs) and quotas for conservation and management of the fisheries resources, caused a recession of the bottom trawl fleet. Today, this bottom trawl fleet corresponds to the 10% of the fishing vessels with operative port[1] in the Basque Country. However, one third of the economic value produced by the fishing sector comes from this fleet (Banco de Datos del Gobierno Vasco, 2019).

Hake constitutes one of the main target species for the bottom trawl fleet (Fig. 4). Specifically, 81% of the landings consists of hake (ICES, 2021b). Prellezo et al., (2017) showed that, in the years 2011-2013, the pair trawl fleet captured almost the 8% of the total northern hake stock and 25% of hake catches in the Bay of Biscay. For these reasons, hake catches in the Bay of Biscay carried out by this fleet are used to feed the assessment model used for the evaluation of the stock. The landings are used for international fisheries advice, provided by the ICES and the STECF (Scientific, Technical and Economic Committee for Fisheries) (e.g., STECF-21-12). In addition, hake is the most consumed fish species in Spain and in the Basque Country, being of 2.59 kg and 4.11 kg per capita per year, respectively (Panel de Consumo Alimentario, MAPA, data of year 2020).

[1] Operative port includes those bottom trawlers with base port in Spain (Basque Country) that land the fish in the Spanish state.

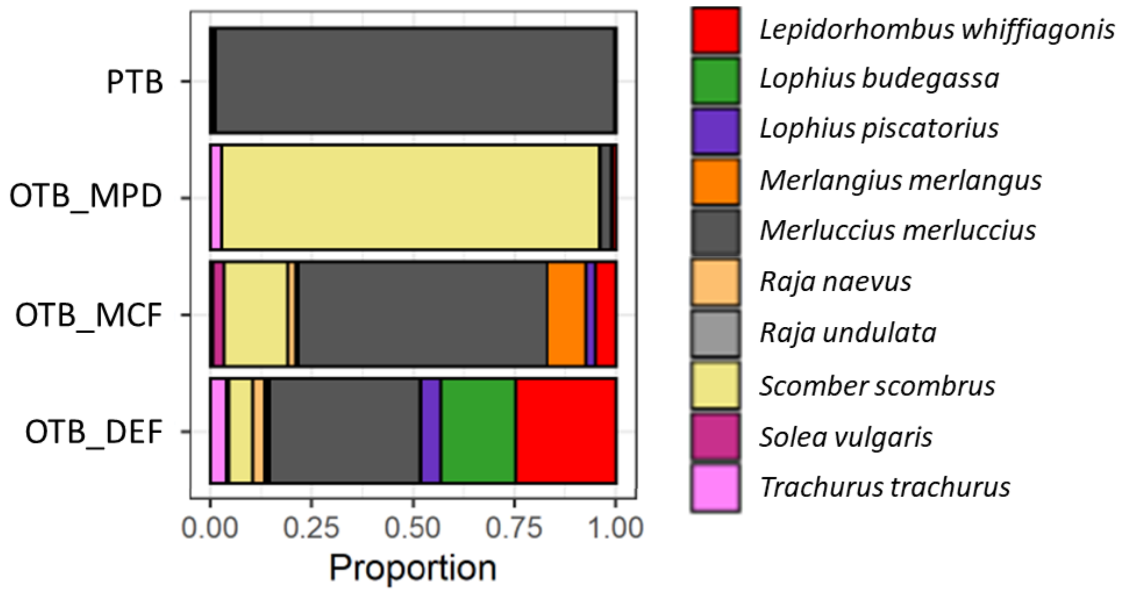


Fig. 4.- Main species landings as percentage within each Spanish bottom trawl métier (group of fishing vessels using similar gear, during the same period of the year and area and which are characterized by a similar exploitation pattern (Ulrich et al. 2012)) in ICES 8abd. PTB: Pair Bottom Trawl; OTB_MPD: Bottom Otter Trawl targeting Mixed Pelagic and Demersal fish; OTB_MCF: Bottom Otter Trawl targeting Mixed Cephalopods and Demersal Fish; OTB_DEF: Bottom Otter Trawl targeting DEmersal Fish. Source: ICES, (2021b).

Apart from hake, there are other relevant species that compose the catch of the bottom trawl fleet in the Bay of Biscay. The composition of the landings in the recent years shows that megrims, and anglerfishes together represent 12% of the landings, whereas mackerel (*Scomber scombrus*) accounts for 5% of the landings (ICES, 2021b). The rest of the catch is composed by a mix of demersal and pelagic species for the pair trawlers, whereas the catch for bottom trawlers is characterized by a mix of species with variable predominance in the catch depending on fishing period and area (ICES, 2021b; Iriondo et al., 2010; Prellezo et al., 2016) (Fig. 5). In general, the stocks mentioned comprise the 65% of the total catches and more than 73% of the total revenue of the bottom trawl fleet in the Bay of Biscay (Fig. 5).

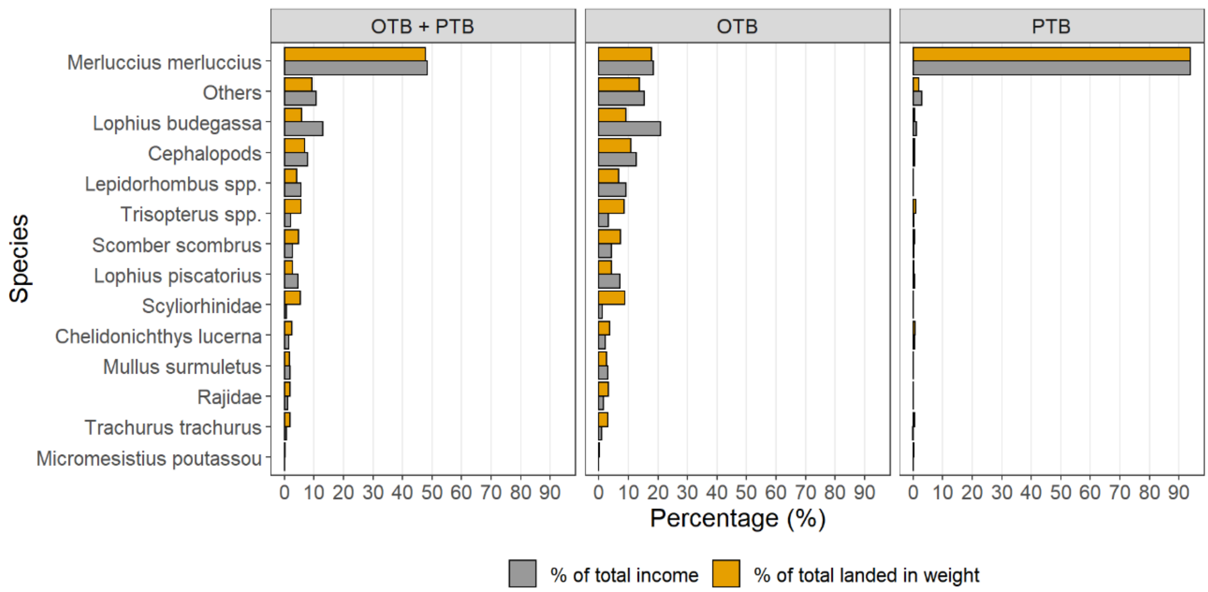


Fig. 5.- Species relative importance in terms of landings (orange) and revenue (grey) for the Basque fleet operating in the Bay of Biscay among years 2014 – 2021. OTB: single other bottom trawlers; PTB: pair bottom trawlers. Data source: AZTI (BRTA).

1.3. Management concerns in the bottom trawl fishery in the Bay of Biscay

The bottom trawl fishery in the Bay of Biscay is a multispecies fishery, sometimes also called mixed fishery (Fig. 4; Fig. 5). Multispecies trawl fisheries are in general characterized by complex combinations of harvested species that vary in productivity (i.e., abundance and state of the stock) and economic value (Fig. 5). Therefore, although theoretically all the commercial species caught can be target species, in practice, within multispecies fisheries, specific catch goals vary according to multiple economic, sociological, technical, and legal factors (Salomon et al., 2014). In the Bay of Biscay demersal trawl fishery, unwanted catch includes undersized and/or damaged target species, valuable species whose quota is not available or has been exhausted, and low value or non-commercial species (Kelleher, 2005). In many multispecies fisheries, the unwanted fraction can match or even exceed the wanted (Hall and Mainprize, 2005; Kelleher, 2005) and unless otherwise regulated, these unwanted catches are discarded at sea, often dead or injured (Broadhurst et al., 2006).

The introduction of the new Common Fisheries Policy (CFP) in 2013 (EU, 2013), which regulates fisheries in European waters, established the so-called Landing Obligation (LO) or "discard ban" (under the provisions of Article 15). This discard ban aimed at eliminating discards of regulated species (i.e., those subject to TAC or quota). With its full introduction in 2019, all EU fisheries are obliged to land the catches of all regulated species to be counted against the quota. This has led to a particularly challenging situation for multispecies fisheries, due to the high potential for choke species that can theoretically limit the fishing effort. The term choke species was first introduced by Schrope (2010) and refers to those species with low remaining quota in a multispecies fishery that constraints the opportunities of catching other species for which the quota has not been exhausted. Consequently, fishing opportunities are lost, which leads to economic losses. In addition, the LO can create additional costs for the industry due to the processing cost of the unwanted fraction of the catch (Hall et al., 2000; Hall and Mainprize, 2005). Both sorting time and handling costs can increase because the fraction of the catch that used to be discarded needs now to be separated and stored. This can only be faced by increasing the number of working hours onboard, or the number of people onboard, which often is not possible. In addition, storing the unwanted fraction could subsequently force the increase of journeys to the harbor due to limited storage space onboard. To partially reduce these consequences, the CFP in its article 15 anticipates some flexibilities and exemptions to the LO. De minimis: allows up to 5% of discards under certain circumstances; inter-species quota flexibility: allows a quota deduction of the target species of up to 9% to be used for landing another species; year to year transfer: allows catching 10% of next year's quota in the current year; High survival rate: allows to discard those species that have high survival rates after discard.

Assuming full compliance with the LO by fishermen, hake, horse mackerel (*Trachurus trachurus*), blue whiting (*Micromesistius poutassou*), and mackerel constitute the main choke species in the Bay of Biscay bottom trawl fishery (Rochet et al., 2014). Scientific discards estimates based on the Spanish National sampling program data revealed that in the period 2014 – 2021, the total unwanted catch of the Basque fleet operating in ICES 8abd was around 37% of the total catch, from which 21% was mainly composed of these four species (Fig. 6). Hake and mackerel often become non-desired species due to legal reasons; catching individuals below the Minimum Conservation Reference Size (MCRS) is main reason for the former and quota exhaustion for the later. On the other hand, commercial reasons lie behind blue whiting and horse mackerel becoming non-desired species, as both species have a relatively low market value compared to the main target species. The price of these two species is highly influenced by freshness thus, only catches from the last hauls before heading harbor can be considered "commercially desirable".

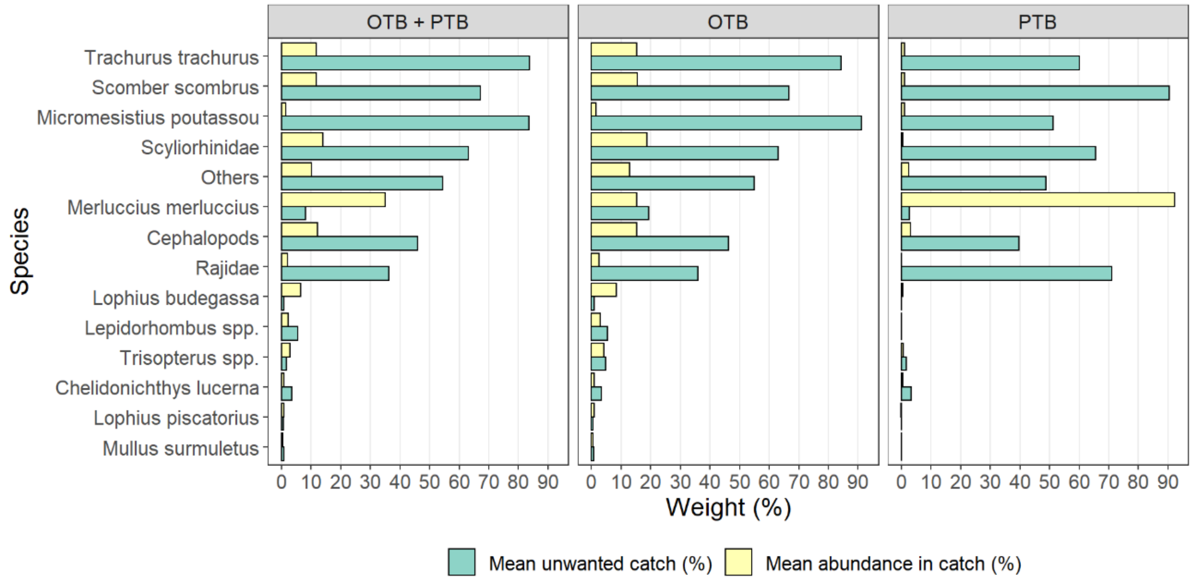


Fig. 6.- Species importance in terms of relative abundance in the catch (% of the total catch) (yellow) and the mean fraction of the unwanted catch relative to the total catch for the specific species (green) in the Basque fleet operating in the Bay of Biscay among years 2014 – 2021. OTB: single otter bottom trawlers; PTB: pair bottom trawlers. Data source: AZTI (BRTA).

Today, the bottom trawl fleet in the Bay of Biscay use the flexibilities and exemptions considered by the CFP to cope with the limitations created by the LO (e.g., BOE, 2022b, 2022c). In the short run, the use of these flexibilities and exemptions can be beneficial for the fleet, first because the issue of choke species is reduced and, second, because the extra effort is not converted into discards but into revenue (Prellezo et al., 2016). However, in the long run, and without any consideration made in terms of the ecosystem functioning as a whole, the results obtained from applying any kind of exemption or flexibility are negative. Fishing beyond the Maximum Sustainable Yield (F_{MSY}), which is defined as the maximum quantity that can safely be removed from the stock while maintaining its capacity to produce sustainable yields in the long term, increases the likelihood for decreasing stock biomasses in the future. Consequently, this could increase the cost of fishing the same quantities or reduce the total catch due to the lower abundances and subsequent lower TACs (Prellezo et al., 2016).

In addition, all this could also be detrimental for other fisheries fishing on the same fish stocks. Landings of the Spanish demersal fleets in divisions 8c and 9a show that horse mackerel, mackerel, and blue whiting constitute 65% of the total landings of these bottom trawlers (single and pair) (ICES 2021a). Therefore, these fleets may be affected by the high fishing mortality in the stocks. Additionally, these species are globally important species (FAO, 2020), especially for pelagic fisheries. For instance, catches of blue whiting exceeded 1.7 million tons in the NE Atlantic being the fifth most landed finfish species in the world. Additionally, some of the horse mackerel and blue whiting stocks are already exploited above the Maximum Sustainable yield and the spawning stock biomass is below that triggering the MSY (MSY $B_{trigger}$) (ICES, 2021b).

1.4. Challenges for the sustainability of the bottom trawl fishery in the Bay of Biscay

The bycatch of unwanted species and sizes, whether they are discarded or landed, is an ethically unacceptable practice that reduces future potential yield and spawning stock biomass. It represents an unnecessary waste of natural resources, and it decreases the efficiency of fishing operations (Crowder and Murawski, 1998; Greenstreet et al., 1999). Therefore, most multispecies fisheries around the world are managed through mandatory technical measures (Kennelly, 2007). These technical measures are designed to restrict the amount of unwanted catch through different strategies. These can entail the restriction of specific fishing areas, restrictions during a specific period, or the modifications of the fishing gear. The last of these strategies aims at modifying the gear selectivity, i.e., the "ability" of the gear to retain or release animals based on factors such as species, size and behavior (MacLennan, 1992).

For trawl gears, size and species selectivity is mostly determined by the characteristics of the codend, i.e., the aft of the gear, where the catch accumulates (Glass, 2000). Therefore, regulations for the selectivity of trawl gears have historically been focused on mesh size and mesh orientation in the codend (Glass, 2000; Herrmann et al., 2009). However, selection devices or other gear modifications can be introduced in the codend or ahead of it to select out undersized individuals and/or unwanted species.

In the Bay of Biscay, most of the technical regulations implemented in the last decades aimed at improving the stock status of the northern hake stock. In the second half of the twentieth century, fisheries of the NE Atlantic were heavily exploited throughout, and many commercial fish stocks experienced a severe decline in biomass by the early 2000s (Zimmermann and Werner, 2019). Specifically, in November 2000, ICES reported that the stock of hake in ICES sub-areas 3 – 7 and 8abde was at serious risk of collapse (EC, 2001a). Therefore, the CFP undertook a major reform in 2002 (Daw and Gray, 2005). The 2002 reform aimed at reducing fishing pressure on over-exploited stocks by introducing recovery plans to allow depleted fish stocks to recover, and long-term management plans to protect healthy stocks (EC, 2009; Kraak et al., 2013). Therefore, in the Bay of Biscay bottom trawl fishery, several technical regulations were implemented to stimulate the recovery of hake (EC, 2001a; 2001b; 2002; 2004). Among other measures, in 2001 (EC, 2001b, 2001a), the minimum codend mesh size for trawlers fishing the northern hake stock in the Bay of Biscay was changed from 70 mm to 100 mm diamond meshes.

This measure, together with area closures in the area contributed towards a substantial reduction in fishing pressure for most northern European fish stocks in the following years (Cardinale et al., 2013) and a reversal of stock decline, with prospects for recovery (Fernandes and Cook, 2013). Thus, the total effort of the EU fishing fleet fell by 25% from 2003 to 2014 (Zimmermann and Werner, 2019)). Among the stocks showing signs of recovery, from year 2006 on, the northern hake stock seemed to experience one of the fastest biomass increases, reaching a spawning stock biomass (SSB) well above the minimum recommended level (Baudron and Fernandes, 2015; ICES, 2012). Since then, reported landings increased (ICES, 2012).

Given the improvements of the northern hake stock, in 2006 the European Union accepted to provide a voluntary alternative to the mandatory use of a 100 mm codend mesh size (EC, 2006a). Specifically, the deployment of bottom trawls with a minimum codend mesh size of 70 mm was permitted, provided that a 100 mm square mesh panel (SMP) was inserted in the middle of the top panel of the rear tapered section of the trawl (Fig. 7). This configuration intended to improve the selectivity for undersized hake (Alzorriz et al., 2016).

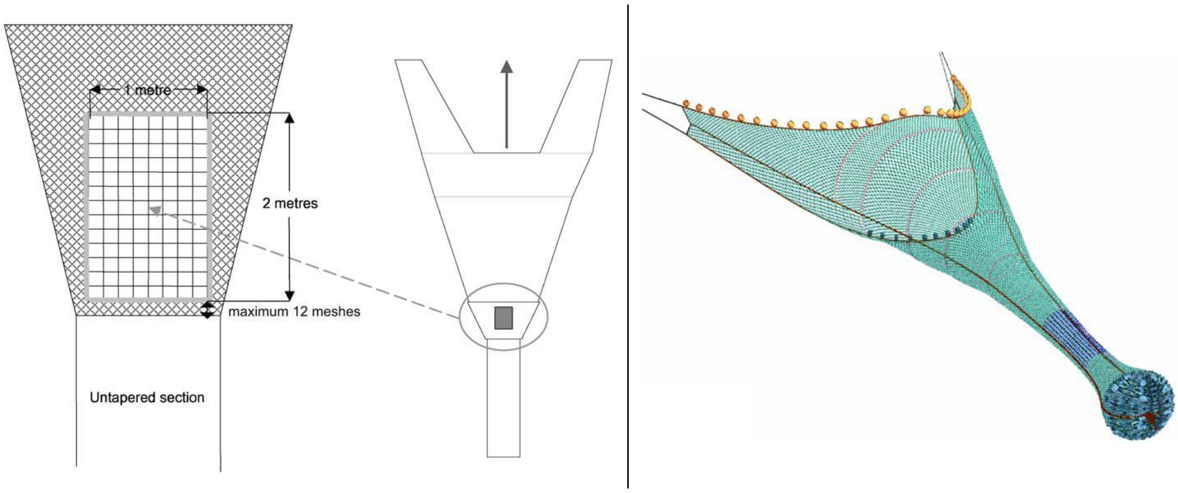


Fig. 7.- Location of the SMP in the trawl gear and mandatory specifications. Source: Catchpole and Revill, (2008); EC, (2006a).

Today, both 100 mm mesh size codend and 70 mm mesh size codend together with a 100 mm SMP may provide difficulties to comply with the fishing regulations regarding catch composition and economic profitability. Using a 100 mm diamond mesh codend in the Basque bottom trawl fishery may lead to losses in marketable catch and reductions in revenue. For this reason, currently, the gear composed of the SMP with a 70 mm diamond mesh codend is the one mostly used by the fleet. However, this option has demonstrated to perform unsatisfactorily because it retains unwanted bycatch, which can include undersized individuals and choke species (Fig. 6) (Alzorriz et al., 2016). Specifically, the high retention of those species stems from the low release efficiency of SMP and the subsequent non-optimal size selection of codend diamond meshes (Alzorriz et al., 2016). In general, results show that even if some species manage to escape through SMPs, less active species, such as hake, do not manage to escape through it efficiently (Alzorriz et al., 2016). In most studies, the authors concluded that the low release efficiency of the panel is a consequence of the low contact between the fish and the panel (Alzorriz et al., 2016; Brčić et al., 2018; Herrmann et al., 2015). Additionally, a 70 mm mesh size codend has demonstrated to retain high percentages of undersized hake. Alzorriz et al., (2016) showed that approximately 52% of the catch in number of undersized hake (< MCRS = 27 cm) was retained by the codend of the trawl used by the Basque fleet. A potential solution to avoid unwanted catches is to improve the selective properties of the fishing gear so that unwanted individuals can escape.

Chapter 2. Objective

Given the challenges of the demersal trawl fishery in the Bay of Biscay described in Chapter 1, the following thesis objective is formulated:

to identify, develop, and evaluate SMP and codend modifications that can improve the catch composition while maintaining the efficiency in the demersal trawl fishery in the Bay of Biscay.

The thesis was addressed through the following sub-objectives:

1. Test of specific selection devices and gear modifications as potential solutions to improve the release of unwanted species and sizes.
2. Understand the mechanical and behavioral components of the size selectivity process for the relevant species in the Bay of Biscay demersal trawl fishery.
3. Establish a framework to make predictions for the size selectivity of SMPs, diamond mesh codends and the combination of both devices.
4. Develop tools to communicate complex results in an easy and understandable way to the fishing sector and fisheries managers.

Chapter 3. Review of potential gear modifications to improve size and species selectivity in the Bay of Biscay bottom trawl fishery

This chapter reviews trawl gear modifications with potential to improve the size selective performance of the bottom trawls used in the Bay of Biscay. Specifically, this chapter reviews potential ways to improve the SMP release efficiency, codend size selectivity and species separation inside the trawl gear.

3.1. Square mesh panels

SMPs are simple selective devices usually applied in demersal trawl fisheries where codend selectivity alone is not sufficient to prevent catches of unintended species or sizes (Brčić et al., 2016; Briggs, 1992; Campos and Fonseca, 2004; Kennelly and Broadhurst, 2021; Revill et al., 2007). SMPs are mounted in the trawl with mesh bars parallel and perpendicularly to the towing direction of the trawl, maintaining an open mesh shape independent of the tension in the netting (Fig. 8) (Graham et al., 2003). The mesh openness of the SMPs, compared to that of diamond meshes, which varies during the towing, provides higher potential for the release of roundfish (Armstrong et al., 1998; Briggs, 1992; Herrmann et al., 2009; Isaksen and Valdemarsen, 1986; Krag et al., 2016, 2011; Robertson, 1983).

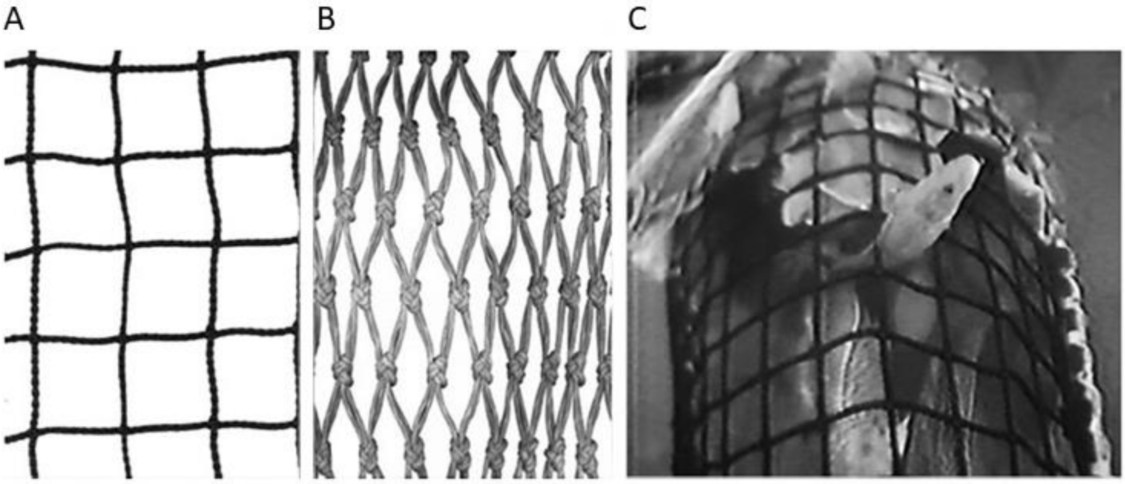


Fig. 8.- (a) Single twine square meses typically used in SMPs; (b) Double twine diamond meshes typically used in codends; (c) Example of a roundfish escaping through the SMP just in front of the catch accumulation zone. Source: Herrmann et al., (2015).

SMPs were first introduced into the legislation in the Northern European *Nephrops* (*Nephrops norvegicus*) fishery in 1992, primarily to improve the release of undersized gadoids like whiting (*Merlangius merlangus*) (Briggs, 1992). SMPs are often installed at the upper panel of the extension piece of the trawl (Krag et al., 2008; Nikolic et al., 2015), where they were believed to support the release of roundfish bycatch (Armstrong et al., 1998; Briggs, 1992; Drewery et al., 2010; Isaksen and Valdemarsen, 1986; Krag et al., 2008; Robertson, 1983) while preventing the loss of crustaceans such as *Nephrops*, which usually enter the codend close to the lower panel (Main and Sangster, 1985). Since then, they have been introduced in other crustacean (Broadhurst, 2000; Catchpole and Revill, 2008) and fish-directed fisheries (EU, 2019). Today, SMPs are compulsory when targeting specific species in some fishing areas (EU, 2019), mainly in the North Sea (ICES 4), the Northwestern Waters area (ICES 5, 6, 7), the Bay of Biscay (ICES 8abde) and the Iberian Waters (ICES 8c).

The applicability and efficiency of SMPs have been broadly studied (Brčić et al., 2018, 2016; Broadhurst and Millar, 2022; Herrmann et al., 2015; Krag et al., 2017; O'Neill et al., 2006; Santos et al., 2016; Sistiaga et al., 2018; Zuur et al., 2001). In several fish directed fisheries, the performance of SMPs has been unsatisfactory regarding reduction in captures of undersized fish of commercial species (Alzorriz et al., 2016; Brčić et al., 2016; Bullough et al., 2007; Gatti et al., 2020; ICES, 2004). In most cases, the low release efficiency of the panel is caused by low contact probability between the fish and the panel (Alzorriz et al., 2016; Brčić et al., 2016; Herrmann et al., 2015).

For a fish to be subjected to size selection process in SMPs, it first needs to contact the SMP (Herrmann et al., 2009; Sistiaga et al., 2011). Contact can be defined as an attempt made by the fish to escape through the specific selection device that leads to a size selection process (Santos et al., 2016; Sistiaga et al., 2010). However, underwater recordings have revealed that some species prefer following the route that is most open and stay clear of the netting (Glass et al., 1995; Glass and Wardle, 1995), which can reduce their contact probability with the SMP. In the Bay of Biscay bottom trawl fishery, the escape of some commercially relevant species through the SMP meshes is very low (Alzorriz et al., 2016). In the research conducted by Alzorriz et al., (2016), the authors observed that hake, red mullet (*Mullus surmuletus*) and pouting (*Trisopterus luscus*) tended to stay close to the lower panel and did not interact with the SMP, which could reduce their probability to encounter the SMP meshes. Specifically, hake appeared to be little active inside trawls (Alzorriz et al., 2016), making it particularly challenging to achieve sufficient release efficiency through SMP meshes. In the same study, individuals of some pelagic and semi-pelagic species (e.g., horse mackerel and blue whiting) were observed to escape through the SMP, but others tended to swim under the SMP for long periods until they became exhausted and drifted back to the codend. Some authors speculate that for those swimming in the towing direction, it is not attractive to change their trajectory by ca. 90º unless the most open path is blocked for example, by large aggregations of fish (Herrmann et al., 2015). Further, when fish individuals enter the SMP area, some may already be exhausted and consequently, they may not be able to attempt active escape (Winger et al., 2010), as drifting in the direction of the codend may be more energy-efficient (Peake and Farrell, 2006). Therefore, the effective release of fish through SMPs relies, not only in the size selection potential of the meshes, but on the distribution of the fish inside the trawl, their swimming capability and willingness to contact its meshes (Brčić et al., 2018; Herrmann et al., 2015).

A number of researchers have tried to improve SMP contact probability and release efficiency using different strategies. One of these strategies aims at taking advantage of the natural behavior of the fish by positioning the device in the area where they presumably will attempt escape. Thus, placing the SMP close to the codline is one of the most tested positions for SMPs (e.g., Herrmann et al., 2015). At the aft end of the codend, fish do not have the option to drift further back and are obliged to make potential escape attempts close to the catch accumulation zone. In general, the closer to the codline the SMP is inserted, the higher the rate of escape of species such as whiting, haddock (*Melanogrammus aeglefinus*) and cod (*Gadus morhua*) (Catchpole and Revill, 2008; Graham et al., 2003; Graham and Kynoch, 2001; Herrmann et al., 2015; Revill et al., 2007). Graham and Kynoch, (2001) demonstrated that a SMP located in the front part of the codend released more small haddock than a SMP located at the beginning of the extension piece. Similarly, Herrmann et al., (2015) demonstrated that the release efficiency of cod through a BACOMA codend, which consists of a SMP at the upper panel, depended on the overlap of the SMP and the catch-accumulation zone in the codend.

Despite the positive results reported by different authors, locating the SMP close to the codline can also involve drawbacks and some studies have documented poorer release efficiency of SMPs in that position (i.e., between 1 and 6 m from the codline). They speculated that the cross-sectional area of the codend close to the catch accumulation zone is greater than further forward in the codend. The potential increase in distance to the netting at that point may make more difficult for fish with low swimming capability contacting the panel (Armstrong et al., 1998; O'Neill et al., 2006). In addition, Armstrong et al., (1998) explained that the exhaustion of fish once they get to the catch accumulation zone may also decrease escape chances through SMPs located in this area. Similarly, large catch size may overcrowd the SMP area, limiting the chance for fish to escape through SMP meshes (Armstrong et al., 1998). Finally, placing a SMP in the aft part of the codend in a multispecies fishery, such as the one in the Bay of Biscay, may entail excessive loss of specific valuable roundfish species due to the diversity of species caught, their corresponding morphologies and behaviors, as well as the variability in their MCRS. Therefore, a more appropriate strategy needs to be applied to address the low release efficiency of the SMP in the Bay of Biscay bottom trawl fishery.

Several other studies have tried to improve contact probability and release efficiency of SMPs placed in the extension piece by means of influencing fish behavior. Specifically, some authors have demonstrated that the escape behaviour of fish can be manipulated by applying mechanical and visual stimuli in the surroundings (e.g., Glass et al., 1995; Glass and Wardle, 1995; Grimaldo et al., 2017; Herrmann et al., 2015). Glass et al., (1995) showed that fish refuse to use the clearest path and try to penetrate the meshes around them when the open path is mechanically or visually blocked in some way. For instance, presenting the fish with the illusion of a blockage in the form of a black tunnel just behind of the SMP or square mesh section, caused that fish swimming towards the codend turned and tried to penetrate SMP meshes (Glass et al., 1995; Glass and Wardle, 1995). However, under dark conditions, the visual stimuli based on the contrast of the netting color regarding the surrounding netting may be reduced, as well as the avoidance reaction.

At fishing depths of the bottom trawlers in the Bay of Biscay, a visual stimulus that relies on the available light close to the seabed might not be enough to drive fish towards the selective devices and effectively increase SMP release efficiency. For this reason, mechanical blocking of the path towards the codend could be a better strategy to use. Several studies aimed at increasing SMP release efficiency by attaching vertically inclined ropes with floats (to provide mechanical blockage and vibration) in the vicinity of the SMP. These simple stimuli increased the likelihood of some species to contact the SMP or square mesh section meshes (Gatti et al., 2020; Grimaldo et al., 2017; Herrmann et al., 2015; Krag et al., 2017). Krag et al., (2017) for instance, significantly improved the contact probability and release efficiency for cod without affecting the catch of *Nephrops* (Fig. 9a) by placing inclined ropes with floats beneath the SMP, whereas Herrmann et al., (2015) tried to stimulate the escape behavior of cod inside the trawl by using similar ropes.

Over the past few decades, other visual stimulus like light emitting diodes (LEDs), attached directly to fishing gears, have been increasingly used either to attract or repel fish from a specific area or device (e.g., Geraci et al., 2021; Grimaldo et al., 2017; Hannah et al., 2015; Karlsen et al., 2021; Lomeli et al., 2018; Lomeli and Wakefield, 2019; Nguyen and Winger, 2019; Southworth et al., 2020). This has led some studies to illuminate different parts of the gear; grids (Larsen et al., 2018), SMPs (Southworth et al., 2020), the footrope (Lomeli et al., 2020) and the headrope (Geraci et al., 2021) (Fig. 9bcde), to favor or deter escape behavior (Grimaldo et al., 2017), attract towards an opening (Lomeli and Wakefield, 2019), or guide fish inside the trawl (Karlsen et al., 2021; Melli et al., 2018) (Fig. 9f). Southworth et al., (2020) for instance, evaluated the differences in catch retained in a standard otter trawl, relative to the same gear fitted with a SMP with and without LEDs on it. They found that when using a SMP in shallow waters the unwanted bycatch of whiting and haddock was reduced by 86% and 58%, respectively whereas when in deep and darker water, no change in catch was observed compared to the trawl without the SMP. However, when LEDs were attached to the SMP, haddock and flatfish catches were reduced by 47% and 25%, respectively in deep waters.

Considering the results obtained by the different studies, the application of any of these devices could also be beneficial in the Bay of Biscay trawl fishery. Additionally, such mechanical and visual stimulators, that aim to trigger fish escape behavior to improve the release efficiency of the SMP, has never been tested for some globally relevant species in this fishery.

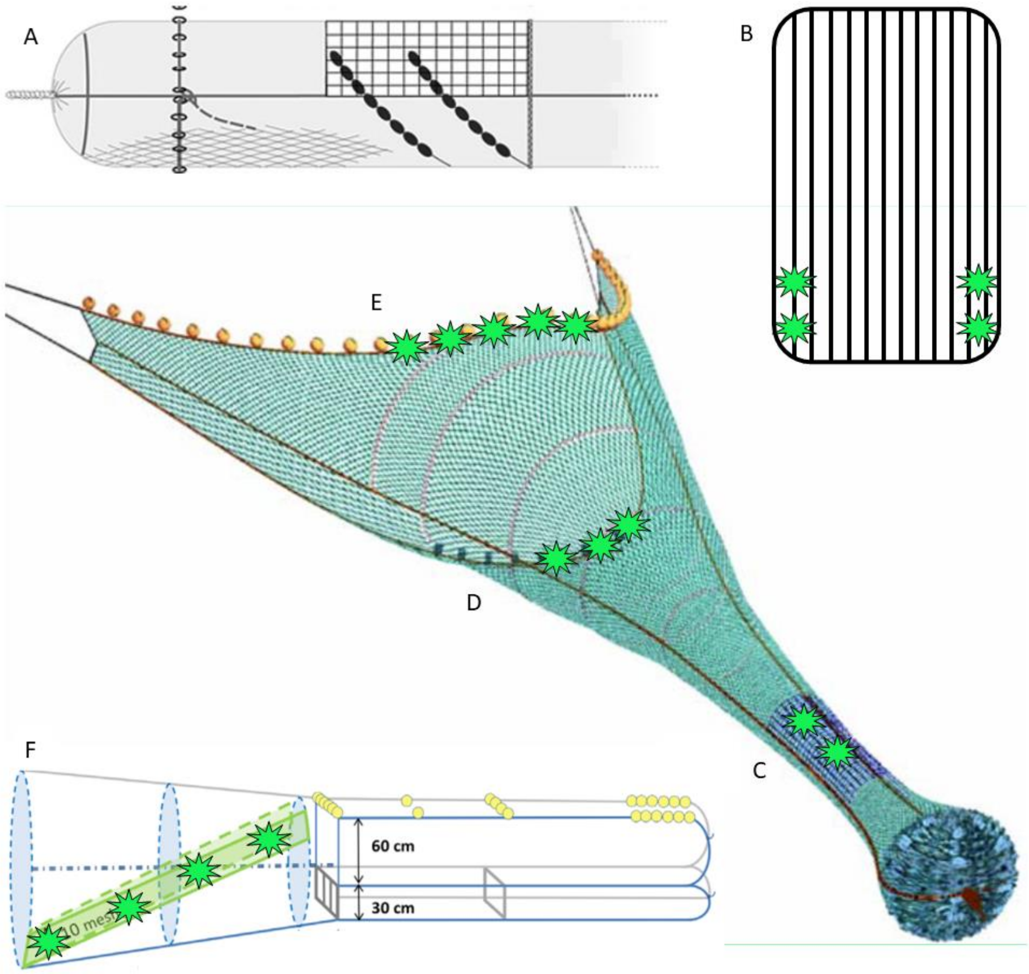


Fig. 9.- Potential strategies and positions to locate mechanical (e.g., ropes) and behavioral (LED lights) stimulation devices inside the trawl gear. Source: Catchpole and Revill, (2008); Herrmann et al., (2015); Karlsen et al., (2021).

A SMP attached in the extension piece of the gear provide fish with an opportunity to attempt to escape. However, this opportunity is influenced by the time they spend in the region of the panel and competition for available escape gaps, i.e., open square meshes. Especially at high speeds, fish is expected to pass through the SMP area relatively fast. Therefore, it could be assumed that for a given towing speed, the opportunity for escape would increase by increasing the panel area (e.g., Arkley, 2001). However, few studies have documented differences in size selectivity when using a larger SMP compared to a smaller one. Arkley (2001) stated that a prolonged exposure to square mesh netting as the fish move through the trawl, may result in the fish becoming acclimatized to the panel, lessening the escape response. However, Gatti et al., (2020) showed that a SMP expanded to the whole cylinder (square mesh cylinder, 3.2 m long) located at the extension piece proved to significantly increase the release efficiency of haddock, whiting and megrim. Following the principle of increasing fish chances for contacting the SMP, Santos et al., (2016) tested 10 m long SMPs, integrated into the sides of the last part of the trawl belly, that were supplemented by a device that guided fish towards the SMPs. The results showed that the contact probability of hake and megrim (together with other species) improved significantly compared to a SMP alone, located at the upper panel of the extension piece.

Presenting an escape opportunity to fish does not always guarantee escape. An escape response is required. Therefore, designing a suitable SMP in terms of mesh size and area, taking advantage of the natural behavior of the target species or influencing their escape behavior are necessary to improve SMP release efficiency. Considering the variety of species and behaviors involved in the bottom trawl fishery in the Bay of Biscay, changing SMP position, size and using mechanical/visual stimulators can be potential strategies to improve the SMP release efficiency.

3.2. Codends

Owing to their simplicity and ease of handling on board the fishing vessel, the use of codends made of diamond-mesh netting is widespread in commercial fisheries (Herrmann et al., 2013a; Wileman et al., 1996). Traditionally, adjusting mesh size has been the strategy used by fisheries managers to control size selection in codends (Frandsen et al., 2011; Madsen, 2007; Millar and Fryer, 1999; Pope, 1975; Wileman et al., 1996) however, this does not always lead to the desired size selection (MacLennan, 1992). Diamond mesh codends often deliver highly variable size selectivity (Bak-Jensen et al., 2022; Robertson and Stewart, 1988). During fishing, the forces acting on the codend produced by the catch building up causes that most meshes in the codend, except for some rows just ahead of the catch accumulation zone (Herrmann, 2005a, 2005b), get longitudinally stretched (i.e., closed; Fig. 10) (Herrmann et al., 2007).

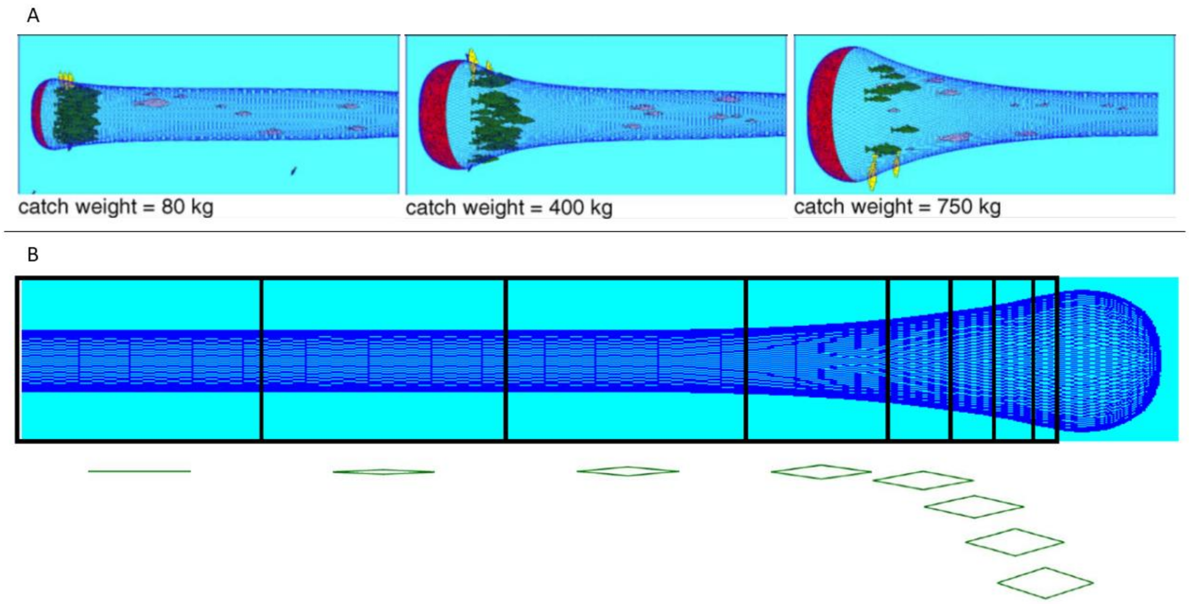


Fig. 10.- (a) Shape of codend for different catch weights. Source: Herrmann, (2005b); (b) Mesh openness for different places along the codend. Source: Frandsen et al., (2010a).

Codends can be modified in multiple ways to better select out unwanted catches. It is well-known that factors such as mesh size, mesh shape, twine material, twine thickness, codend circumference (i.e., no. of meshes around) and several other factors can influence fish likelihood to escape through codend meshes (Herrmann et al., 2013a; Herrmann and O'Neill, 2006; Jones et al., 2008; O'Neill et al., 2003; O'Neill and Kynoch, 1996; Sala and Lucchetti, 2011). In the Bay of Biscay, the codend used by the fleet does not perform satisfactorily and retains large quantities of undersized fish (Alzorriz et al., 2016). However, voluntarily increasing mesh size is rarely chosen by fishermen because it may lead to loss of commercial catch. Therefore, it is necessary to explore additional strategies to optimize and improve exploitation patterns in the fishery.

Codends can be mechanically modified in order to influence the probability of fish to physically pass through the meshes. For example, turning diamond meshes 45º (T45 codend) and making them square has been a widely used strategy to improve selectivity in many trawl fisheries and across many species' assemblages (e.g., Düzbastilar et al., 2017; He, 2007; Kennelly and Broadhurst, 2021; Lucchetti, 2008; Robertson and Stewart, 1988; Tokaç et al., 2014; Walsh et al., 1992). Opposite to diamond mesh codends, the meshes stay more open during the catch process due to the orientation of the mesh bars (Fig. 11a) (Krag et al., 2011; Robertson and Stewart, 1988). This can improve fish escape probability, especially for roundfish because of their shape (Fig. 11b). The ability of square meshes to improve release efficiency and provide stable selectivity has been demonstrated for roundfish, including horse mackerel and hake (Campos and Fonseca, 2003; Halliday and Cooper, 2000; Sala et al., 2008). In consequence, square mesh codends have been introduced in many fisheries to replace diamond mesh codends, for example, in the Mediterranean multispecies demersal trawl fisheries (EC, 2006b).

However, although the effect of turning the meshes can be beneficial for some species, the benefit is less evident for flatfish species, whose flat morphology may fit diamond meshes better (Fig. 11b) (Bayse et al., 2016; Tokaç et al., 2014). Square mesh codends can therefore result in unchanged or worsened selectivity for flatfish species (Dahm et al., 2003; Madsen, 2007; Sala et al., 2008). Thus, fisheries managers need to consider that by introducing devices based on square meshes into a multispecies fishery with both roundfish and flatfish species, the retention and potential discards of flatfish may increase (Walsh et al., 1992).

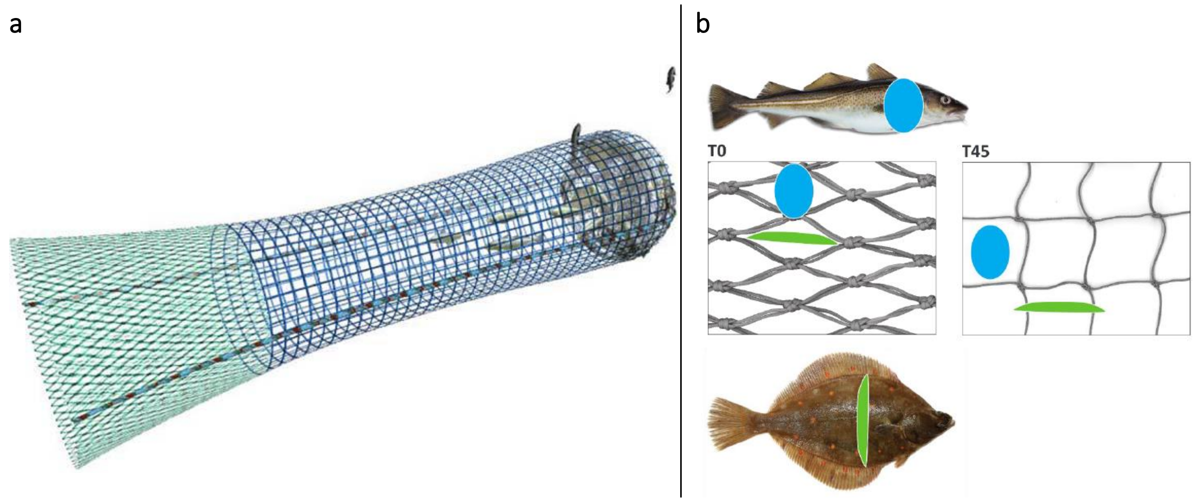


Fig. 11.- (a) T45 codend (diamond netting turned 45º). Source: Catchpole and Revill, 2008; (b) Nominal geometries of traditional T0 (diamond mesh codend) and T45. The cross sections of roundfish (blue) and flatfish (green) illustrate the potentially opposite selectivity properties of the different netting configuration for these species. Source: Santos, (2021).

A different approach to improve codend size selectivity of increased use in the last years is shortening codend lastridge ropes (LR) (Fig. 12). In a codend, 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 and Valdemarsen, 1990). When LR are shortened, the length of the netting is fixed in a shorter length and the load of the catch building up in the codend is born by the ropes earlier. Therefore, regardless the catch size, the meshes cannot be completely stretched and consequently, they are more open (Fishing Technology Unit, 1993; Ingólfsson and Brinkhof, 2020; Isaksen and Valdemarsen, 1990; Lök et al., 1997).

In addition to the more open meshes, shortened LR provide slack meshes along the codend, which may be fully deformed by the effort of the fish while trying to escape (Sistiaga et al., 2021). Slack meshes in standard diamond mesh codends are usually present during the first or last stages of the fishing process, and they have been identified to play an important role in the size selection process, especially when the codend comes to the surface (Herrmann et al., 2016a). The effect of LR on size selectivity has been tested in different fisheries and for different species and, in general, they have shown that size selectivity for roundfish species is improved compared to equivalent codends with non-shortened LR (Brothers and Boulos, 1994; Einarsson et al., 2021; Hickey et al., 1995; Ingólfsson and Brinkhof, 2020; Jacques et al., 2021; Lök et al., 1997; Sistiaga et al., 2021). Although the effect of LR has not been tested for flatfish species, increasing mesh opening angle (OA) by means of LR could find an intermediate mesh openness that may be beneficial for roundfish and not as prejudicial as a square mesh for flatfish.

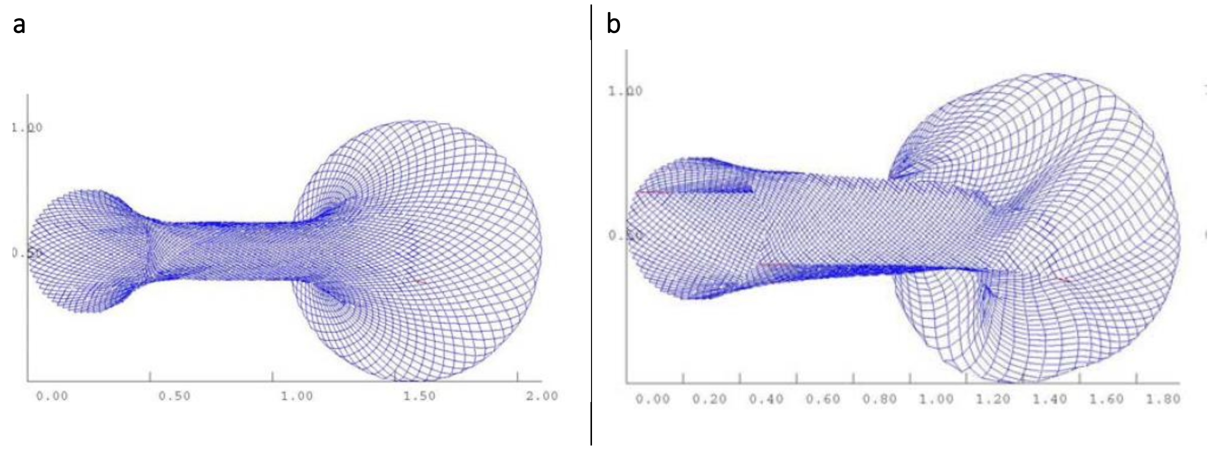


Fig. 12.- (a) Standard diamond mesh codend; (b) Shortened LR codend. Source: Priour and Herrmann, (2005).

Therefore, given the low escape probability of undersized fish through diamond mesh codend used in the Bay of Biscay and the mix of species present, codend size selectivity could potentially be optimized by increasing mesh openness. Turning 45º mesh orientation or shortening LR may lead codend meshes to better correspond with the morphology of the undesired species in this fishery and subsequently lead to a more adequate size selection process.

3.3. Species separation devices

Although the modifications in sections 3.1. and 3.2. can improve size selectivity in the multispecies Bay of Biscay bottom trawl fishery, they may not be sufficient on their own. Similar morphology of both target and bycatch species (e.g., Krag et al., 2010) or extremely different morphology of two target or bycatch species (e.g., Lomeli and Wakefield, 2016) may imply non-optimal gear size selectivity. Therefore, several studies have aimed at exploiting fish behaviour to improve size selectivity and/or supplement other modifications on the gear (Bayse and He, 2017; Bublitz, 1996; Glass and Wardle, 1995; He et al., 2008; Ryer, 2008). Those studies aimed specifically at exploiting fish reactions to specific selection devices or their natural distribution inside the trawl gear; for example, attraction to light or preference for the lower panel (Engaas et al., 1999; Karlsen et al., 2019; Krag et al., 2009a, 2009b; Melli et al., 2019, 2018). Therefore, gear modifications based on the natural distribution of the fish inside the trawl or modifications that aimed at influencing fish behavior in the trawl have been tested.

A behavioral-based strategy to improve the selectivity of trawl gears in multispecies fisheries can be to separate species into different codends followed by a subsequent and respective size selection process in each of them (Fig. 13) (Ferro et al., 2007; Karlsen et al., 2019; Krag et al., 2009a; Melli et al., 2019, 2018).

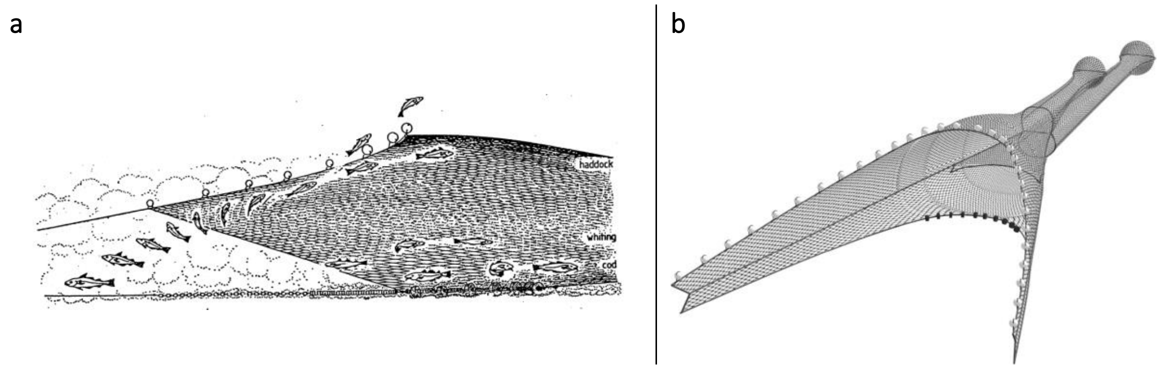


Fig. 13.- (a) Illustration showing the behaviour of different fish species in the trawl mouth; some lift when they fall back into the trawl, others enter the trawl low and are passively transported towards the codend. Source: Main and Sangster, 1981. (b) Bottom trawl with a separator panel that divides the net into two compartments (i.e., codends). Source: Ferro et al., (2007).

Several researchers have used species specific differences in vertical distribution inside the trawl to reduce unwanted catches, i.e., by separating species that enter the gear low from species that distribute themselves higher in the gear (Fryer et al., 2017; Karlsen et al., 2019; Krag et al., 2009a, 2009b; Larsen et al., 2021) (Fig. 13). Species separation devices have been used both in fish and crustaceans directed fisheries (Fryer et al., 2017; Karlsen et al., 2019, 2015; Krag et al., 2009a, 2009b; Larsen et al., 2021). Ferro et al., (2007) for example, achieved to effectively separate an important proportion of the catch in the upper codend, letting cod and few other species in the lower codend, allowing the subsequent size selective device (a grid) to release undersized cod. Karlsen et al., (2015) separated fish from *Nephrops* using a horizontally divided codend and aimed to improve this separation by encouraging fish to swim upwards with a frame at the entrance of the lower codend. Flatfish are commonly observed swimming near the lower panel of the trawl (Bublitz, 1996; Fryer et al., 2017; Ryer, 2008). In the Baltic Sea cod-directed trawl fishery, where a flatfish species is the main bycatch species, Santos et al., (2020) applied a simple flatfish excluder in the lower panel of the extension piece of the trawl to take advantage of this species' behaviour. The results demonstrated that the bycatch of flatfish was effectively reduced while maintaining the catches of the targeted cod.

Further, in some studies, both mechanical and visual stimulators have been applied to increase the proportion of fish entering in one or the other compartment (Karlsen et al., 2021; Melli et al., 2019, 2018; O'Neill et al., 2022). Specifically, Melli et al., (2018) aimed at using LED lights to exploit fish phototactic responses (moving towards or away from light sources) and although no clear species-specific phototactic response was identified, they obtained significant changes in vertical separation when the lights were attached in the upper compared to the lower compartment. O'Neill and Summerbell, (2019) fitted an illuminated line at different positions of a two-level trawl and found out that no matter where the light was located, the proportion of species that swam over the panel ending up in the upper compartment of the trawl was significantly reduced during nighttime.

In the Basque bottom trawl fishery, species separation has not been attempted despite the differences in species behavior assumed for some of the species involved. Previous studies have revealed that hake tends to swim close to the lower netting panel in the trawl (Alzorriz et al., 2016). Similarly, megrim, like most flatfish, enter the trawl close to the seabed and remain there (Main and Sangster, 1982, 1981; Ryer, 2008; Thomsen, 1993). On the other hand, horse mackerel, mackerel and blue whiting, are pelagic and semi-pelagic species which are expected to distribute themselves higher up in the trawl. Thus, the range of behaviors expected for the different species in this fishery highlights the potential for bycatch and target species separation.

Chapter 4. Assessment of size selectivity through experimental sea trials

Size selectivity can be defined as the probability that a given fish size is retained conditioned it enters the gear. Experiments to test size selectivity can be designed in different ways. In this chapter, a general description of the approaches used to assess the size selectivity of the gear designs tested in this thesis is provided. Specifically, experimental methods to collect and analyze selectivity data from one or multiple size selection devices is presented. In addition, a method to study the separation efficiency in a vertically divided trawl is presented.

4.1. Size and species selectivity

A size selection process occurs when the size distribution of fish caught in the trawl is different to the size distribution of the fish population in the fishing area (Wileman et al., 1996) Across the size distribution of fish entering the trawl, fish of each length class (l), i.e., fish classified into groups often by a length interval of 0.5 or 1.0 cm, will have a certain probability of being retained in the gear. For fish of similar size, the retention probability can be affected by multiple factors such as fish morphology, level of exhaustion when attempting to escape, the orientation when encountering the mesh or selective device, variation in mesh size and openness, and catch rates, all contributing to the variability in the selection process (Grimaldo et al., 2017; He, 1993; Herrmann, 2005b; Wileman et al., 1996).

There are two main experimental methods to collect the size and species selectivity data for a gear: the paired-gear method and the covered-codend method. In the paired-gear method two gears of equal overall dimensions are towed alternatively or alongside each other (Wileman et al., 1996). In one of those gears, the test gear, the selectivity device to be tested is installed, whereas the other gear, the control gear, is built in small meshes that are considered to be non-selective. Although the paired-gear method is widespread, it is an indirect method that assumes fish population entering the test and control gears have the same size distribution. The covered-codend method on the other hand is a direct method, where the fish that actually escapes the gear is collected.

With the covered-codend method, the fish fraction retained by the gear is accumulated in the codend, whereas the fraction of fish that escapes the gear is collected in a small-mesh netting cover (e.g., Bahamon et al., 2006; Madsen et al., 1998; Pope, 1975; Tokaç et al., 2014; Wileman et al., 1996). The main benefits of this method are the simplicity of the tools required to analyze the collected data, and the precision of the resulting estimates, often achieved with relatively low sampling effort compared to the paired-gear method (Herrmann et al., 2016b; Millar, 2010; Sistiaga et al., 2010). For these reasons, the covered-codend technique has been preferred for the experimental trials carried out within this thesis.

Despite the several advantages of the covered-codend method, the use of covers also entails some challenges. They may obstruct the meshes in the selection device creating a masking effect, restrict water flow through the codend, influence fish behavior due to visual stimuli, or compromise gear performance due to higher drag resistance (Cheng et al., 2022; Madsen and Holst, 2002; O'Neill and Kynoch, 1996; Pope, 1975). To prevent all these potential flaws, covers are often made of materials with neutral or slightly positive buoyancy (Wileman et al., 1996) and rigged with elements specifically designed to maintain a sufficient and stable space between the cover and the selectivity device studied. A traditional method to keep the cover netting clear of the codend meshes is the use of large hoops fixed to the circumference of the cover, which in practice can be difficult to handle (Krafft et al., 2016; Kynoch et al., 2004; Madsen et al., 1998; Tokaç et al., 2010). Attaching kites around the cover is another option. Kites generate hydrodynamic forces that keep the cover clear of the selectivity device investigated, making them a simpler and handier alternative to hoops (He, 2007; Madsen et al., 2001).

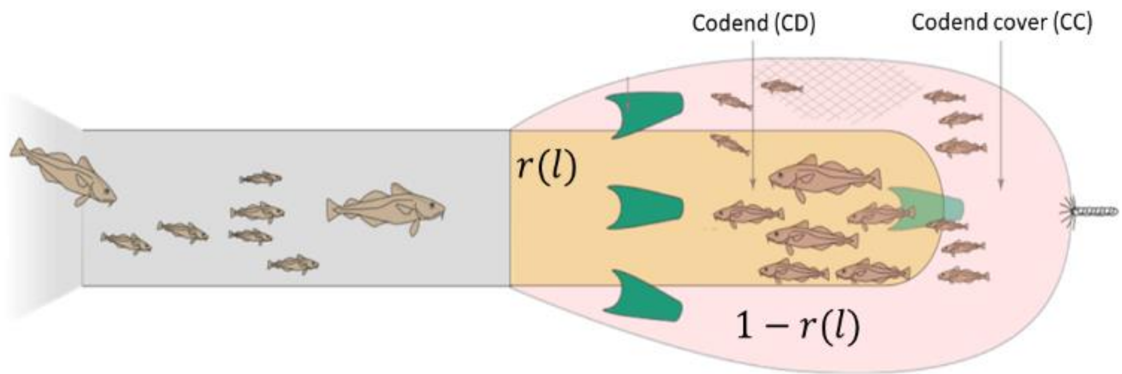
Depending on the number of size selection devices in a trawl gear, the experimental design can differ (i.e., the number of covers used). A simple gear where the size selection is given by a single device will only require a single cover, whereas for a gear with two selection devices, both single- and dual-covered methods can be used to estimate size selectivity. The challenges of using independent covers with respect to use a single cover are that there is an additional compartment to be considered and that the practical operations on board can be more challenging. However, one of the main advantages of the dual-covered method is that both individual and combined size selectivity of the devices in the gear can be estimated with increased precision compared to the single-covered method (Sistiaga et al., 2010). In every case, size selection is estimated species by species, due to differences in morphology and behavior.

4.1.1. Single size selection system

In single size selection systems, a small-mesh netting covers the selection device, for example a codend, and retains the fish escaping through it (Fig. 14a). Thus, the number and the length of the fish retained in the codend (CD) and codend cover (CC) can be obtained. Count data of the number of the fish in each compartment is created for each length class (l) (Herrmann, 2005c; Wileman et al., 1996). The codend retention probability $r(l)$ can be modelled by a parametric function leading to s-shaped selectivity curve, which increases from 0.0 to 1.0 with fish length (Fig. 14b) (Santos, 2021). The simplest and most often applied selectivity model is the *Logit* function (Wileman et al., 1996), which is 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) (1). The SR parameter defines the steepness of the selection curve. This model is often used to describe simple size selection processes through codend meshes:

$$r(l,\boldsymbol{v}) = Logit(l, L50, SR) = \frac{exp\left(\frac{ln(9)}{SR} \times (l - \mathrm{L50})\right)}{1 + exp\left(\frac{ln(9)}{SR} \times (l - \mathrm{L50})\right)} \quad (1)$$

a



b

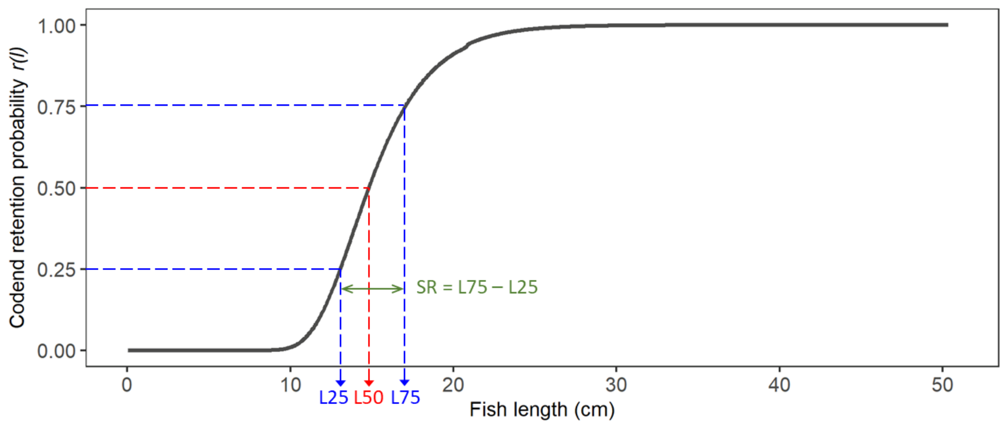


Fig. 14.- (a) Single-cover system applied on a trawl gear consisting of a single selection process (i.e., codend). Source: inspired by Santos, (2021). (b) Common s-shaped curve describing bottom trawl size selectivity. Model parameters, L50 and SR, are also depicted.

Other models commonly used for fitting s-shaped selection curves to covered-codend data are the *Probit* (2), the *Gompertz* (3) and the *Richards* (4) models (Larsen et al., 2019; Wileman et al., 1996). The term $\boldsymbol{\Phi}$ in the *Probit* function (2) refers to the cumulative distribution function of a standard normal distribution (Wileman et al., 1996). All these four basic models are described by the parameters L50 and SR except for the *Richards* model, which requires an additional parameter that describes the asymmetry in the curve (δ) (Wileman et al., 1996).

$$r(l,\boldsymbol{v}) = Probit(l, \mathrm{L50}, SR) \approx \Phi\left(\frac{1.349}{SR} \times (l - \mathrm{L50})\right) \quad (2)$$

$$r(l,\boldsymbol{v}) = Gompertz(l, \mathrm{L50}, SR) \approx \exp\left(-\exp\left(-\left(0.3665 + \frac{1.573}{SR} \times (l - \mathrm{L50})\right)\right)\right) \quad (3)$$

$$r(l,\boldsymbol{v}) = Richards(l, \mathrm{L50}, SR, \delta) = \left(\frac{exp\left(\ln\left(\frac{0.5^{\delta}}{1.0 - 0.5^{\delta}}\right) + \left(\frac{\ln\left(\frac{0.75^{\delta}}{1.0-0.75^{\delta}}\right) - \ln\left(\frac{0.25^{\delta}}{1.0-0.25^{\delta}}\right)}{SR}\right)(l - \mathrm{L50})\right)}{1.0 + exp\left(\ln\left(\frac{0.5^{\delta}}{1.0 - 0.5^{\delta}}\right) + \left(\frac{\ln\left(\frac{0.75^{\delta}}{1.0-0.75^{\delta}}\right) - \ln\left(\frac{0.25^{\delta}}{1.0-0.25^{\delta}}\right)}{SR}\right)(l - \mathrm{L50})\right)}\right)^{1/\delta} \quad (4)$$

The s-shaped size selection models above account for situations in which all fish are subjected to the same size selection process in a specific device. However, this is not always the case. Size selection can be subject to one or more size selection processes. To describe these potential processes, more complex models, often based on the *Logit* model, have been developed. The *DLogit* (5) and *DSLogit* (6) models combine two *Logit* models. *DLogit* (5) assumes that a fraction C_1 of the fish will be subjected to one logistic size selection process with parameters $\mathrm{L50}_1$ and SR_1, while the remaining fraction $1 - \mathrm{C}_1$ will be subjected to another logistic size selection process with parameters $\mathrm{L50}_2$ and SR_2 (Herrmann et al., 2016a):

$$r(l,\boldsymbol{v}) = DLogit(l, \mathrm{C}_1, \boldsymbol{v}_1, \boldsymbol{v}_2) = \mathrm{C}_1 \times r_1(l, \boldsymbol{v}_1) + (1.0 - \mathrm{C}_1) \times r_2(l, \boldsymbol{v}_2) \quad (5)$$

C_1 is a number between 0.0 and 1.0. $r_1(l, \boldsymbol{v}_1)$ and $r_2(l, \boldsymbol{v}_2)$ describe the first and second size selectivity processes, respectively (5). The fraction C_1 is subjected to r_1 and the remaining fraction to r_2.

The *DSLogit* model is similar to the *DLogit* model, but it is sequential, meaning that the proportion of individuals available for the second size selection process are assumed to consist of those that did not escape in the first process (Herrmann et al., 2016a; Noack et al., 2017):

$$r(l,\boldsymbol{v}) = DSLogit(l, \mathrm{C}_1, \boldsymbol{v}_1, \boldsymbol{v}_2) = \left(1.0 - \mathrm{C}_1 + \mathrm{C}_1 \times r_1(l, v_1)\right) \times r_2(l, v_2) \quad (6)$$

Once one of the models mentioned in (1 – 6) is fitted to the size selection data, the parameters in $\boldsymbol{v}$ are estimated using a Maximum Likelihood Estimation (MLE) approach. This is a method used to determine values for the model parameters that maximize the likelihood for the experimental data obtained. For this purpose, the following expression is minimized, which corresponds to maximizing the likelihood for obtaining the observed experimental data:

$$-\sum_{l}\sum_{j=1}^{m}\left\{nCD_{lj} \times \ln\left(r(l,\boldsymbol{v})\right) + nCC_{lj} \times \ln\left(1.0 - r(l,\boldsymbol{v})\right)\right\} \quad (7),$$

where nCD_{lj} and nCC_{lj} are the numbers of fish in the codend and cover for length class l in haul j, respectively, and $\boldsymbol{v}$ represents the parameters in the model. The outer summation in expression (7) is over the length classes l in the data, and the inner summation is over the hauls j (from 1 to m).

Often, only a fraction of the fish caught during the fishing trials can be measured due to operational reasons, for example, when catch exceeds a maneuverable quantity in terms of the available time and crew for processing the fish. In that case, the subsample factor (q) is calculated for each catch compartment separately, as the ratio of weight/counts of the measured fish to the total weight/counts of the catch. Being qCD_j the subsample factor of the codend, and qCC_j the subsample factor of the cover, the likelihood for obtaining the observed experimental data would be:

$$-\sum_{l}\sum_{j=1}^{m}\left\{\frac{nCD_{lj}}{qCD_j} \times \ln\left(r(l,\boldsymbol{v})\right) + \frac{nCC_{lj}}{qCC_j} \times \ln\left(1.0 - r(l,\boldsymbol{v})\right)\right\} \quad (8)$$

4.1.2. Dual size selection systems

A dual-selection system consists of a gear that combines a size selective codend with an additional selection device where fish are selected out of the trawl through, at least, one different size selection process in each device. In a dual-selection system composed of a SMP and a codend, both single- and dual-covered methods can be applied to collect size selectivity data on the SMP and the codend. For SMPs, the size selectivity largely depends on how fish react to its presence. First, fish arrive inside the area where the SMP is located, and they can either actively contact the SMP or simply continue to drift towards the codend (Fig. 15a). Often, a fraction of fish entering the gear do not contact the device, and consequently are not subject to a size selection process by the SMP. Therefore, in such a process, the probability for fish to contact the device C_{SMP} needs to be estimated. Thus, the escape probability for fish through the panel can be modelled by:

$$e_{SMP}(l) = C_{SMP} \times \left(1 - rc_{SMP}(l, \boldsymbol{v}_{SMP})\right), \quad (9)$$

where $rc_{SMP}(l, \boldsymbol{v}_{SMP})$ is the length-dependent probability for fish to be retained by the SMP conditioned it contacts the SMP, and $\boldsymbol{v}_{SMP}$ are the parameters in the model (Fig. 15b). $rc_{SMP}(l, \boldsymbol{v}_{SMP})$ is often described by one of the standard s-shaped size selection models for trawl gears introduced in section 4.1.1: *Logit*, *Probit*, *Gompertz* and *Richards*. C_{SMP} quantifies the fraction of fish entering the selectivity area that contacts the SMP and therefore, is subjected to a size-dependent probability of escaping through it (Fig. 15a). We assumed that the probability of fish coming into contact with the SMP (C_{SMP}) can be modeled by a single length-independent number that ranges between 0.0 and 1.0, with $C_{SMP} = 1.0$ meaning all fish contacted the SMP and attempted to pass through it (9).

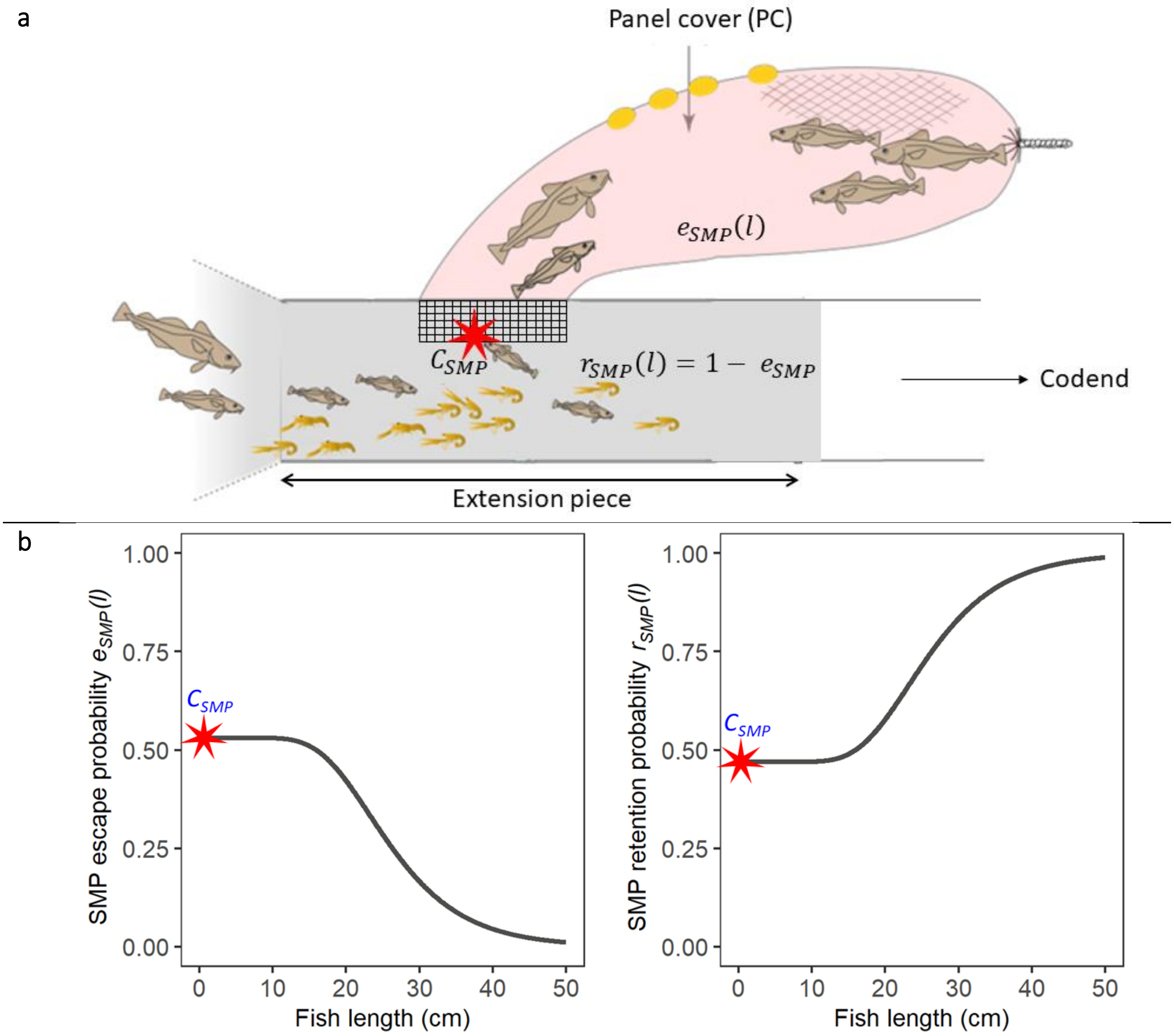


Fig. 15.- (a) Size selection process given at the SMP area. Source: inspired by Santos, (2021). (b) Examples of length-dependent curves describing SMP escape probability and SMP retention probability.

In gears with dual-selection systems, both single and dual-covered methods can be used depending on the aim of the experimental trials. A single-covered method can, for example, be used to obtain selectivity data of one of the devices in the gear, while the other one is blinded. In a gear composed of a SMP and a codend, one single cover over the SMP can be applied while a non-selective, small mesh liner blinds the codend (Fig. 16). This design provides information on the number of fish that escape the SMP (nPC) ending up in the cover, and the number of fish in the non-selective codend (nCL) for each length class l. The SMP escape probability can be estimated by MLE, for which the following expression is minimized, which corresponds to maximizing the likelihood for obtaining the observed experimental data:

$$-\sum_{l}\sum_{j=1}^{m}\left\{\frac{nCL_{lj}}{qCL_j}\times\ln\left(r_{SMP}(l,\boldsymbol{v}_{SMP})\right)+\frac{nPC_{lj}}{qPC_j}\times\ln\left(1.0-r_{SMP}(l,\boldsymbol{v}_{SMP})\right)\right\} \quad (10)$$

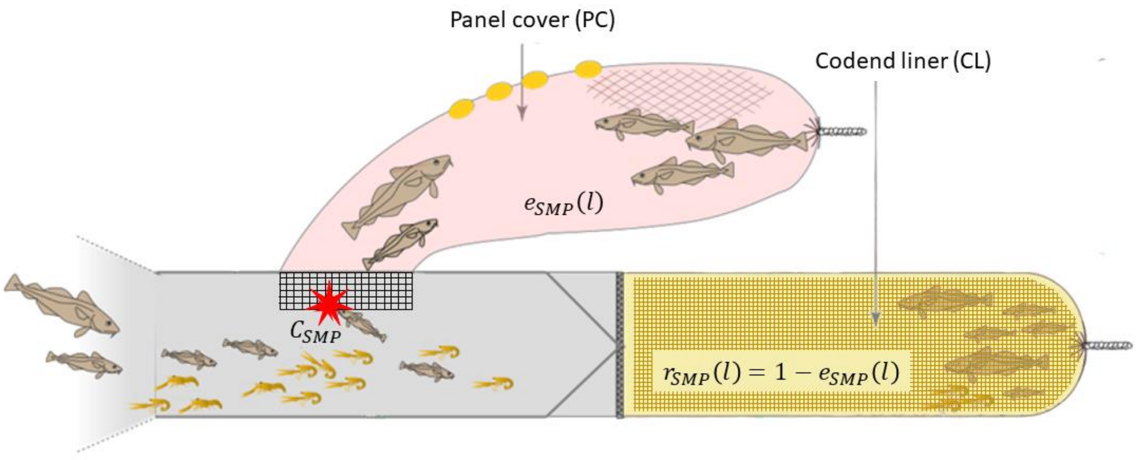


Fig. 16.- SMP + codend setup where a cover (PC) collects the fish escaping through the SMP and the codend is blinded with a liner (CL). Source: inspired by Santos, (2021).

Through the dual-covered method, e.g. one cover over the SMP and one cover over the codend, information related to the performance of two different selectivity devices can be obtained independently and simultaneously (Brčić et al., 2016; Larsen and Isaksen, 1993; Sistiaga et al., 2016, 2010; Zuur et al., 2001) (Fig. 17a). By means of this method, partial and combined assessment of the selectivity properties of both the SMP and the codend, or other additional selection devices can be carried out (Sistiaga et al., 2010; Wileman et al., 1996).

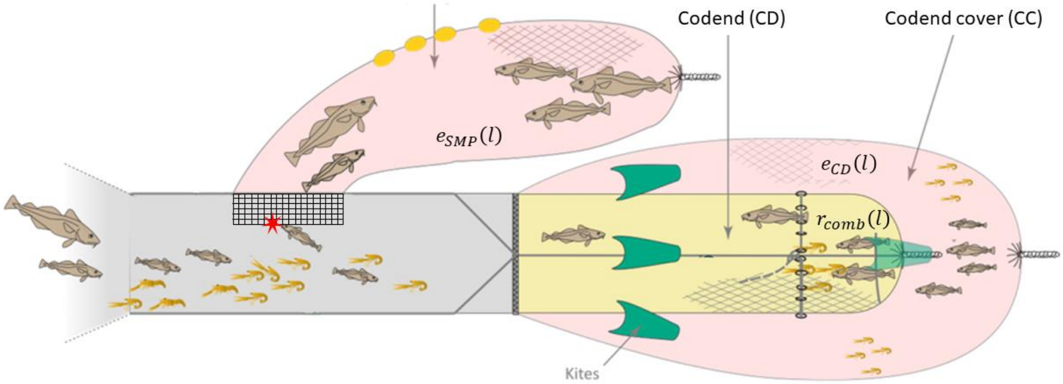
In the dual-covered method fish can be retained in three different compartments (Fig. 17a). Thus, the data includes the number of fish in the SMP cover (nPC), in the codend cover (nCC) and in the codend (nCD). Assuming that the fate of each fish is independent of each other, the number of individuals of a specific length class l present in the three compartments can be modeled using a multinomial distribution with length-dependent probabilities for escape through the SMP ($e_{SMP}(l)$) and through the codend ($e_{CD}(l)$), and retention in the codend ($r_{comb}(l)$). For the fish contacting the SMP and attempting to escape through it, it is assumed that the length-dependent escape probability can be described by an s-shaped model with the parameters $L50_{SMP}$ and SR_{SMP} (9). For the fish entering the codend, it is assumed that the length-dependent retention probability (rc_{CD}), conditioned entering the codend, can be described by a s-shaped model with its corresponding parameters (Fig. 17b), which in terms of escape probability leads to:

$$e_{CD}(l) = (1.0 - e_{SMP}(l)) \times (1 - rc_{CD}(l, \boldsymbol{v})) \qquad (11)$$

Finally, the combined SMP and codend size selectivity leads to:

$$r_{comb}(l) = 1.0 - e_{SMP}(l) - e_{CD}(l) \qquad (12)$$

a



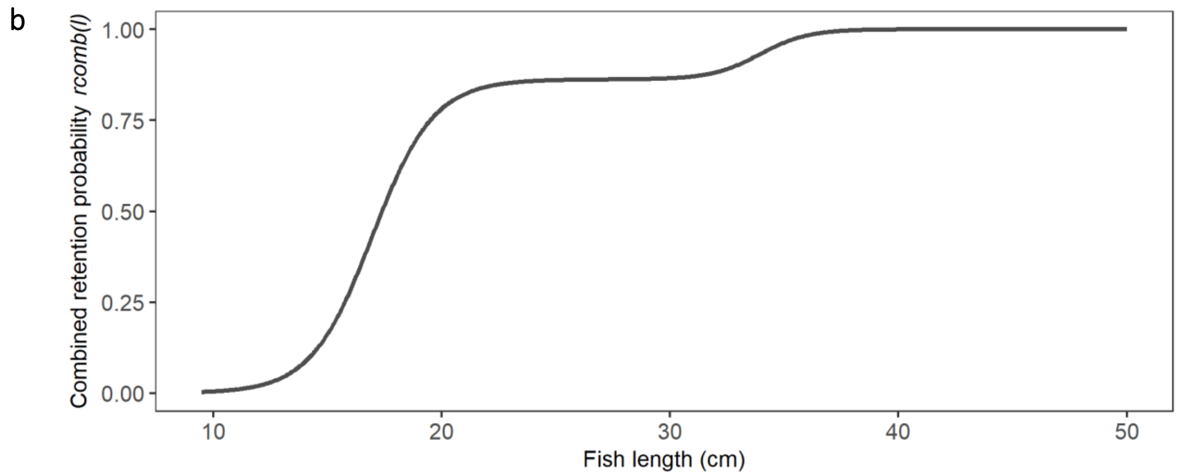


Fig. 17.- (a) SMP + codend setup where a first cover (PC) collects the fish escaping through the SMP and a second cover (CC) collects the fish escaping through the codend meshes (CO). Source: inspired by Santos, (2021). (b) Example of a length-dependent curve describing combined gear retention probability where a dual-selection process can be observed.

The data is summed over hauls and the parameters estimated by maximizing the corresponding likelihood function for the assumed model. Thus, the expression is minimized, which is equivalent to maximizing the likelihood for the observed data:

$$-\sum_{l}\sum_{j=1}^{m}\left\{\frac{nCD_{lj}}{qCD_{lj}}\times \ln\left(r_{comb}(l,C_{SMP},\boldsymbol{v}_{SMP},\boldsymbol{v}_{CD})\right)+\frac{nPC_{lj}}{qPC_{lj}}\times \ln\left(e_{SMP}(l,\boldsymbol{v}_{SMP})\right)+\frac{nCC_{lj}}{qCC_{lj}}\times \ln\left(1.0-r_{comb}(l,C_{SMP},\boldsymbol{v}_{SMP},\boldsymbol{v}_{CD})\right)\right\} \quad (13)$$

Through the single-covered method data, the overall gear size selectivity potential can also be obtained by attaching one single cover over both selection devices (Fig. 18). In this case, the individual contribution of the devices can also be estimated but with less precision (Sistiaga et al., 2010).

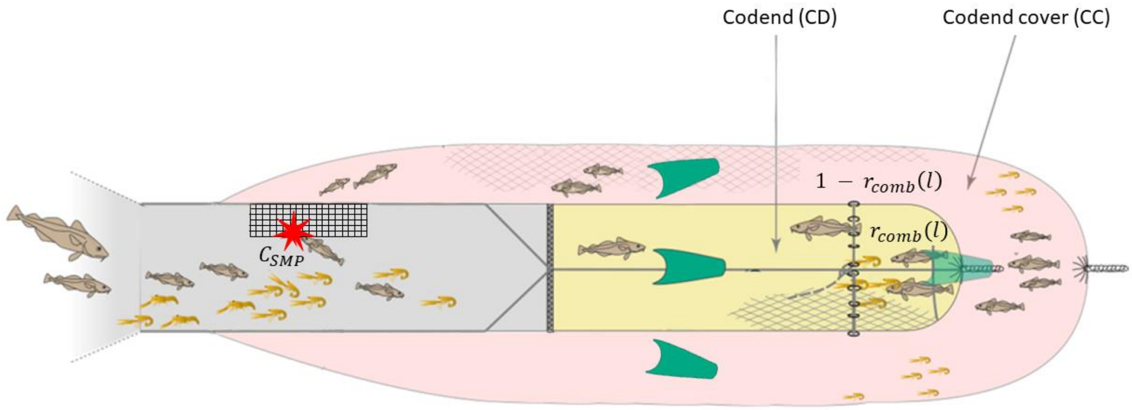


Fig. 18.- Single-covered method in a dual-selection system; fish species escaping through the SMP and codend meses (CD) are collected in the cover (CC). Source: inspired by Santos, (2021).

For this purpose, the expression (14) is minimized, which corresponds to maximizing the likelihood for obtaining the observed experimental data:

$$-\sum_{l}\sum_{j=1}^{m}\left\{\frac{nCD_{lj}}{qCD_{j}}\times \ln\left(r_{comb}(l,C_{SMP},\boldsymbol{v}_{SMP},\boldsymbol{v}_{CD})\right)+\frac{nCC_{lj}}{qCC_{j}}\times \ln\left(1.0-r_{comb}(l,C_{SMP},\boldsymbol{v}_{SMP},\boldsymbol{v}_{CD})\right)\right\} \quad (14)$$

4.1.3. Model evaluation and estimation of uncertainty for size selectivity data

When applying models to describe size selectivity data, a critical inspection of the model fit is necessary to ensure that the models applied can describe the experimental data sufficiently well. The ability of a model to describe the experimental data can be evaluated based on the *p-value*, which quantifies the probability of obtaining by coincidence at least as big a discrepancy between the experimental data and the model as observed, assuming that the model is correct. The *p-value*, which is calculated based on the model deviance and the degrees of freedom, should be >0.05. This would imply more than 5% probability for that the observed deviation between data and modeled size selection curve could well be coincidental. If the fit statistics show that $p<0.05$ and/or that deviances are greater than, approximately, two times the degrees of freedom, then further inspection is needed to determine if the discrepancy can be due to overdispersion in the data or the inability of the model to adequately describe the data (McCullagh and Nelder, 1989). Then, to identify the best model for each species and dataset, the procedure of inspecting goodness of fit is followed by selecting the model with the lowest Akaike Information Criterion (AIC) value (Akaike, 1974). AIC uses the deviation between the fitted model and the experimental data, in terms of loglikelihood expressions 7, 8, 10, 13 and 14, depending on the case, and penalizes for model complexity in the score by the number of parameters in the model.

When pooling haul data, e.g., expressions 7, 8, 10, 13, 14, a double bootstrap method that accounts for both within-haul and between-haul variation (Fryer, 1991) is often used to provide uncertainty estimates around the mean selection parameters and selection curves (Herrmann et al., 2012; Millar, 1993). The uncertainty estimates are most often given as Efron percentile 95% confidence intervals (CIs; Efron, 1982). The double bootstrap method accounts for uncertainty due to between-haul variation by selecting m hauls with replacement from the m hauls available during each bootstrap repetition. Within each resampled haul, the data for each length class are resampled in an inner bootstrap with replacement to account for the uncertainty in the haul (within-haul variation) due to a finite number of fish being caught and length measured in the haul. When applicable, to account for the additional uncertainty introduced by the subsampling, the inner resampling of the data in each length class is performed prior to the raising of the data with the sampling factor (Eigaard et al., 2012).

4.1.4. Delta selectivity

To investigate how different gear designs perform compared to each other, delta selectivity can be estimated. Delta selectivity is estimated by subtracting the predicted, species-specific, retention probability of a gear design with an implemented treatment to the retention probability of a baseline gear design (Herrmann et al., 2018; Larsen et al., 2018).

To infer the difference in retention probability, the following generic delta expression $\Delta r(l)$ is applied:

$$\Delta r(l) = r_{treatment}(l) - r_{baseline}(l) \qquad (15)$$

where $r_{treatment}(l)$ is the retention probability of a specific gear with a treatment, and $r_{baseline}(l)$ is the retention probability value of the baseline gear design.

Efron 95% CIs for $\Delta r(l)$ can also be obtained based on the two bootstrap populations of results for both $r_{treatment}(l)$ and $r_{baseline}(l)$. As the bootstrap resampling is random and independent for the two groups of results, a new bootstrap population of results for $\Delta r(l)$ can be created as shown in Herrmann et al., (2012) and Larsen et al., (2018):

$$\Delta r(l)_i = r_{treatment}(l)_i - r_{baseline}(l)_i \quad i \in [1 \ldots 1000] \qquad (16)$$

where i denotes the bootstrap repetition index. Significant differences in size selection between gears are obtained if the 95% CIs for the delta curves have length classes that do not overlap 0.0 (Fig. 19).

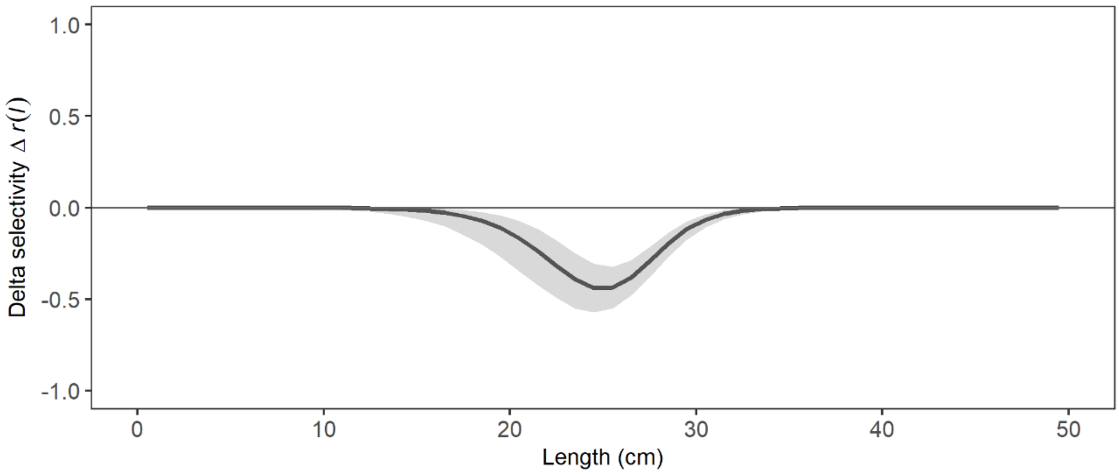


Fig. 19.- Example of a delta curve that shows the difference in the length-dependent retention probability between two gear designs. A significant lower retention probability is observed for individuals between 18 and 32 cm length, approximately with the treatment gear compared to the baseline gear.

4.2. Exploitation pattern indicators

The size selectivity estimates obtained with the models described in section 4.1.1 and 4.1.2 are assumed independent of the size structure of the exploited populations. Therefore, to quantify the benefits of applying a given selection device on the population size structures of the species being fished, the so-called exploitation pattern indicators can be used. These indicators supplement the evaluation of size selective properties with properties that are directly dependent on a population's size structure (Brčić et al., 2016; Sala et al., 2016; Wienbeck et al., 2014). Their simplicity and intuitive meaning make of indicators an useful tool to communicate experimental results with managers and fishing industry. Exploitation pattern indicators often estimate the average percentage of individuals retained below and above the MCRS and the average percentage of individuals retained below MCRS regarding the population that entered the gear:

$$nP^{-} = 100 \times \frac{\sum_{l<MCRS}\{r_{comb}(l) \times nPop_l\}}{\sum_{l<MCRS}\{nPop_l\}}$$

$$nP^{+} = 100 \times \frac{\sum_{l>MCRS}\{r_{comb}(l) \times nPop_l\}}{\sum_{l>MCRS}\{nPop_l\}} \qquad (17)$$

$$nDiscard = 100 \times \frac{\sum_{l<MCRS}\{r_{comb}(l) \times nPop_l\}}{\sum_{l}\{r_{comb}(l) \times nPop_l\}}$$

where $nPop_l$ is the number of fish in the population that entered the gear and is subjected to a size selection process. Exploitation pattern indicators in (17) are estimated for each species independently. The indicator nP^{-} is the percentage of individuals below the species' MRCS retained; nP^{+} is the percentage of individuals above the species' MCRS retained; and $nDiscard$ quantifies the percentage of individuals below MCRS in the catch.

4.3. Species separation in horizontally divided codends

Collecting experimental data on species separation inside the trawl often involves using a trawl gear with horizontally divided codend, which usually leads to an upper and a lower codend (e.g., Karlsen et al., 2021; Melli et al., 2019, 2018). Thus, depending on the distribution of the fish in the trawl, they can end up in either the upper or lower codend, given they are retained. The separation efficiency $VS(l)$

can be defined as the probability of finding a fish individual of length l in the lower compartment given that it is observed in either the upper or lower codend. For each species and each haul, $VS(l)$ is estimated using the catch data. The expected number of fish of length l caught in lower (nL_l) and upper (nU_l) codends (Fig. 20a) can be directly related to the total number of fish caught n_l and $VS(l)$:

$$nL_l = n_l \times VS(l, \boldsymbol{v}) \qquad (18)$$

$$nU_l = n_l \times (1.0 - VS(l, \boldsymbol{v})) \qquad (19)$$

Therefore, according to the definition above, the expected probability for a fish of length l to be captured in the lower codend, conditioned is captured will be:

$$VS_l = \frac{\frac{nL_{lj}}{qL_{lj}}}{\frac{nL_{lj}}{qL_{lj}} + \frac{nU_{lj}}{qU_{lj}}} \qquad (20)$$

where qL_{lj} and qU_{lj} are the sampling factors in the upper and lower compartments, respectively in haul j. A value of $VS(l)$ above 0.5 implies that in the haul j there is a higher probability of finding an individual of length l in the lower compartment, given an equal probability of entering either compartment (Fig. 20b).

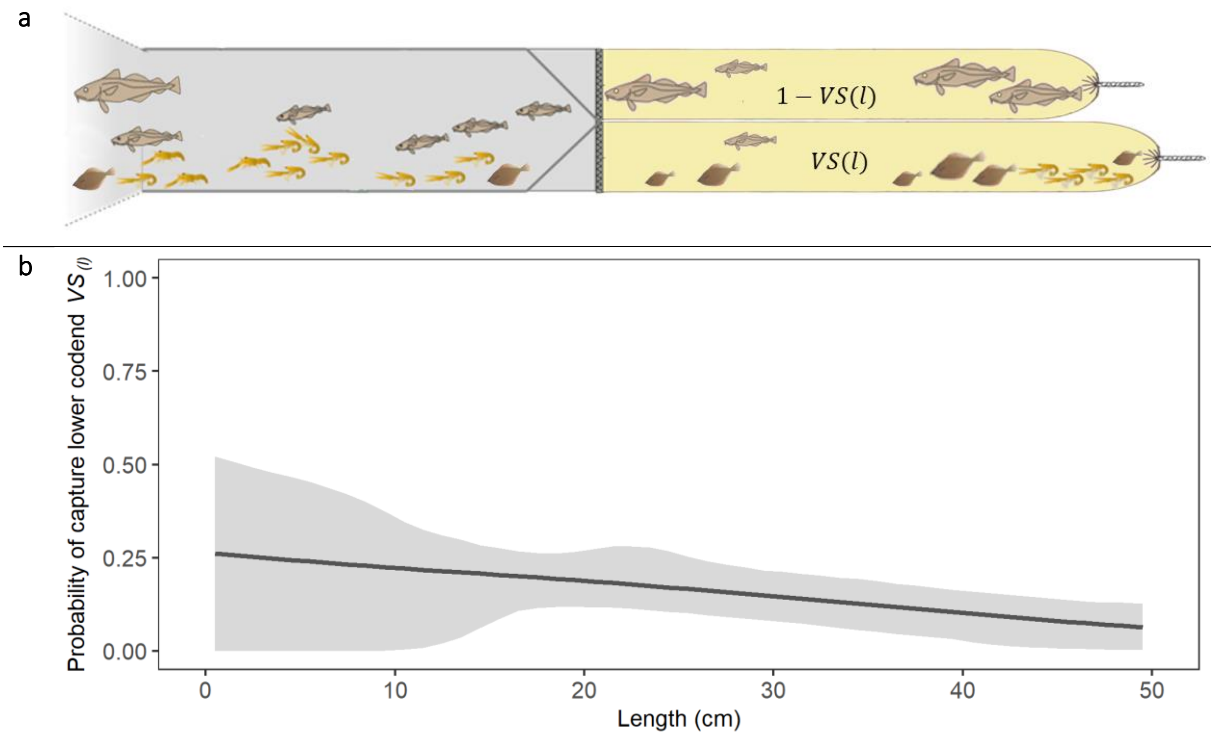


Fig. 20.- (a) Example of vertical separation system applied on a trawl gear. (b) Example of length-dependent probability curve of ending up in the lower codend given captured.

Assuming that the vertical separation summed over hauls is representative of how the vertical separation would perform on average, estimation of the averaged vertical separation is achieved by pooling the data from the different hauls. A parametric model for VS_l is defined by $VS(l, \boldsymbol{v})$, where $\boldsymbol{v}$ is a vector consisting of the parameters of the model. The analysis is therefore reduced to a maximization problem to estimate the values of the parameters in $\boldsymbol{v}$, which makes the observed experimental data averaged over hauls most likely, assuming that the model is able to describe the data sufficiently well. Thus, the expression (21) is minimized with respect to $\boldsymbol{v}$, which is equivalent to maximizing the probability for the observed data:

$$-\sum_{j=1}^{h}\sum_{l}\{nL_{lj} \times ln(VS(l,\boldsymbol{v})) + nU_{lj} \times \ln(1.0 - VS(l,\boldsymbol{v}))\}, \quad (21)$$

where the summations are over length classes l and hauls j. When horizontally divided codend experiments are carried out, the structure of the data collected is the same as in catch comparison experiments. Therefore, an adaptation of this method is used to analyze the data (Karlsen et al., 2021; Krag et al., 2015, 2014a; Melli et al., 2019, 2018). In addition, the model often applied in catch comparison studies is based on polynomials and no structural assumptions about the $VS(l,\boldsymbol{v})$ are taken (Santos, 2021), which provides sufficient flexibility to account for the trends in the experimental data:

$$VS(l,\boldsymbol{v}) = \frac{\exp(f(l,\boldsymbol{v}))}{1.0 + exp(f(l,\boldsymbol{v}))}, \quad (22)$$

where the function $f(l,\boldsymbol{v})$ is a polynomial of, for example, order 4 with parameters $\boldsymbol{v} = (v_0, v_1, v_2, v_3, v_4)$ to model the potential length dependency for the probability of being retained in the lower compartment, conditioned capture. $f(l,\boldsymbol{v})$ is used in the following form:

$$f(l,\boldsymbol{v}) = \sum_{i=0}^{4} v_i \times \left(\frac{l}{100}\right)^i = v_0 + v_1 \times \frac{l}{100} + v_2 \times \frac{l^2}{100^2} + \cdots + v_4 \times \frac{l^4}{100^4} \quad (23)$$

Leaving out one or more of the parameters v_0 to v_4 leads to 31 additional models that can also be considered as potential models for $f(l,\boldsymbol{v})$. Among these models, estimations of the $VS(l,\boldsymbol{v})$ are carried out using multimodel inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017).

The competing models are then ranked and weighed in the estimation according to their $AICc$ values (Burnham and Anderson 2002). The $AICc$ is calculated as the AIC (Akaike, 1974), but it includes a correction for finite sample sizes in the data. Models that result in $AICc$ values within +10 of the value of the model with lowest $AICc$ value ($AICc_{min}$) are considered for the estimation of $VS(l,\boldsymbol{v})$ following the procedure described in Katsanevakis, (2006) and in Herrmann et al., (2017). The result of this multi-model averaging is called combined model, and is calculated by:

$$VS(l) = \sum_i w_i \times VS(l,\boldsymbol{v}_i), \quad (24)$$

with

$$w_i = \frac{\exp(0.5 \times (AICc_i - AICc_{min})}{\sum_i \exp(0.5 \times (AICc_j - AICc_{min}))} \quad (25)$$

The ability of the combined model to describe the experimental data is based on the *p*-value, which is calculated based on the model deviance and degrees of freedom (Herrmann et al., 2017; Wileman et al., 1996). Thus, suitable fit statistics for the combined model to describe the experimental data sufficiently well should include a p>0.05. Similar to covered-codend data, double bootstrapping method (1000 bootstrap repetitions) can be used to estimate the 95% CIs of the length-dependent probability curve, following the description in Melli et al., (2018).

Chapter 5. Simulation work based on the FISHSELECT methodology

Experimental work to test trawl gears under commercial fishing conditions is expensive and time-consuming. Alternatively, computer simulation can be a cost-effective and valuable tool to make predictions and identify gear modifications with potential to improve size selectivity in a specific fishery. This chapter aims at describing the FISHSELECT methodology (Herrmann et al., 2009), a framework of tools, methods, and software developed to determine whether a fish can penetrate a certain mesh by comparing the morphology of fish and the geometry of meshes of interest.

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 (Frandsen et al., 2010b; Gökçe et al., 2015; Herrmann et al., 2016a, 2013b, 2012; Krag et al., 2014b, 2011; Sistiaga et al., 2020, 2011; Tokaç et al., 2018, 2016). The results obtained with the application of FISHSELECT have proven to be coherent with the results obtained from experimental sea trials (e.g., Herrmann et al., 2013b, 2012; Sistiaga et al., 2011). In addition, the results obtained with this method can help to interpret results from experimental sea trials.

5.1. Prediction of size selectivity

To predict the size selectivity potential of different gears using FISHSELECT, the fish cross section (CS) shape of each of the species of interest needs to be measured and their compression potential estimated. For this purpose, both the FISHSELECT software and specific measuring equipment are needed.

5.1.1. Measurement of fish shape

In FISHSELECT, the morphological characteristics of individual fish are defined by the size and shape of CSs of its body at different points. When the morphological data for a certain species are collected, it is important to cover as wide size range as possible because not all body parts grow proportionally with size. For each fish, length (in mm) and weight (in g) are registered, and the size and shape at different CSs measured using a mechanical sensing tool called the Morphometer (see Herrmann et al., 2009). The Morphometer consists of an aluminum frame and measuring sticks that can be moved horizontally and fixed at the desired position (Fig. 21ab). The numbers and positions of the CSs registered are different for each fish species and are established based on the positions likely to determine size selection. The shapes registered on the Morphometer for each CS are converted to a digital image using a flatbed scanner and the image is finally digitized using the image analysis tools implemented in the FISHSELECT software (Herrmann et al., 2009) (Fig. 21cd).

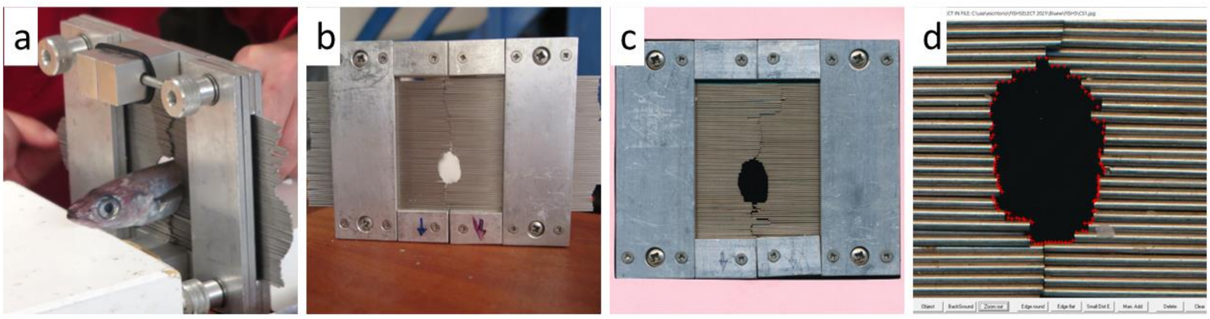


Fig. 21.- (a – b) Illustration of the use of a morphometer on blue whiting and (c – d) subsequent image analysis implemented in the FISHSELECT software.

Once the CSs for each fish have been digitized, they are modeled by different geometrical shapes in FISHSELECT software tool (Herrmann et al., 2009; Tokaç et al., 2016) (Fig. 22). To quantify the ability of a particular shape to describe the CS of a fish the mean R^2 and mean AIC values are estimated. R^2 has a value range from 0.0 to 1.0, quantifies the ratio of total variance in the data that is explained by the model and is used to evaluate the ability of the different models to describe the CS shapes. A value close to 1.0 implies that the model describes the data well. Everything else being equal, the model resulting in the highest R^2 is preferable. However, a more flexible model requiring a larger number of parameters to define the shape would, in general, be expected to produce a higher R^2 value (Sistiaga et al., 2011). To be able to assess whether the gain in the modeling of the shape is worth the cost of increasing the number of parameters in the model, the mean AIC value can be used. Following the estimation of the AIC values, all models considered are ranked and the model with the lowest AIC value chosen. The completion of this step provides the ability to produce virtual populations defined by the relationships between fish length and the CS shape parameters, including their variability (Herrmann et al., 2009).

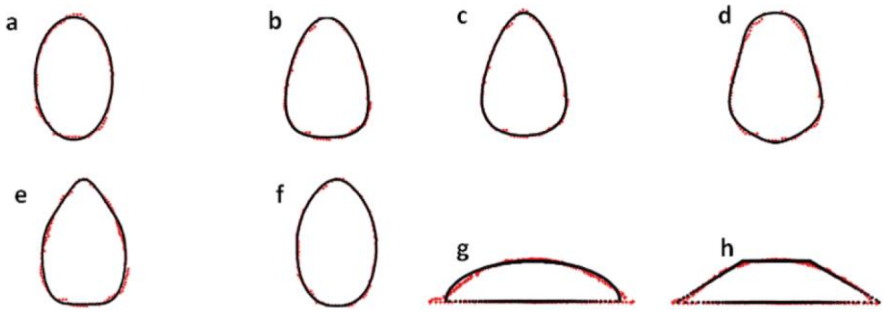


Fig. 22.- Illustration of some of the parametric shapes available in FISHSELECT: Shapes like (a)–(f) are typically used for roundfish while (g)–(h) are normally used on flatfish species. Source: Grimaldo et al., (2016)

5.1.2. Estimation of fish compression

Fish can be compressed both dorsoventrally and laterally, which may increase its chances to pass through a certain mesh. To assess the compression potential of a species at each CS, “fall-through” experiments are conducted. Fall-through experiments determine if a fish can physically pass through a certain rigid shape. Specifically, each fish needs to be allowed to fall through meshes perforated in rigid nylon templates by the force of gravity alone (Herrmann et al., 2009) (Fig. 23). The shapes tested normally include diamonds, hexagons, and rectangles; however, there are no restrictions to the shapes one can test and use in FISHSELECT.

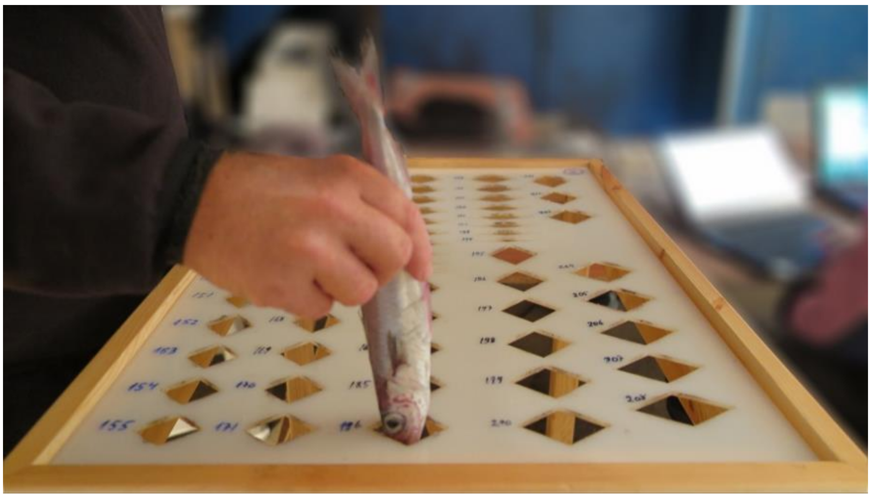


Fig. 23.- Illustration of the fall-through procedure on blue whiting. Each interchangeable plate contains a number of different mesh sizes and shapes where each fish is tested. All fish included in the study need to be tested in all meshes.

To determine the optimal compression level at the different CSs and establish a penetration model for each species, size selection simulations of the fish in the virtual population need to be conducted. The size selectivity simulations include all the meshes in the rigid templates and different symmetrical and/or asymmetrical fish CS compression levels. For example, a symmetrical compression of 10% for a CS shape would apply a dorsal and ventral compression of 10% to the CS in the simulations. An asymmetric compression model on the other hand applies different dorsal, lateral and ventral compression levels to each CS (Herrmann et al., 2012). The output of the size selection simulations consists of "Yes/No" results for each fish, mesh and compression level included in the simulations, which answers whether the fish passes through the mesh in each case. The results for each compression model tested are then compared to the fall-through results obtained during the data collection phase (Fig. 24). Finally, the penetration model with the highest Degree of Agreement value (DA) with the fall-through results is selected for predictions in FISHSELECT. DA varies between 0% and 100% and should be close to 100% for the penetration model selected to be acceptable (see Herrmann et al., (2009) and Sistiaga et al., (2011) for the mathematical expression and further information about DA).

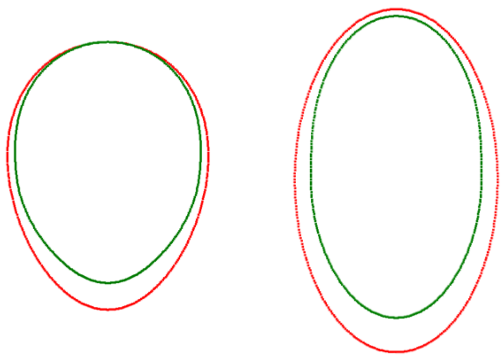


Fig. 24.- Shape of the optimal penetration model (green) overlapped on the original shape modeled from the morphometer (red) for blue whiting.

5.1.3. Predictions based on penetration model and virtual population

Once the penetration model for the species investigated is defined and a virtual population with the CS shapes for each fish individual in it is created, size selection predictions for an unlimited number of mesh shapes can be made for the specific species.

The output from the prediction simulations in FISHSELECT has the same structure as covered-codend data (Wileman et al., 1996), where each fish that passed through the mesh in the simulation is considered to end up in the cover, while the fish that did not is considered to be retained in the codend. A *Logit* size selection model (1) is fitted to each covered-codend dataset to obtain a size selectivity curve. Based on the data obtained for all meshes included in the prediction simulations, design guides for gear size selectivity can be created. For a specific type of mesh in a codend for example, design guides quantify the effect of mesh size and OA on L50 in terms of isocurves (curves with equal L50) (Fig. 25) (Herrmann et al., 2009).

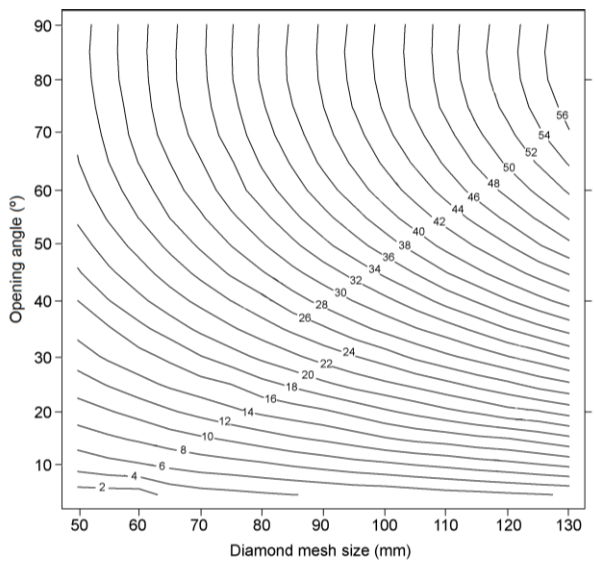


Fig. 25.- Example of design guide for diamond meshes showing L50 isocurves as a function of mesh size and mesh OA.

5.2. Understanding experimental size selectivity results

The FISHSELECT methodology enables reproducing experimental size selection curves considering the potential contribution of different meshes, for example, meshes with different OAs (Herrmann et al., 2016a) or different shapes projected from the perspective of the fish when it contacts the mesh.

In the first step for the experimental size selection curve reproduction, the length of fish with retention likelihood between 5% and 95% (L05 – L95), in steps of 5%, are calculated as reference points in the experimental curve by numerical methods implemented in the SELNET software (Herrmann et al., 2013b). Once the L05 – L95 are obtained, the experimental size selection curve can be reproduced based on different combinations of contributions from the different OAs by simulation. The contributions are expressed in terms of weight factors that sum up 100% and are estimated using the approach described by Herrmann et al., (2016a, 2013b). The application of this method results in a list of relative contributions of the different OAs that best can reproduce the experimental size selection curve.

The application of this approach can be especially useful to understand the mechanisms behind size selection processes in fishing gears (e.g., Frandsen et al., 2010b; Herrmann et al., 2016a). For example, historical grid selectivity data for Greenland halibut (*Reinhardtius hippoglossoides*) shows considerably lower L50 values than those expected from the morphology of the fish (Herrmann et al., 2013b). Using FISHSELECT, Herrmann et al., (2013b) explained that those differences could be caused by the ability of fish to contact the grid with a more or less optimal angle of attack and identified the angles from which the fish most frequently tried to pass through.

In the bottom trawl gear used in the Bay of Biscay, fall-through experiments on hake have demonstrated that the SMP size selection potential is higher than that achieved experimentally i.e., individuals that should be able to escape considering their size and morphology, do not always do so (e.g., Alzorriz et al., 2016; Herrmann et al., 2009; O'Neill et al., 2006; Santos et al., 2016). To date, the reasons behind this mismatch is not known and the FISHSELECT methodology may be a useful tool to shed light on the mechanisms determining SMP size selection for this and other species.

Chapter 6. Research questions

Based on the objectives described in Chapter 2, the review on the potential ways to improve gear size selectivity made in Chapter 3, the description of the approaches used to assess size selectivity made in Chapter 4, and the description of a size selectivity simulation tool to make predictions based on fish morphology made in Chapter 5, the specific research questions for this thesis are:

1. Can the release efficiency of the SMP used in the Bay of Biscay be improved by means of mechanical and visual stimulators?
2. Can the release efficiency of the SMP used in the Bay of Biscay be improved changing its size and/or position?
3. Can we understand SMP and codend size selectivity in the demersal trawl fishery in the Bay of Biscay based on fish morphology and behavior?
4. Can alternative combinations of SMP and codend designs improve the current exploitation patterns based on the gear used in the Bay of Biscay bottom trawl fishery?
5. Is it possible to develop graphics to systematically illustrate the effect of multiple gear changes on selectivity and exploitation patterns?
6. Can differences in species behavior be utilized to separate species in a vertically divided codend in the Bay of Biscay demersal trawl fishery?
7. Does a codend with shortened lastridge ropes provide optimal escape opportunities for different fish species relevant for the Bay of Biscay demersal trawl fishery?

Chapter 7. Trawl selectivity studies in the Bay of Biscay demersal trawl fishery

In this chapter, trawl selectivity studies conducted in the Bay of Biscay demersal trawl fishery are presented. All of them are focused on relevant species of the fishery, i.e., hake, horse mackerel, blue whiting, and to lesser extent mackerel, megrim and anglerfish. Papers I and II present results of modifications applied to the SMP area aiming at improving fish-SMP contact probability and subsequent release efficiency of undersized fish. Specifically, Paper I tests both mechanical and visual stimulators to improve SMP release efficiency. Paper II tests both visual stimulators as well as changes in size and position of the SMP to increase the fraction of fish contacting it. Paper III establishes a framework for predicting the size selection of blue whiting through different SMPs and diamond mesh codends based on the morphological characteristics of this species. Paper IV aims at identifying which SMP and codend design combination leads to the best exploitation patterns in this fishery and uses graphic tools to systematically explore, evaluate and illustrate the effect of the different gear designs. Paper V accounts for that the Basque bottom trawl fishery includes many target and bycatch species with distinct behaviors and therefore, aims at separating species in different codends where different selective processes can then be applied. Finally, in Paper VI, a short LR codend is tested as a potential alternative to improve size selectivity in the Bay of Biscay demersal trawl fishery.

7.1. SMP modifications to improve fish contact probability (Paper I and II)

Papers I and II address sub-objective 1 in Chapter 2 and Research Questions 1 and 2 in Chapter 6. In Papers I and II, different potential stimulators and modifications in SMP size and position were tested to improve fish-SMP contact probability. Selectivity experiments using mechanical and visual stimulators that aimed at influencing fish behavior were presented. In paper I inclined ropes attached in the SMP area as well as those ropes together with floats were tested to mechanically stimulate fish contacting the SMP meshes. Besides, the effect of visual stimulators based on blue LED lights attached on the SMP were tested and compared to a baseline gear design with no stimulation (Fig. 26). In Paper II the effect of attaching white LED lights over the SMP compared to attaching them in front of it was investigated. Also, the effect of increasing SMP size compared to the effect of maintaining standard sized SMP located at the lower panel of the extension piece was tested (Fig. 27).

All these configurations were tested onboard a scientific fishing vessel in ICES area 8bc, and the experiments were conducted using dual-covered method. During the sea trials reported in Paper I (June 2017), selectivity data for hake, horse mackerel and blue whiting were collected, whereas data for hake and blue whiting was collected during sea trial in Paper II (June 2018). The selectivity data for these species was analyzed based on the parametric models introduced in Section 4.1, which provided estimates for the selectivity parameters (L50 and SR), the SMP contact probability parameter (C_{SMP}) and individual and combined size selection curves of SMP and diamond mesh codend. In addition, the selectivity results in Paper I were supplemented with exploitation pattern indicators so that the performance of the SMP and the consequences of using such gears were quantified based on the specific population fished.

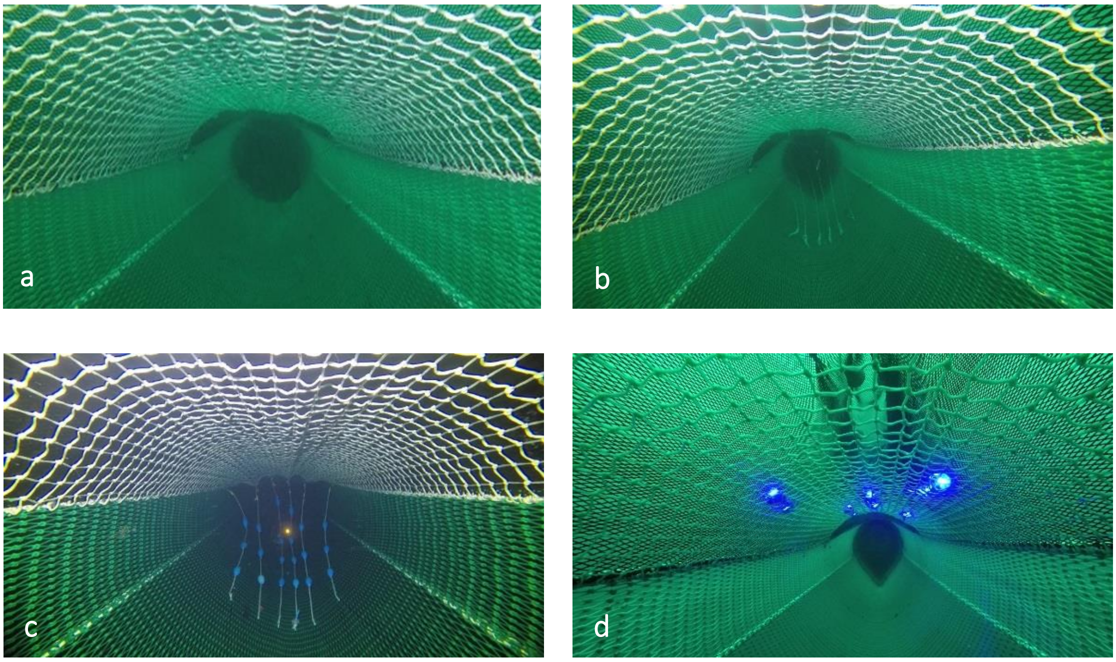


Fig. 26.- Different configurations tested in paper I: (a) no-stimulation; (b) stimulation by ropes; (c) stimulation by floats; (d) LED light-based stimulation.

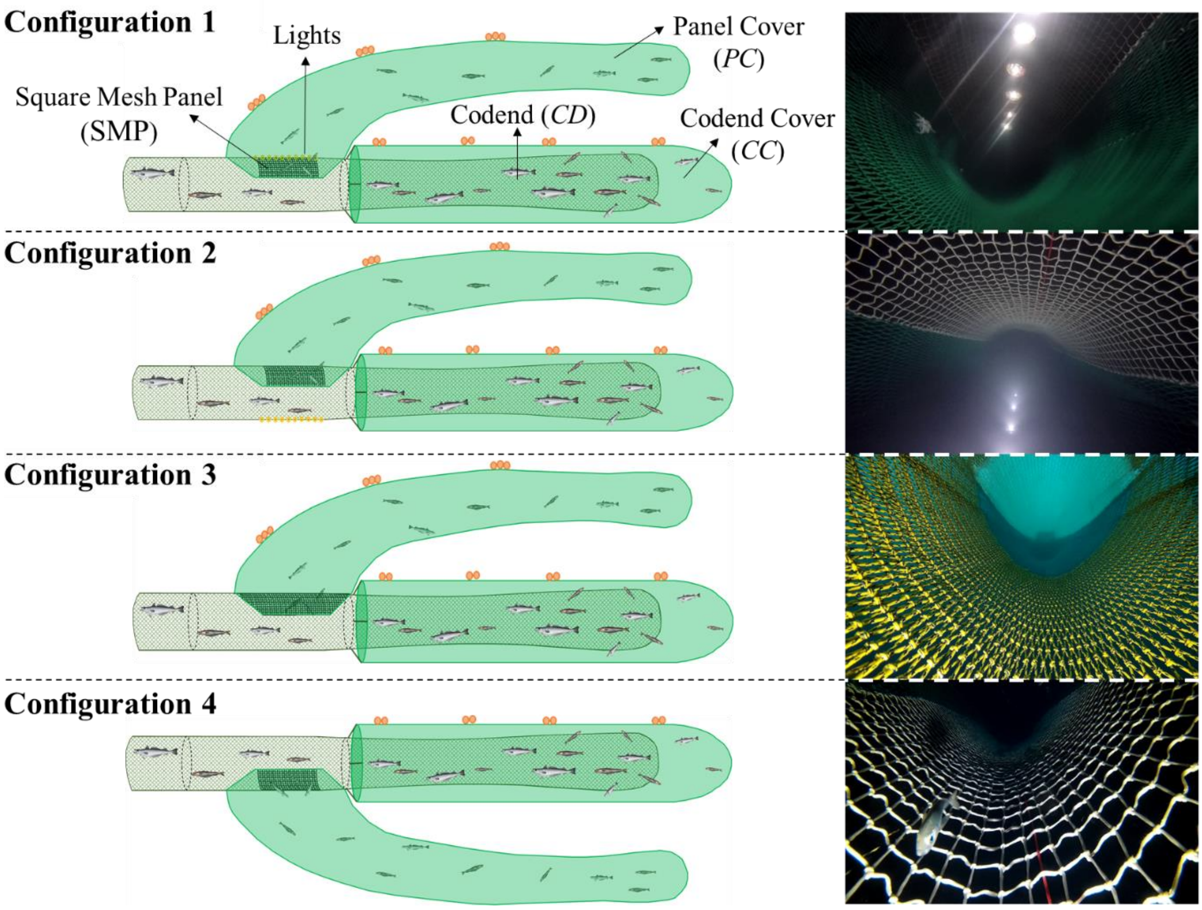


Fig. 27.- Different configurations tested in Paper II: Conf. 1: a standard SMP inserted in the upper panel with 10 white LED lights placed longitudinally over it. Conf. 2: the same as Conf. 1, but with 10 white LED lights placed longitudinally in the lower panel in front of the SMP. Conf. 3: a large SMP inserted in the upper panel. Conf. 4: a standard SMP inserted in the lower panel. Standard SMP: mesh size (M), 82.7 mm; area (A), 2.64 m2. Large SMP: (M), 80.0 mm; (A), 4.77 m2.

Paper I showed that the stimulators used had variable effects on the species tested. The contact probability of hake with the SMP remained around 1% for all configurations tested. Underwater recordings showed that hake did not react to the stimulators used and in line with results reported by Alzorriz et al., (2016), it mainly entered the trawl close to the lower panel and drifted back towards the codend. In addition, between 38% and 46% of the undersized hake that entered the gear was retained in the codend. Results in Paper II showed that the contact probability of hake remained low when white LED lights were attached over or in front of the SMP. However, when the position of the SMP was changed to the lower panel of the extension piece, contact probability of hake with the SMP significantly increased to 33% (CI: 10–94%).

Blue whiting showed higher contact probability (between 20% and 27%) and subsequent release efficiency through the SMP than hake for the baseline and floats configurations (Paper I). When ropes with floats were attached in the SMP area, the contact probability of blue whiting improved by 30% compared to the baseline configuration. Opposite, the release efficiency of blue whiting significantly decreased when the blue LED lights were used compared to the baseline configuration. Underwater recordings showed an active swimming behavior of this species, which could have resulted in higher physical contact with the SMP. In Paper II, no significant differences on the SMP contact probability were reported between LED lights attached over or in front of the SMP. However, the contact probability of blue whiting increased to 45% (CI: 26–66%) when the large SMP was inserted in the upper panel compared to the standard SMP located at the lower panel.

Finally, horse mackerel, which was only caught in sufficient numbers during the sea trials presented in Paper I, showed no significant differences in escape probability through the SMP with any of the stimulators tested. However, they showed 40% less overall retention for a specific length range when the design with ropes was used. Codend L50 value with this configuration was significantly lower than with baseline design, which could cause the differences in the overall retention probability of horse mackerel. Underwater recordings showed that horse mackerel tried to avoid contact with the stimulators based on ropes and floats by swimming in front of them until reaching exhaustion and drifting towards the codend.

Thus, underwater recordings revealed clear behavioral differences between species that could be exploited to improve the size selection performance of SMPs in future research (e.g., Papers II – V). In addition, results in Paper II showed that taking advantage of fish behavior in the aft part of the trawl may be a practical way to improve SMP contact probability. Hake, which was identified to enter the trawl close to the lower panel, showed significant higher contact probability with the SMP when it was located at the lower panel of the extension piece compared to the large SMP located at the upper panel. Blue whiting, which showed to swim actively in the extension piece of the trawl, had significantly higher contact probability with the large SMP at the upper panel compared to the standard SMP at the bottom panel of the extension piece.

7.2. Understanding size selectivity in a SMP and codend configuration based on fish morphology and behavior (Paper III)

Theoretically estimated SMP size selection based on fish morphology has shown not to match with the experimentally obtained size selection results for some species in the Bay of Biscay (Alzorriz et al., 2016). Alzorriz et al., (2016) showed that the expected L50 values for hake, pouting and red mullet making contact with a 100 mm SMP should be 51.05 cm (CI: 50.50–52.03 cm), 26.10 cm (CI: 25.58–26.50 cm) and 31.49 cm (CI: 31.02–31.52 cm), respectively. However, the same study showed that the experimentally obtained values were: 37.56 cm (CI: 25.50–37.62 cm), 13.05 cm (CI: 13.05–27.52 cm) and 20.52 (CI: 16.01–20.56 cm), respectively. Additionally, the results from these comparisons showed that the experimental size selection curves were less steep than expected, i.e., higher SR value. Santos et al., (2016) speculated that such differences between the experimental and the theoretical estimates could be related to the contact mode of fish with the meshes in the gear. Paper III in this thesis investigated the size selection process of blue whiting through SMP and codend meshes based on fish morphology and behavior. The aim with the paper was to address sub-objective 2 and 3 in Chapter 2 and Research Question 3 in Chapter 6, and to fill the existing knowledge gap regarding the mechanisms affecting SMP size selectivity. The study established a framework that allows making accurate predictions of the size selection of blue whiting through different SMPs and diamond mesh codends. Blue whiting had the highest contact probability with the SMP among the species investigated in Papers I and II. In paper III it was hypothesized that its size selection through SMP is determined by different fish contact angles with SMP meshes (Fig. 28), i.e., for a specific mesh size, the closer the contact angle gets to 90º, the larger the projection of the mesh from the fish's perspective and, consequently, the higher the probability for that a fish can pass/squeeze itself through that specific mesh. In addition, assuming that once in the codend fish gets multiple attempts to escape, it was hypothesized that codend size selection is determined by the different codend mesh OAs.

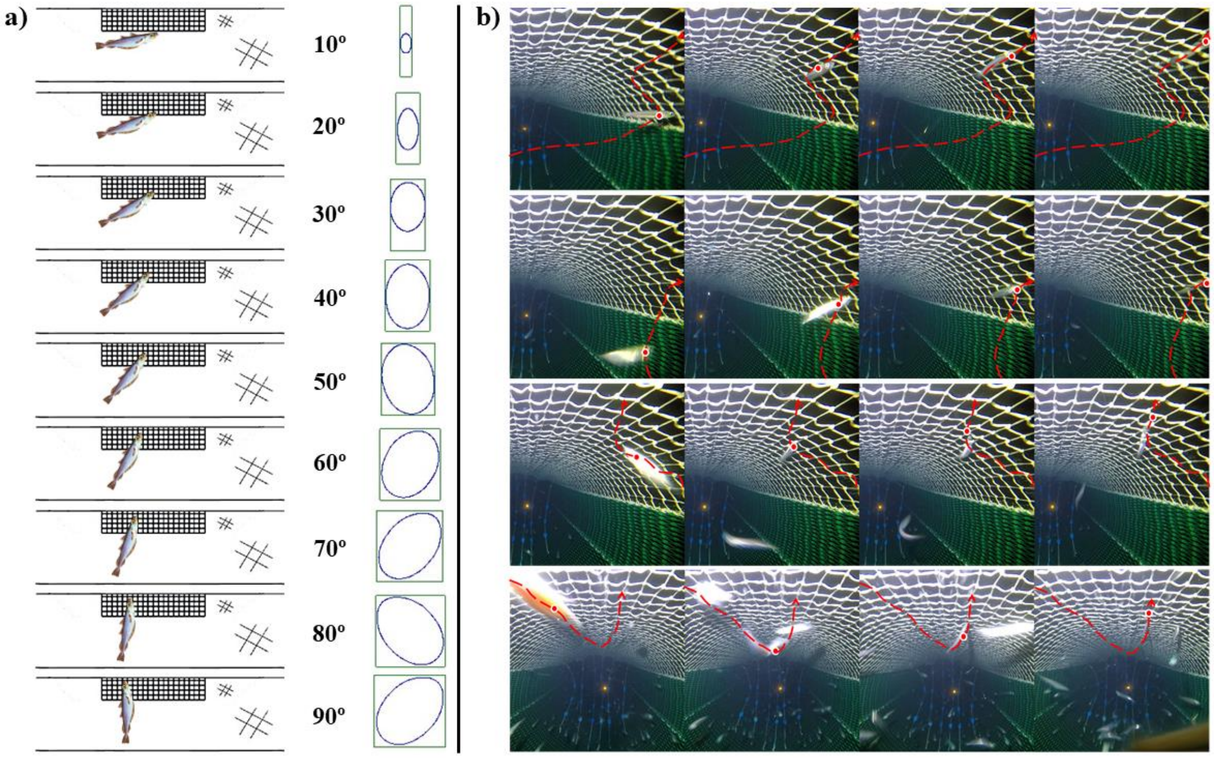


Fig. 28.- (a) Different CAs (ranging from 10º to 90º) for blue whiting attempting to escape through SMP meshes. The column to the right for each of the angles shows the shape of the projected mesh for the different CAs (green rectangle) and the cross-section of the largest blue whiting that would pass through it (blue circle). (b) Underwater recordings from experimental trials (Paper I) showing fish trajectory (red arrow) for each escape attempt with different CAs through an SMP.

The predictive framework proposed involved a three-step approach. In the first step, CS morphology of blue whiting and its compression potential was modeled using FISHSELECT. The second step consisted of testing whether the experimental selectivity of blue whiting through the SMP, the codend, and the combination of both could be explained by the morphology models developed and different SMP contact angles (Fig. 28) and codend mesh OAs. Once the models were validated, the third step consisted of making size selectivity predictions for different combinations of SMP and diamond mesh codends.

The results showed that the simulated size selectivity based on contact angles for the SMP and on OAs for the diamond mesh codend can explain the experimentally obtained size selectivity data. Thus, it was demonstrated that SMP size selectivity can be explained by the contact angle of the fish with respect to the SMP when trying to escape through it. These results enabled making reliable size selection predictions of multiple combinations of SMP and codend mesh sizes.

The predictions showed that the meshes in the codend determined the overall size selection of the gear to a great extent due to the limited escape of blue whiting through the SMP (Paper I). However, they also showed that increasing SMP contact probability without modifying its mesh size may result in important changes in gear selectivity. In addition, the results suggested that increasing SMP contact probability and favoring an optimal contact angle 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.

Thus, Paper III contributes to the understanding of size selectivity processes in SMPs and contributes to more accurate predictions on fish size selectivity through gears where a SMP is a gear component.

7.3. Optimal SMP and codend combination in the Bay of Biscay demersal trawl fishery (Paper IV)

The literature covering the size selectivity potential of different SMP and codend designs typically tests a limited number of designs, often due to logistic, practical and economic reasons. For example, it is important to conduct sufficient hauls with each of the different gear configurations tested to estimate the selection of each gear with reasonable precision, which limits the number of different configurations that can be tested during sea trials. Therefore, research combining results from several experiments has become more common in the field of fishing gear technology in recent years (Fryer et al., 2017, 2016; Melli et al., 2020; O'Neill et al., 2020), and has proven to be a suitable tool for exploring a broad range of gear configurations with limited resources for experimental sea trials (Favaro and Côté, 2015; Fryer et al., 2017; Melli et al., 2020; Reinhardt et al., 2018).

Paper IV addresses sub-objective 1 in Chapter 2 and Research Question 4 in Chapter 6 by combining new size selection data of different SMP and codend designs with existing data for hake and blue whiting. In this study, individually and combined size selection potential of a number of SMP and codend designs were estimated and the exploitation patterns of those combinations for a variety of fishing scenarios quantified. Further, the work addresses sub-objective 4 and Research Question 5 using novel graphic tools to explore, evaluate and illustrate alternative gear designs in terms of size selectivity and exploitation pattern indicators.

New selectivity data for hake and blue whiting were collected onboard a scientific vessel in ICES area 8c in June 2019. In addition, the selectivity data collected for these two species during the sea trials in Papers I and II were included in the analysis. Individually, size selectivity of (i) a small SMP located at the top panel of the extension piece (SMP_{TS}); (ii) a large SMP located at the top panel of the extension piece (SMP_{TL}); (iii) a small SMP located at the bottom panel of the extension piece (SMP_{BS}); (iv) a large SMP located at the bottom panel of the extension piece (SMP_{BL}); (v) a diamond mesh codend (CD_D) and (vi) a square mesh codend (CD_S), were estimated by means of the models introduced in section 4.1. Later, all SMP designs (including the absence of it) and all codend designs were combined leading to ten different gear combinations (Fig. 29), and the sequential combined size selectivity was modelled for each case. In addition, exploitation pattern indicators were estimated to evaluate the potential consequences of using any of the ten designs on different population scenarios. Finally, the results were categorized based on a traffic light system to simultaneously visualize results for both species and ease their interpretation.

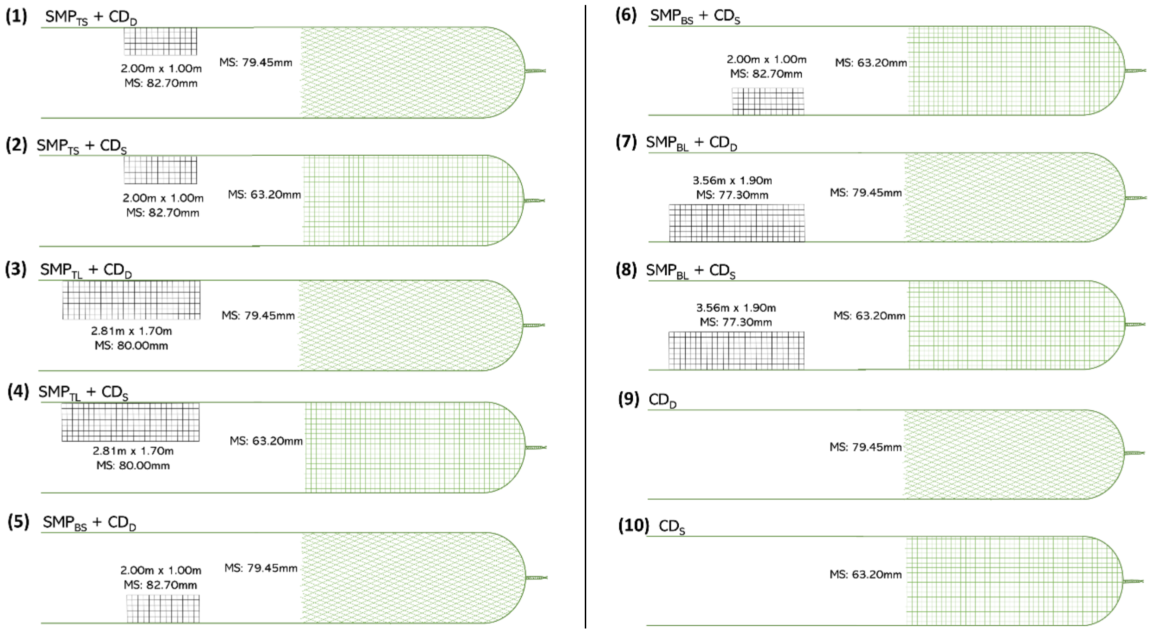


Fig. 29.- Ten trawl gear configurations included in the study that resulted from combining different SMP and codend designs considered. MS: mesh size.

To investigate the effect of the gear modifications implemented on the size selectivity and exploitation pattern of hake and blue whiting, treatment trees were applied. Treatment trees connect the different gear designs tested in a tree-like structure, starting with a reference gear that stepwise connects to the remaining gear designs (Fig. 30). The reference gear design established was the one used by the fleet today, SMP$_{TS}$ + CD$_D$. Every step in the tree implies a single gear modification (Fig. 30). In each step, the delta selectivity curves and size selectivity for the treatment gear, baseline gear and reference gear designs were shown with the corresponding CIs. Following the same approach, a treatment tree was applied to depict catch profiles of the treatment and the reference gear designs. Each step in the tree showed differences in the fish population retained by the treatment gear compared to the reference gear design (Fig. 30).

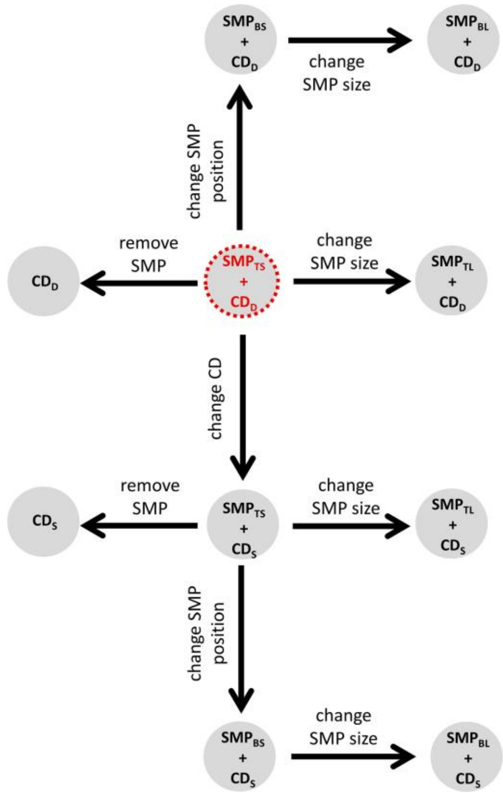


Fig. 30.- Treatment tree diagram. Arrows represent the delta comparisons carried out. Red circle indicates the reference gear design.

The results in Paper IV showed that using SMP_{BL} decreased the retention probability of undersized hake. In addition, any SMP design combined with CD_D retained high proportion of undersized individuals compared to CD_S. Specifically, changing codend geometry from CD_D to CD_S reduced the retention probability of hake by 61.97% (CI: 51.76–73.70%). The results for blue whiting showed that any gear design that included a SMP at the top panel of the trawl increased the escape probability for this species (SMP_{TS} and SMP_{TL}) together with any codend design. SMP_{TS} + CD_S would significantly affect the retention probability of blue whiting by releasing up to 43.75% (CI: 30.52–57.09%) more individuals of 24 cm than the SMP_{TS} + CD_D gear design. Given that catches of blue whiting are often non-desired due to market preferences, the release of commercial-sized individuals may be beneficial for the fishery.

Thus, Paper IV contributes with potential combinations of SMP and codend designs that can improve the exploitation pattern of hake and blue whiting simultaneously. It also provides new ways of investigating and illustrating size selectivity and exploitation pattern indicator results. Treatment trees showed to be a useful tool that improved the readability and interpretation of selectivity results and therefore, may aid the identification of promising and compatible gear designs in the future. Additionally, the traffic-light system used to illustrate exploitation pattern indicators provided a quick and easy way to determine which gear combination leads to the best exploitation pattern regarding the fish population and the management goals. It also highlighted potential strategies for fishing vessels operating in the Bay of Biscay.

7.4. Species separation using fish behavior and visual stimulation (Paper V)

Paper V addresses sub-objective 1 in Chapter 2 and Research Question 6 in Chapter 6 by testing a modified trawl with a horizontal grid placed on the lower panel of the extension piece that leads to an additional lower codend (Fig. 31). This trawl configuration intended to guide those species that hold themselves close to the lower panel in the trawl to pass through the horizontal grid into the lower codend, while directing the rest of the species to the upper codend. Furthermore, the effect of artificial light on the separation of the species in this trawl was also tested. The objective of Paper V was to find out if this modified trawl could lead to an effective separation of species that would allow subsequent size selection processes in the different codends.

The trawl configuration tested included an 80 mm two-panel netting section split into two compartments (i.e., upper and lower extension and codend) by a 80 mm horizontal separator panel that kept both extensions separated. Ahead of this section, a guiding panel was installed forcing fish to swim into the upper extension and over the horizontal separator panel. Here, a horizontal passage section with rectangular gaps (grid-like shape) was installed just below the main flow of fish (Fig. 31a). In order to maximize both round- and flatfish probability to pass through the grid, the bar spacing of the grid was wide. Thus, fish needed to pass through it to end up in the lower compartment (Fig. 31a). In addition, a fiber optic cable connected to laser diode pod that emitted blue light was attached on the grid, which made the grid luminescent when turned on (Fig. 31b).

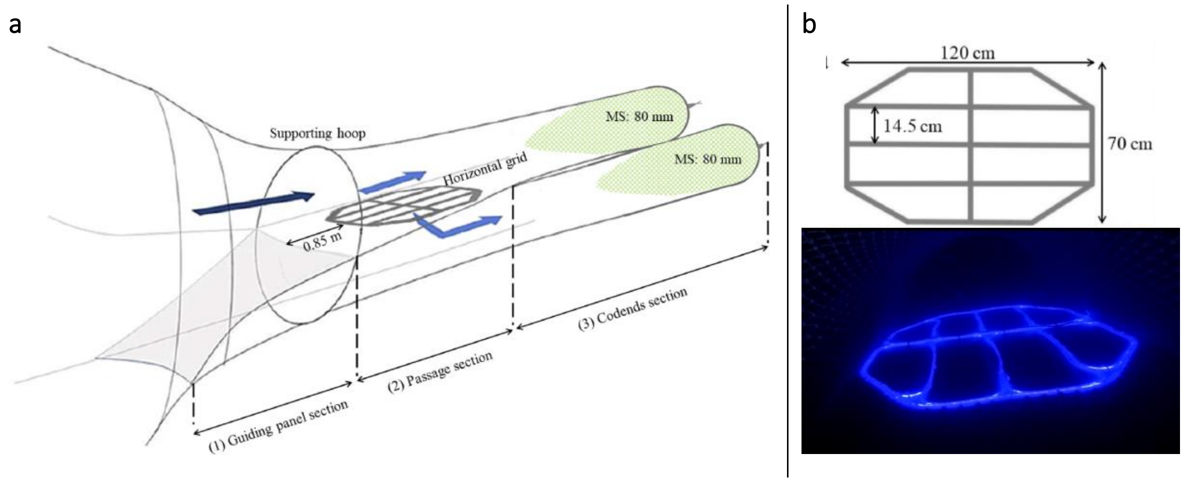


Fig. 31.- (a) Gear diagram and specification of different sections. MS: mesh size. (b) Technical characteristics of the grid used and underwater picture of the illuminated grid.

The experiments to test this section were carried out onboard a commercial fishing vessel in ICES area 8b. Ten hauls were conducted with the light switched on and ten with light switched off, in alternated order. Turbidity levels inside the gear were measured in every haul and underwater recordings were carried out in those hauls with the grid light switched on. The species included in the data analysis were hake, megrim, anglerfish, horse mackerel and mackerel. The catch comparison method adapted to a divided codend study, as introduced in Section 4.3, was used to determine the length-dependent probability of each species being captured in the lower codend, conditioned capture. Also, the probability of fish ending up in one or the other codend when the lights were switched on or off was estimated.

The results showed that less than 25% of the individuals of all species investigated passed through the grid and were retained in the lower codend. No significant differences were found when the grid was illuminated compared to when it was not illuminated. The specific conditions in the Basque bottom trawl fishery, i.e., high turbidity levels, high towing speed, may influenced the performance of the gear in this fishery. Consequently, the design was found to have limited potential to improve species and size selection in the Bay of Biscay demersal trawl fishery.

The findings from Paper V showed that the trawl design tested was not able to efficiently separate species by means of hake and megrim passage through the grid under the conditions this fishery operates. It was concluded that a simpler approach could probably be used to take advantage of the behavioral differences between the species in this fishery, in the line of those proposed by Karlsen et al., (2019) or Melli et al., (2018).

7.5. Escape opportunities in codends with and without shortened lastridge ropes (Paper VI)

Paper VI in the thesis addressed sub-objectives 1 and 2 in Chapter 2 and Research Question 7 in Chapter 6 by estimating the size selectivity potential of a diamond mesh codend with 20% shortened LR compared to a standard diamond mesh codend with no LR (Fig. 32). The study also estimated fish escape chances through a standard and shortened LR codend based on fish morphology and mesh shape. Additionally, Paper VI investigated if optimal codend mesh openness is achieved for the size selection of the different species studied.

During the sea trials carried out in ICES area 8bc, selectivity data for hake, horse mackerel and blue whiting were collected. The models used to describe codend size selection were the logistic models introduced in section 4.1, with and without accounting for selectivity contact. One of the main findings in this study was that the codend used by the demersal trawl fleet in the Bay of Biscay with 20% shortened LR improved escape probability of horse mackerel and blue whiting. Specifically, L50 for a 79 mm mesh size codend increased from 14.56 cm (CI: 13.16–15.76 cm) to 20.74 cm (CI: 17.31–23.92 cm) for horse mackerel and from 22.23 cm (CI: 20.28–22.97 cm) to 24.30 cm (CI: 23.05–25.91 cm) for blue whiting. The escape probability for hake did not change significantly.

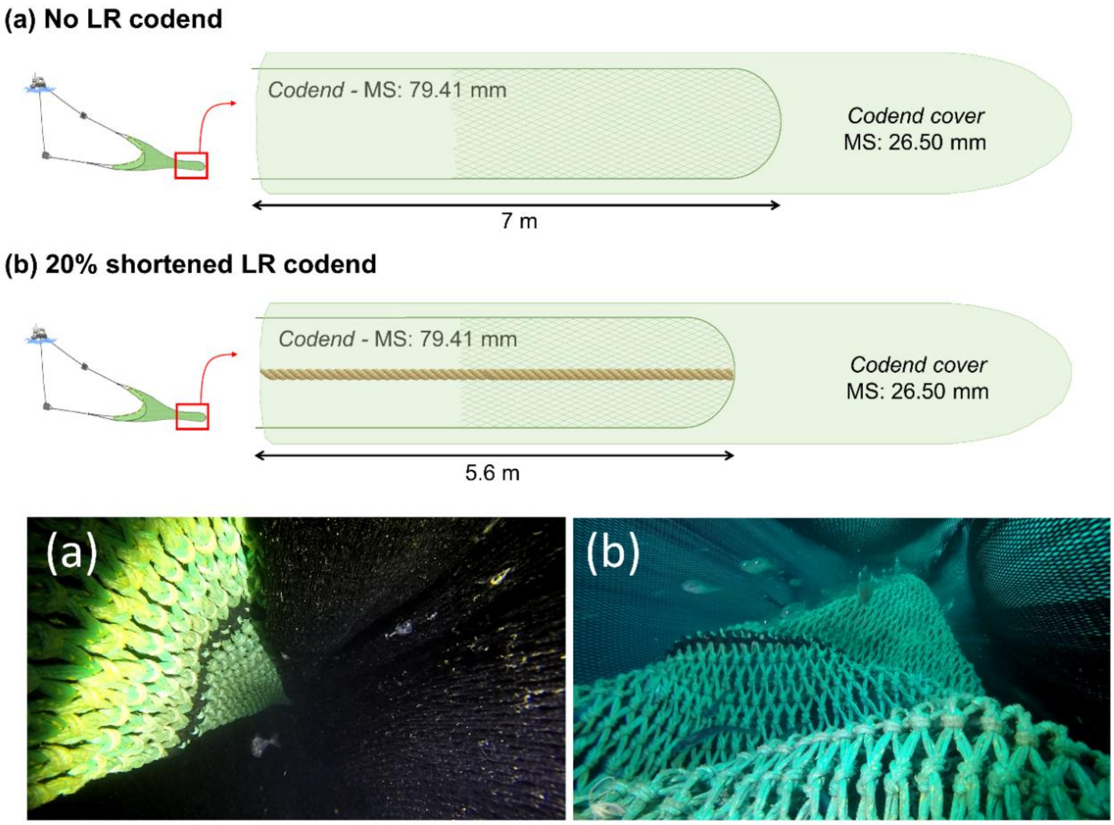


Fig. 32.- (a) No LR codend length and mesh size (MS) specifications and underwater image of it; and (b) 20% shortened LR codend specifications and underwater image of it. Both underwater images were taken from a camera positioned between the codend and the codend cover.

In addition, morphology data of hake, horse mackerel and blue whiting were collected and, using the facilities in the FISHSELECT software tool, the potential contribution of the different codend mesh OAs to the explanation of the experimental size selectivity curve obtained for each case (species and gear) was estimated. The objective was to understand the fish escape chances based on available mesh OAs, find out the optimal mesh openness for the escape of the different species studied and to predict potential selectivity of different codend designs.

The analysis of mesh OA contribution to the explanation of the selectivity results showed that, with the shortened LR codend, the availability of meshes with high OAs can be expected to be larger. However, the higher availability of more open meshes does not necessarily imply that fish use them to escape. Potential differences on the distribution of these open meshes along the codend due to the effect of the LR, together with fish behaviour, could explain the size selectivity differences found between species. The mesh openness achieved with 20% shortened LR was below that necessary to obtain optimal escape opportunities for these species. Even so, the predictions carried out showed that codend with shortened LR can reduce retention probability of all species in the same extent as increasing codend mesh size considerably.

Chapter 8. Discussion

This thesis presents recent gear selectivity research conducted in the Bay of Biscay demersal trawl fishery. Earlier research in the field for this area is limited to a few studies (Alzorriz et al., 2016; Vogel et al., 2017). Therefore, the work carried out provides considerable advances in the understanding, development, and adaption of the trawl gear used in the Bay of Biscay demersal trawl fishery.

Papers I – IV aim at increasing the release efficiency of SMPs for potential unwanted catch in this fishery. The results demonstrate that adapting the position of the SMP to the natural behavior of fish in the trawl can be a more effective strategy than using mechanical and visual stimulators to increase fish contact probability. Specifically, placing a SMP in the lower part of the extension piece has demonstrated efficient release of undersized hake and therefore, it can be a partial solution to the challenges in this fishery (Paper II and IV). This gear modification can also be beneficial for other fisheries where capture of undersized hake is of concern. For example, in the Mediterranean multispecies demersal trawl fishery (Maynou et al., 2021), where locating the SMP closer to the codline may not be considered due to the high risk of releasing other commercially valuable species and sizes, this gear modification can be of interest.

The research conducted in this thesis shows that, to obtain the desired exploitation patterns in the Bay of Biscay demersal trawl fishery, the selectivity should not rely solely on the SMP size selection. Accounting for codend size selectivity is also necessary. Thus, the codend modifications tested are another major contribution of this thesis. Square mesh codends (Paper IV) and shortened LR codends (Paper VI), have demonstrated to improve the gear size selectivity for hake, horse mackerel and blue whiting in this fishery. However, further research is needed to optimize codend mesh size and shape for other valuable species in the fishery.

The theoretical work based on the FISHSELECT software tool conducted in the thesis contributes to the understanding of size selectivity processes in SMPs (Paper III). The results obtained, i.e., SMP size selection is determined by different fish contact angles, shed light on the existing inconsistency between the experimentally obtained size selection results and those expected based on fish morphology (Alzorriz et al., 2016). The approach used in this thesis applying FISHSELECT allowed making more accurate SMP size selection predictions, which can be of great relevance in trawl fisheries where SMPs are used. In addition, through the FISHSELECT methodology, effective size selection predictions for different relevant species and multiple selection devices have been carried out (Paper III, VI). This demonstrates the high value of the theoretical work conducted and its potential as a cost-effective tool to identify promising gear designs without having to test a wide range of less promising gears at sea, which is a waste of resources. In addition, the design guides published for hake, horse mackerel and blue whiting can be useful to adjust mesh size and shape in many pelagic and demersal fisheries that harvest these species around the world.

The behavioral differences reported between the species investigated and the potential use of these differences to improve gear size selectivity are another important contribution of this thesis. The knowledge gained with the work carried out has led to new gear designs that take advantage of these behavioral differences and improve the size selectivity of different species (Papers I – V). Further, the results obtained highlight the importance of considering fish behaviour when designing and implementing selectivity devices. Future work should apply quantitative analysis of fish behaviour relative to selectivity devices (Santos et al., 2020). This type of research would not only deepen the understanding of fish behavior but would also help identifying behavioral patterns that could be better exploited to improve selectivity in different commercial fisheries.

The graphic tools used to illustrate the results within this thesis can be of broad application in the field of fishing gear technology. The use of treatment trees demonstrates improved readability and interpretation of selectivity results, leading to the identification of promising gear designs. The use of this graphical tool shows to be especially useful to explore the potential for size selection of multiple gear designs simultaneously. Further, this way of presenting selectivity results facilitates the communication of the effect of single and multiple gear modifications at the same time. This new way of presenting selectivity results can be interesting not only for research purposes but also for the fishing industry and managers (Paper IV).

The selectivity data analysis in this thesis was supplemented with exploitation pattern indicators, which show the outcome of using a particular fishing gear on a specific fish population structure (Papers I, IV and V). Exploitation pattern indicators are considered of great interest for the fishing industry to evaluate the cost-benefit of using a specific gear. In this thesis, a traffic-light system was used to categorize indicator results, which provides an easy way to interpret these results, particularly for multispecies scenarios (Paper IV). This can help the fishing industry in the pursuit of specific exploitation pattern goals and fishery managers to accelerate gear evaluation processes and their potential implementation into the legislation.

Advances in gear technology provide tools to adjust gear size selectivity. However, other strategies may need to be explored if full compliance with the LO is to be achieved. Often, fishermen use their experience and knowledge to avoid areas and times where catch compositions do not match the desired catch profile. In recent years, numerous analytical procedures have utilized fisheries and vessel location data to identify and predict how catch compositions are likely to vary over space and time and how these relate to fisheries dynamics (Calderwood et al., 2020; Fraser et al., 2008; Mateo et al., 2017; Paradinas et al., 2016). A more systematic understanding of the target and bycatch species' distribution may aid fishermen on the decision-making of where to fish to optimize fishing effort. This, together with the development of specific gear designs, may help fishermen to improve their exploitation patterns under the provisions of the LO.

This thesis addresses bycatch challenges facing the demersal trawl fishery in the Bay of Biscay and overall, the results obtained in Papers I-VI contribute to fulfill the main objective of the work: *to identify, develop, and evaluate SMP and codend modifications that can improve the catch composition while maintaining the efficiency in the demersal trawl fishery in the Bay of Biscay.* It provides fishermen and fisheries managers with new data and potential trawl gear modifications for more selective fisheries that will help solving current and future challenges for the industry.

8.1. Final remarks

The aim of this thesis is to develop technical solutions to avoid unwanted catches in the Bay of Biscay demersal trawl fishery. The research carried out provides selectivity results for several gear modifications that, to some extent, have demonstrated to improve the exploitation patterns for different commercially relevant species in the fishery. Therefore, the implementation of these modifications could be beneficial for fishermen at times and/or areas where the excessive catch of unwanted species or sizes can limit their access to other resources. However, ensuring the implementation of gear solutions by the fishing industry, as those investigated within this thesis, is often challenging. The LO is intended to encourage the fishing industry not to catch unwanted sizes and species. The penalties applied in the new legislation may be an incentive for fishermen to use new gears that have proved to reduce unwanted catch. Therefore, in spite of the challenges often associated with the implementation of new fishing gears in commercial fisheries, one could hope that the incentives brought by the LO may facilitate the uptake of research-based gear developments, like those developed in this thesis.

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Papers I – VI

Paper I

“Stimulating release of undersized fish through a square mesh panel in the Basque otter trawl fishery”

Fisheries Research 224 (2020) 105431

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Stimulating release of undersized fish through a square mesh panel in the Basque otter trawl fishery

Elsa Cuende[a,*], Luis Arregi[a], Bent Herrmann[b,c], Manu Sistiaga[d,e], Iñigo Onandia[a]

[a] AZTI-Tecnalia, Marine Research Division, Txatxarramendi ugartea w/n, 48395, Sukarrieta, Spain
[b] SINTEF Ocean, Fishing Gear Technology, Willemoesvej 2, 9850, Hirtshals, Denmark
[c] The Arctic University of Norway, UiT, Breivika, N-9037, Tromsø, Norway
[d] SINTEF Ocean, Fishing Gear Technology, Brattørkaia 17C, 7010, Trondheim, Norway
[e] Institute of Marine Research, Postboks 1870 Nordnes, Bergen, 5817, Norway

ARTICLE INFO

Handled by Morales-Nin

Keywords:
Square mesh panel (SMP)
Basque bottom otter trawl
Release efficiency
Contact probability

ABSTRACT

Discards of regulated species in the Basque mixed trawl fishery are a challenge. In 2006, a square mesh panel (SMP) was introduced in the fishery to increase the release efficiency of undersized fish. However, studies have shown that the selectivity in this fishery is based on codend selectivity and the release through the SMP is inefficient due to low contact between fish and the SMP. In order to improve contact, we tested four different gear configurations that use different stimulators to lead fish to the panel: without stimulation, with stimulation based on ropes, with stimulation based on ropes and floats, and with stimulation based on LED lights. The experiment was carried out on three of the potential choke species for the fishery: hake (*Merluccius merluccius*), horse mackerel (*Trachurus trachurus*), and blue whiting (*Micromesistius poutassou*). The results showed that stimulators did not significantly improve the release efficiency of hake and horse mackerel through the panel. For blue whiting, stimulation with floats had a significant positive effect on release efficiency, whereas LED light-based stimulation had the opposite effect. In general, the contribution of the SMP to the overall release efficiency of the selective system (SMP + codend) was low. Underwater recordings confirmed that the stimulators generally were not able to lead fish towards the SMP.

1. Introduction

Fisheries in general have great social and economic implications for coastal communities in the Basque Country (Haig, 2008), which is a region located in the north of Spain. Basque bottom trawling began in the early twentieth century, and its productivity peaked in the late 1970s when 53% of the Spanish trawling fleet fishing in EU community waters (ICES VIab, VIIbcghj, VIIIabd) was Basque. The demersal trawl fishery in this area is a multispecies fishery that includes more than 100 different species (Rochet et al., 2014), but hake (*Merluccius merluccius*), megrim (*Lepidorhombus* spp.), and anglerfish (*Lophius* spp.) are the main target species. However, other species such as horse mackerel (*Trachurus trachurus*), blue whiting (*Micromesisitius poutassou*), and mackerel (*Scomber scombrus*) can be important as choke species (Schrope, 2010) depending on the fishing ground, season, quota availability, and commercial value (Iriondo et al., 2008, 2010; Rochet et al., 2014).

Awareness about discard reduction in fisheries has increased worldwide (Catchpole et al., 2005; Gillespie, 2002; Santurtún et al., 2014). Discards in fisheries can occur for several reasons, including capture of individuals below minimum legal size, exhaustion of quota, low commercial value, damaged or degraded individuals in the catch, or high grading (Anderson, 1994; Pascoe, 1997). Since 1980, several technical regulations have been implemented in the EU with the aim of reducing discards (Franco, 2007; Santurtún et al., 2014). However, discarding is still a common practice in some European fisheries (Uhlmann et al., 2013). Rochet et al. (2014) analyzed available data from observer discard monitoring, catch landings, and/or nominal fishing effort from 2011 to 2013 and found that the total discard of the Spanish fleet operating in ICES VIIIabd was around 60–65% of the total catch. Thus, unwanted catches and discards constitute a substantial waste that negatively affects the sustainable exploitation of marine resources (Kelleher, 2005). This perception has motivated the establishment of the Landing Obligation (LO) under the provisions of Article 15 of the 2013 reform (EU et al., 2013). Its main objective is to eliminate discards of commercially exploited stocks. By 2019, all EU fisheries are obliged to land the catches of regulated species to be counted against the quota.

In recent decades, several fishing regulations have been implemented specifically to stimulate the recovery of hake (EC, 2001a;

* Corresponding author.
E-mail address: elsacuende@gmail.com (E. Cuende).

https://doi.org/10.1016/j.fishres.2019.105431
Received 24 April 2019; Received in revised form 24 October 2019; Accepted 27 October 2019
Available online 19 November 2019

2001b; 2002; 2004). In 2002 (EC, 2002), the minimum codend mesh size for trawlers fishing the northern stock of European hake in the Bay of Biscay was changed from 70 mm to 100 mm diamond mesh. In 2006 (EC, 2006), fishermen were given the alternative of using a 70 mm diamond mesh codend combined with a square mesh panel (SMP) (2 m long, 1 m wide, 100 mm mesh size) inserted in the upper panel of the extension piece of the trawl instead of a 100 mm diamond mesh codend. Currently, the gear composed of the SMP with a 70 mm diamond mesh codend is the one most used by the fleet.

Several studies have investigated the functionality and release efficiency potential of SMPs (Briggs, 1992; Santos et al., 2016; Zuur et al., 2001). In general, results show that even if some species manage to escape through SMPs, less active species, such as hake, do not manage to escape through it efficiently (Alzorriz et al., 2016). In most cases, the authors concluded that the low release efficiency of the panel is a consequence of the low contact between the fish and the panel (Alzorriz et al., 2016; Brčić et al., 2017; Herrmann et al., 2014). To improve the contact, some mechanical (Kim and Whang, 2010) and visual stimulators (Glass and Wardle, 1995; Grimaldo et al., 2017) have been used to guide fish towards SMPs or netting walls (Grimaldo et al., 2018; Herrmann et al., 2014).

The main goal of the present study was to determine if the release efficiency of the SMP used in a demersal trawl in the Bay of Biscay could be improved by adding ropes, floats, and LED light-based stimulators. The study focused on individuals of hake, horse mackerel, and blue whiting, which may compromise the activity of the fleet due to their potential as choke species. Specifically, we aimed to answer the following research questions:

- What is the release efficiency of the selection system composed of a SMP and 70 mm diamond mesh codend for hake, horse mackerel, and blue whiting?
- What are the contributions of the SMP and the 70 mm diamond mesh codend to the combined selectivity of the system?
- Can the release efficiency of the SMP be improved by adding different stimulators based on ropes, floats, or LED lights for the three species investigated?

2. Material and methods

2.1. Sea trials and data collection

The sea trials were carried out on board the oceanographic vessel *Emma Bardan* (29 m length overall; 900 Kw) from 8 to 19 June 2017. The fishing was carried out in a specific area within ICES divisions VIIIc and VIIIb that correspond to Spanish and French waters (Fig. 1). This area normally contains high densities of hake juveniles at this time of year and therefore was considered to be suitable for the experiments. During the experimental period, 32 valid hauls were conducted at depths that varied between 106 and 128 m.

The gear used in the experiments was a four-panel bottom trawl called GOC73 (Bertrand et al., 2000). This trawl is built according to the standard bottom trawl survey manual for the Mediterranean (MEDITS et al., 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 m^2; 350 Kg), 100 m sweeps, and a light rockhopper ground gear (with 3 × 40 Kg chain + 15 Kg chain on the bosom). While fishing, the trawl had a horizontal opening of 16 m and a vertical opening between 2.7 and 3.2 m. The towing speed during the cruise was 3.0–3.3 knots which was the maximum for the vessel.

In this study, we used a SMP (mesh size 82.7 mm) inserted into the upper panel of the extension piece of the trawl, 1 m in front of the joint between the codend and the extension piece (Fig. 2). A previous study carried out with a 100 mm SMP (Alzorriz et al., 2016) showed that the low release efficiency of the panel was due to poor contact between the fish and the panel rather than to an inappropriate mesh size. In fact, the results of the study showed that fish over Minimum Conservation Reference Size (MCRS) that managed to contact the panel were able to escape through it. Therefore, and in order to avoid the loss of valuable catch, the mesh size of the panel used in the present study was reduced to 82.7 mm (3 mm polyamide (PA) twine) (Table 1). The codend, used together with the panel, was 7.0 m long and made of 72.8 mm meshes (4 mm PA double twine). All meshes were measured with an electronic OMEGA mesh gauge (Fonteyne et al., 2007) according to the guidelines described in regulation EC et al., 2008.

The selectivity data were collected using the dual-cover method (Fig. 2) described in Zuur et al. (2001) and Sistiaga et al. (2010). The cover used over the SMP was 13 m long with 26.1 mm mesh size (1.2 mm PA twine). It was built based on the design of Larsen and Isaksen (1993) and was equipped with nine floats (N-50/8 type; 135 mm diameter; 0.760 Kg buoyancy each) to ensure its expansion. The cover over the codend was 9 m long and constructed of 26.5 mm mesh size (1.3 mm PA twine) (Table 1; Fig. 2). To expand the codend cover we used nine pairs of floats (N-25/5 type; 100 mm diameter; 0.300 Kg buoyancy each), eight kites (four per panel), and four chains (1 Kg each) in the lower panel. Table 1 summarizes details about the specifications of the different parts of the trawl.

We tested four different gear configurations:

1 No-stimulation: used as baseline, consisted on the SMP with no stimulators added (Fig. 3a);
2 Stimulation by ropes: consisted of six inclined elastic ropes attached on one side to the bottom panel of the square mesh section and on the other side to the upper panel at the end of the SMP. The purpose was to partially obstruct the passage of fish toward the codend, guiding them upwards towards the SMP (Fig. 3b);
3 Stimulation by floats: this configuration added oval plastic floats to the inclined ropes described in the former configuration (3-4 floats on each rope, T80/5 type, 118 x 52 mm, 0.085 Kg buoyancy each). The floats provided vibration to the guiding ropes while towing (Fig. 3c);
4 Stimulation by LED lights: ten blue LED lights (CENTRO Power Light, Standard model SW2) were placed over the SMP to attract fish towards the panel and increase contact probability (Fig. 3d).

Each haul was carried out with one configuration at a time, completing a total of eight hauls for each configuration. The species included in the data analysis were hake *(Merluccius merluccius)*, horse mackerel, *(Trachurus trachurus)* and blue whiting *(Micromesistius poutassou)*. After each haul, these species were measured to the nearest centimeter below. When the catch exceeded a maneuverable quantity in terms of the available time and crew for processing the fish, randomly selected subsamples of the catch were taken, and the subsample ratio was calculated. In some specific hauls, once the subsample was sorted, and if the representation of some species was still too big to handle, a randomly selected sample from the sorted subsample was taken. Consequently, we expected that in those specific hauls the less abundant species would be weakly represented. Therefore, we established a protocol for acceptance, meaning that the hauls that did not pass the limits established in the protocol were discarded. The haul protocol acceptance was based on two conditions: 1) sampling factor for a compartment had to be at least 0.05 and 2) in case of subsampling in a compartment, the product of the number measured in the compartment and the compartment sampling factor needed to be at least 4.

Underwater recordings were carried out to check the correct performance of the gear and collect information about fish behavior relative to the stimulators tested. The camera (Camera type: GoPro Hero 3) was attached at different locations in the trawl (Table 2) together with a CREE underwater torch (Brinyte DIV01; CREE XM-L2(U2) LED; max1000 lm).

2.2. Selectivity model for the gear

In the experimental setup used in this study, fish entering the trawl first encountered the SMP and could escape if they swam up to it and if their body size, shape, and orientation allowed them to pass through the meshes. If any of these requirements were not met, the fish entered the size selective codend, where a further selection process took place.

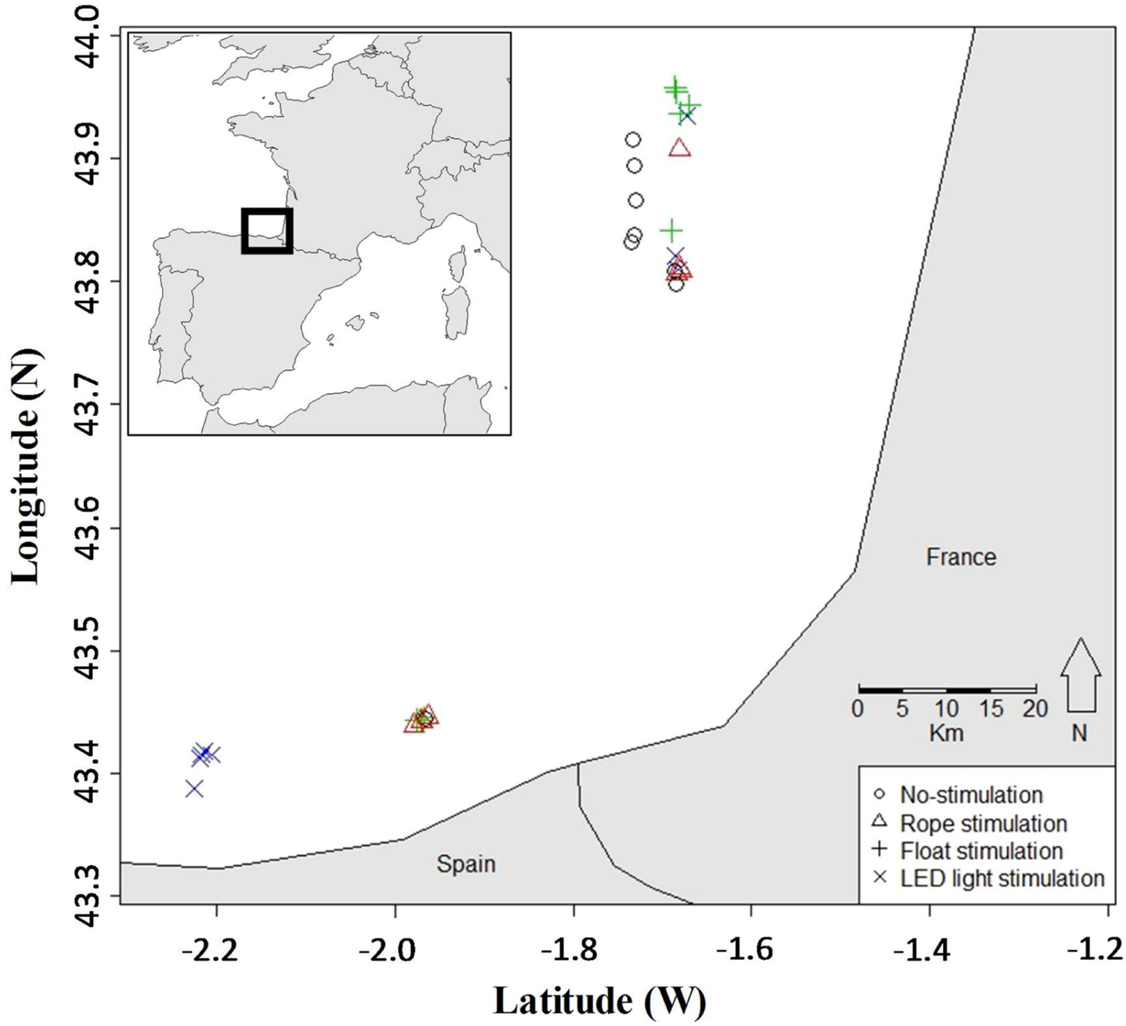

Fig. 1. Sampling area and fishing position for all hauls conducted during the cruise.

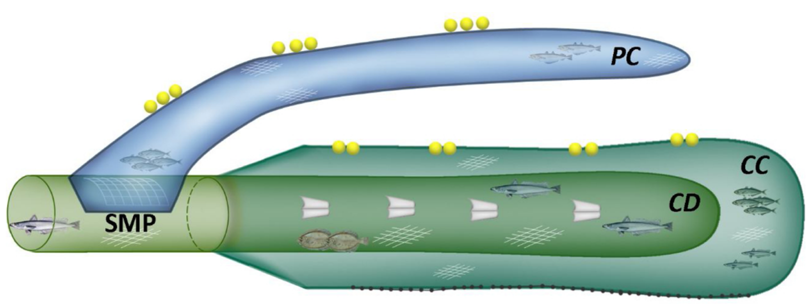

Fig. 2. Scheme of the module built with the square mesh panel (SMP), codend (CD), and the different net covers (SMP cover (PC) and codend cover (CC)) used to collect the escapement.

Table 1
Specifications of the gear used during the cruise.

	Codend *(CD)*	Codend cover *(CC)*	SMP	SMP cover *(PC)*	Extension piece
Twine material	Substitute by Polysteel	Single braided PA	Single braided PA	Single braided PA	Single braided PE
Thickness (mm)	4	1.3	3	1.3	3
Mesh size* (mm)	72.8	26.5	82.7	26.1	75.3
Length (m)	7	9	2.2	13	5
Width (m)	-	-	1.2	-	-

* Measured with an OMEGA gauge (Fonteyne et al., 2007) according to EC et al., 2008.

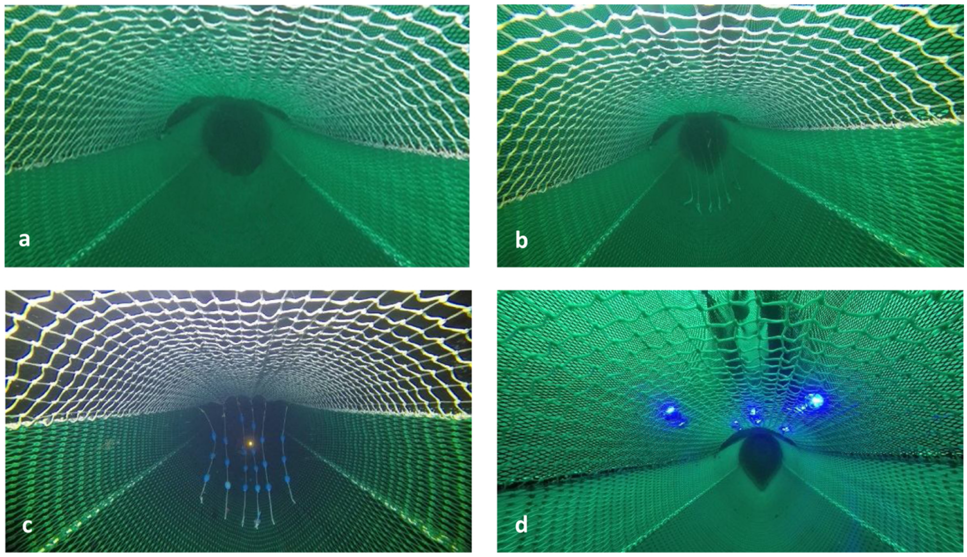

Fig. 3. Different configurations tested on the SMP: (a) no-stimulation; (b) stimulation by ropes; (c) stimulation by floats; (d) LED light-based stimulation.

If the fate of each individual fish is assumed to be independent of the others, the number of fish of length l retained in the three compartments, codend (*CD*), SMP cover (*PC*), and codend cover (*CC*) (Fig. 2), can be modelled using a multinomial distribution with length-dependent probability of being retained in the codend r_{comb} (l); escapement through the SMP e_{SMP} (l); and escapement through the codend e_{codend} (l). The combined retention can be modelled as:

$$r_{comb}(l) = 1 - e_{SMP}(l) - e_{codend}(l) \tag{1}$$

where l represents fish length. This type of model has been previously used in several studies to investigate combined selection of SMPs and diamond mesh codends (Alzorriz et al., 2016; Brčić et al., 2017; O'Neill et al., 2006; Zuur et al., 2001).

The first selection process takes place when a fish encounters the SMP zone, where it can be size-selected if it makes contact with the panel. The contact parameter (*C*) quantifies the fraction of fish entering the selectivity area that makes contact with the device and, therefore, is subjected to a size-dependent probability of escaping through it. In this case, we assume that the probability for fish to come into contact with the panel can be modelled with the length-independent parameter C_{SMP}. This parameter can take values from 0.0 to 1.0 depending on the fraction of individuals contacting the panel. If C_{SMP} is equal to 1.0, all fish come into contact with the panel, whereas if C_{SMP} is equal to 0.0, none do. This leads to the following model for e_{SMP} (l):

$$e_{SMP}(l) = C_{SMP} \times (1 - rc_{SMP}(l, \boldsymbol{v}_{SMP})), \tag{2}$$

where $rc_{SMP}(l,\boldsymbol{v}_{SMP})$ is the selection model for fish making contact with the SMP and having a suitable orientation to achieve a size-dependent probability of passing through the SMP mesh, and $\boldsymbol{v}_{SMP}$ are the parameters of model $rc_{SMP}(l,\boldsymbol{v}_{SMP})$ and therefore, represented by a vector. A further assumption is that the probability $rc_{SMP}(l,\boldsymbol{v}_{SMP})$ can be described by standard S-shaped size selection models for trawl gears. We considered four S-shaped size selection curves: *Logit*, *Probit*, *Gompertz*, and *Richard*. Further information about these models, their respective parameters $\boldsymbol{v}$, and estimation of the selectivity parameters *L50* and *SR* (*L50* is the length at which a fish has a 50% chance of being retained by the gear, whereas *SR* is the difference between *L75* and *L25*) can be found in Wileman et al. (1996).

To model the size-dependent codend retention probability $rc_{codend}(l,\boldsymbol{v}_{codend})$, it was assumed that every fish entering the codend came into contact with the codend meshes and that $rc_{codend}(l,\boldsymbol{v}_{codend})$, like $rc_{SMP}(l,\boldsymbol{v}_{SMP})$, could be modelled by a *Logit*, *Probit*, *Gompertz*, or *Richard* model. Estimation of codend escape involves the fish that have not escaped through the SMP. The above considerations led to the following model for e_{codend} (l):

$$e_{codend}(l) = (1 - rc_{codend}(l, v_{codend})) \times (1 - e_{SMP}(l, C_{SMP}, v_{SMP})) \tag{3}$$

Table 2
Camera specifications corresponding to each haul and configuration tested. Light color corresponds to the light attached to the camera.

Haul nº	Stimulator	Position of the cameras (light color: red (R) or white (W) or none (N))
8	None	Lower panel, joint between codend and extension piece (W)
13	Ropes	Lower panel, behind the SMP (W).
14	Ropes	Lower panel, behind the SMP (W).
15	Ropes	Lower panel, behind the SMP (W).
16	Ropes	Lower panel, behind the SMP (W) and Upper panel, before the SMP (R).
18	Ropes	Lower panel, behind the SMP (W).
23	LED lights	Upper panel, before the SMP (N).
25	LED lights	Over the codend, in between the codend cover and the codend (W).
26	LED lights	Over the codend, in between the codend cover and the codend (W) and Upper panel, before the SMP (W).
28	Floats	Lower panel, behind the SMP (W).
31	Floats	Upper panel, before the SMP (W).
32	Floats	Over the codend cover (W) and Lower panel, behind the SMP (W).
34	Floats	In the codend (W) and on the float line, behind the floats (W).
35	Floats	On the float line, behind the floats (W).
36	None	Over the codend, in between the codend cover and the codend (W) and over the codend cover (W).
37	None	On the float line, behind the floats (W).

2.3. Model estimation

The values of C_{SMP}, $\boldsymbol{v}_{SMP}$, and $\boldsymbol{v}_{codend}$ for selection models (1)–(3) are species-specific and depend on the gear configuration. Therefore, the values were obtained separately for each species and gear configuration using Maximum Likelihood Estimation (MLE) by pooling the experimental data over the hauls j (*1* to *m*) with the specific gear configuration and minimizing:

$$-\sum_{l}\sum_{j=1}^{m}\left\{\frac{nCD_{lj}}{qCD_j}\times\ln(r_{comb}(l, C_{SMP}, v_{SMP}, v_{codend}))+\frac{nPC_{lj}}{qPC_j}\times\ln(e_{SMP}(l, C_{SMP}, v_{SMP}))+\frac{nCC_{lj}}{qCC_j}\times\ln(e_{codend}(l, C_{SMP}, v_{SMP}, v_{codend}))\right\} \quad (4)$$

where for each haul j and length class l, nCD_{lj}, nPC_{lj}, *and* nCC_{lj} are the numbers of individuals length-measured in the *CD*, *PC*, and *CC*, respectively; and qCD_j, qPC_j, and qCC_j are their respective subsampling factors (ratio of length-measured to total number of fish in each compartment). In total, 16 models were considered to describe the overall trawl size selectivity based on the combination of the four S-shaped functions considered for $rc_{SMP}(l)$ and $rc_{codend}(l)$. The 16 models were tested against each other and the one with the lowest AIC value (Akaike's Information Criterion; Akaike, 1974) was selected. MLE using equation (4) with (1) to (3) requires pooling experimental data over hauls. This results in stronger data for average size-selectivity estimation at the expense of not considering explicit variation in selectivity between hauls (Fryer, 1991). To account correctly for the effect of between-haul variation when estimating uncertainty in size selection, a double bootstrap method was used (Herrmann et al., 2012). We estimated the 95% Efron percentile confidence intervals (95% CIs) (Efron, 1982) for the parameters in equations (1)–(3) and for the resulting $e_{SMP}(l)$, $e_{codend}(l)$, and $r_{comb}(l)$ curves. To estimate the 95% CIs, 1000 bootstrap iterations were carried out. All analyses were done using the software tool SELNET (Herrmann et al., 2012).

The models were validated based on p-value estimations and model deviance versus degrees of freedom (Wileman et al., 1996). When the p-value was < 0.05 and deviance was much bigger than the degrees of freedom, the residuals were inspected to determine whether the discrepancy between model and experimental data was the result of overdispersion.

To infer the effect on the length-dependent SMP escape probability, $e_{SMP}(l)$ and on the combined retention, $r_{comb}(l)$, when changing from the no-stimulation configuration to a specific stimulation configuration, the difference in the estimated value for $p(l)$ was calculated as follows:

$$\Delta p(l) = p_{stim}(l) - p_{base}(l), \quad (5)$$

where $p_{base}(l)$ represents the value for $e_{SMP}(l)$ or $r_{comb}(l)$ for the no-stimulation design and $p_{stim}(l)$ is for the stimulator design. Efron 95% CIs for $\Delta p(l)$ were obtained based on the two bootstrap populations of results (1000 bootstrap repetitions in each) for both $p_{base}(l)$ and $p_{stim}(l)$. As they are obtained independently, a new bootstrap population of results was created for $\Delta p(l)$ by:

$$\Delta p(l)_i = p_{stim}(l)_i - p_{base}(l)_i \; i \in [1...1000], \quad (6)$$

where i denotes the bootstrap repetition index. As the bootstrap resampling was random and independent for the two groups of results, it is valid to generate the bootstrap population of results for the difference based on (6) using the two independently generated bootstrap files (Herrmann et al., 2018). Based on the bootstrap population, Efron 95% CIs can be obtained for $\Delta p(l)$ as described above.

2.4. Estimation of exploitation pattern indicators

The effect of the SMP on the exploitation pattern of the gear was quantified by estimating the values for a number of indicators (described in detail below) using the data collected during the fishing trials. To quantify to what extent the experimental gear supports a sustainable and efficient fishery, the average percentage of retained individuals below (rP_-) and above (rP_+) MCRS were estimated for each species individually based on the population size structure for the different species entering the gear during the experimental fishing. The Minimum Conservation Reference Size (MCRS) for hake and horse mackerel are 27 and 15 cm length, respectively. For blue whiting, which does not have MCRS, we used its estimated marketable size limit, 18 cm length. This length is based on a regulation that establishes a maximum of 30 individuals of blue whiting per kilo for commercialization (Dorel, 1986; EC, 1996).

The formulae used to calculate rP_- and rP_+ values are as follows (Brčić et al., 2017):

$$rP_- = 100\times\frac{\sum_j\sum_{l<MCRS}\left\{\frac{nCD_{jl}}{qCD_j}\right\}}{\sum_j\sum_{l<MCRS}\left\{\frac{nCD_{jl}}{qCD_j}+\frac{nCC_{jl}}{qCC_j}+\frac{nPC_{jl}}{qPC_j}\right\}}$$

$$rP_+ = 100\times\frac{\sum_j\sum_{l>MCRS}\left\{\frac{nCD_{jl}}{qCD_j}\right\}}{\sum_j\sum_{l>MCRS}\left\{\frac{nCD_{jl}}{qCD_j}+\frac{nCC_{jl}}{qCC_j}+\frac{nPC_{jl}}{qPC_j}\right\}} \quad (7)$$

where the outer summation in (7) is over hauls j over the hauls with the specific gear configuration and the inner summation is over length classes l.

The indicators rP_- and rP_+ quantify the effect of fishing on the population structure of the target species with the specific gear. A small value of rP_- means that the gear retains only a small fraction of individuals below MCRS. High rP_+ values, preferably close to 100, would mean that most individuals over MCRS that enter the gear are retained. To quantify the extent to which the SMP releases the fish that entered the trawl, the averaged percentage of individuals below (esP_-) and above (esP_+) MCRS that escaped through the panel compared to those entering were estimated for the species investigated. The formulae used to calculate esP_- and esP_+ values are as follows:

$$esP_- = 100\times\frac{\sum_j\sum_{l<MCRS}\left\{\frac{nPC_{jl}}{qPC_j}\right\}}{\sum_j\sum_{l<MCRS}\left\{\frac{nCD_{jl}}{qCD_j}+\frac{nCC_{jl}}{qCC_j}+\frac{nPC_{jl}}{qPC_j}\right\}}$$

$$esP_+ = 100\times\frac{\sum_j\sum_{l>MCRS}\left\{\frac{nPC_{jl}}{qPC_{jl}}\right\}}{\sum_j\sum_{l>MCRS}\left\{\frac{nCD_{jl}}{qCD_j}+\frac{nCC_{jl}}{qCC_j}+\frac{nPC_{jl}}{qPC_j}\right\}} \quad (8)$$

For the SMP to have a positive effect on the exploitation pattern of the targeted species, esP_- should be significantly above zero and esP_+ close to zero. Furthermore, to quantify the SMP contribution to the overall escapement that occurs during the experimental fishing, an average percentage of individuals below ($resP_-$) and above ($resP_+$) MCRS escaping through the SMP, compared to the overall escapement, were estimated for the investigated species. The formulae used to calculate $resP_-$ and $resP_+$ values are as follows:

$$resP_- = 100\times\frac{\sum_j\sum_{l<MCRS}\left\{\frac{nPC_{jl}}{qPC_j}\right\}}{\sum_j\sum_{l<MCRS}\left\{\frac{nCC_{jl}}{qCC_j}+\frac{nPC_{jl}}{qPC_j}\right\}}$$

$$resP_+ = 100\times\frac{\sum_j\sum_{l>MCRS}\left\{\frac{nPC_{jl}}{qPC_{jl}}\right\}}{\sum_j\sum_{l>MCRS}\left\{\frac{nCC_{jl}}{qCC_j}+\frac{nPC_{jl}}{qPC_j}\right\}} \quad (9)$$

For the SMP to have any major effect on the exploitation pattern for the fishing gear, at least one of the parameters in (9) should have a value much higher than zero. The 95% confidence bands for rP_-, rP_+, esP_-, esP_+, $resP_-$ and $resP_+$ values were estimated using the double bootstrap method described above, taking into account between-haul variation and within-haul variation in the exploitation pattern.

3. Results

3.1. Overview of the sea trials

During the experimental period, 32 hauls were carried out and length measurements for 5852 hake, 5720 horse mackerel, and 7524 blue whiting were taken (Table 3). However, based on the acceptance protocol established, the final pool of hauls included in the analysis consisted of 28 hauls for hake, 25 for horse mackerel, and 23 for blue whiting. The number of fish captured and length-measured in each of the configurations and species are provided in Table 3.

3.2. Release efficiency

Table 4 summarizes the model combinations resulting in the lowest AIC value for each configuration tested. In some cases, there were alternative models with identical AIC values, meaning that the support for these other models was equally strong. In those cases, the simplest model was chosen. The fit statistics showed that, for hake and horse mackerel, models (2) and (3) were able to describe the experimental data well for most configurations (Table 4; Figs. 4,5). In the case with stimulation by floats, the low p-value associated with horse mackerel was attributed to overdispersion of the data because there was no clear pattern in the deviations between the experimental data and the fitted escape probability curve (Fig. 5). This overdispersion was probably caused by the heavy subsampling in the data collection process.

Among the tested configurations, the SMP release efficiency of hake and horse mackerel in the Bay of Biscay was low (Figs. 4,5), with an estimated escape below 1% in most cases (Table 4). The only exception was the LED light treatment for horse mackerel, in which the release efficiency was close to 4% for the smallest sizes (Fig. 5*j*). This was also manifested in the C_{SMP} values obtained, which were estimated to be 0.01 for hake in every configuration and below 0.03 for horse mackerel in every case, meaning that only a low proportion of these fish made contact with the SMP (1 and 3%, respectively) (Table 4). Figs. 4 and 5 show that most of the individuals of these species that escaped did so through the codend. Even so, in the case of hake, $L50_{comb}$ was around 17 cm (Table 4), and for individuals of 27 cm length (hake's MCRS) the retention probability was above 90% for every configuration (Fig. 6).

The modelling enabled comparison of gear selectivity with and without stimulation. The results showed that the release efficiency of the panel with stimulation did not significantly differ from no-stimulation situation (Fig. 7*a*, *c*, *e*). The release efficiency through the SMP for horse mackerel did not differ significantly among configurations (Fig. 8*a, c, e*). However, the overall retention of this species was significantly lower when using rope stimulation (Fig. 8*b*), reaching an estimated effect of 40% less escape for some length classes (between 12 and 20 cm in size). Differences in codend size selectivity when using ropes caused these differences in gear retention, as the $L50_{CD}$ for the rope configuration was significantly different from that of the baseline design (Table 4).

For blue whiting, the panel contact values were higher than for hake and horse mackerel in all configurations tested (between 20 and 53%), but the wide 95% confidence intervals made the inference for blue whiting uncertain (Table 4; Fig. 6). $L50_{comb}$ values were estimated to be over its marketable size (18 cm; this species does not have a MCRS) in all configurations, and because the selection ranges (*SR*) were quite narrow, individuals below 18 cm had low probability of being retained. The poor p-values for almost all treatments (Table 4) were probably due to overdispersion in the data created by heavy subsampling ratios, as the experimental data and the fitted escape probability curve showed no clear deviation patterns.

The results show that the configuration with floats significantly improved the release of blue whiting through the SMP for a range of lengths (10–15 cm) (Fig. 9*c*). However, the improved release of this configuration was not manifested in the combined retention of the gear (Fig. 9*d*). In this case, $L50_{CD}$ values (between 19.3–22.4; Table 4) show that the small fish not released in the first selection process through the panel would escape anyway in the second process through the codend due to its selection properties. In contrast, LED lights over the SMP had a statistically significant negative effect on the release of this species through the panel (between 15 and 27 cm; Fig. 9*e*). Consequently, the combined retention of blue whiting between 21 and 27 cm was significantly higher (Fig. 9*f*).

Regarding the exploitation pattern, the values obtained for rP_{-} and rP_{+} show that the exploitation pattern of the selective system, consisting of SMP and codend, was species-dependent (Table 5). For hake, rP_{+} was high (above 96.0%) for every configuration, although rP_{-} was estimated to be relatively high too, meaning that a large fraction of small hake was also retained (around 46% for ropes and floats stimulation treatments and around 41% for LED light stimulation). For blue whiting, rP_{-} was estimated to be below 1.3% for every configuration. In contrast, for horse mackerel with no-stimulation and LED light treatments rP_{-} values were estimated to be 27.8% (CI: 12.2–46.6%) and 22.1% (CI:17.4–27.3%), respectively, implying that a larger fraction of undersized individuals of these species entering the gear were retained. For horse mackerel, the rP_{+} value was relatively high, as the retention rate was above 69.7% for every configuration, except for rope stimulation (40.5% (CI: 16.9–64.1)). Blue whiting above 18 cm had a retention of almost 90% when lights were used, but it was below 66% for the rest of the tested configurations.

The results show that the SMP does not affect the exploitation pattern of hake or horse mackerel much, as the values for esP_{-} and esP_{+} for every configuration were low. For undersized hake, the estimated values (*esP-*) were below 1%, with the upper confidence limit never

Table 3
Summary of hauls used, no. of individuals retained in the codend (*CD*), codend cover (*CC*), and SMP cover (*PC*), no. of individuals < MCRS, and length range of all individuals caught. The number of fish measured is given in brackets. [1]MCRS for hake: 27 cm; [2]MCRS for horse mackerel: 15 cm; [3]blue whiting does not have a MCRS but it has a minimum marketable size of 30 individuals/Kg (EC, 1996). This is equivalent to 18 cm in length according to the weight-length ratio for this species (Dorel, 1986).

Stimulation/design	No-stimulation	Ropes	Floats	LED lights
Hake				
No. of hauls used	8	6	6	8
Lenght range (cm)	7-58	7-56	8-58	7-60
Total no. in *CD*	1015 (1015)	543 (543)	832 (832)	1045 (1045)
No. in *CD* < MCRS[1]	621 (621)	325 (325)	412 (412)	497 (497)
Total no. in *CC*	986 (986)	375 (267)	473 (473)	697 (647)
No. in *CC* < MCRS[1]	983 (983)	367 (263)	465 (465)	695 (645)
Total no. in *PC*	16 (16)	6 (6)	11 (11)	11 (11)
No. in *PC* < MCRS[1]	10 (10)	4 (4)	7 (7)	7 (7)
Horse mackerel				
No. of hauls used	7	5	6	7
Lenght range (cm)	10-35	10-36	10-35	10-39
Total no. in *CD*	1222 (926)	2378 (465)	1344 (876)	1745 (768)
No. in *CD* < MCRS[2]	292 (235)	300 (65)	419 (245)	502 (257)
Total no. in *CC*	839 (644)	6500 (476)	3839 (838)	1886 (496)
No. in *CC* < MCRS[2]	733 (564)	3491 (249)	3442 (739)	1705 (440)
Total no. in *PC*	37 (37)	69 (69)	19 (19)	106 (106)
No. in *PC* < MCRS[2]	23 (23)	23 (23)	13 (13)	68 (68)
Blue whiting				
No. of hauls used	8	6	3	6
Lenght range (cm)	7-31	8-31	10-32	10-31
Total no. in *CD*	1619 (936)	1037 (556)	333 (333)	1209 (513)
No. in *CD* < MCRS[3]	47 (40)	21 (11)	17 (17)	67 (39)
Total no. in *CC*	5512 (1033)	2894 (544)	2132 (533)	4290 (471)
No. in *CC* < MCRS[3]	5184 (914)	2570 (459)	2016 (504)	4213 (461)
Total no. in *PC*	2387 (1015)	1227 (609)	2438 (598)	1121 (383)
No. in *PC* < MCRS[3]	1914 (606)	926 (395)	2258 (550)	1060 (358)

Table 4
Selected models based on the lowest AIC values, selectivity results and fit statistics are shown for the different species, configuration, and compartment (square mesh panel (SMP); codend (CD) and combined effect of the codend and the SMP (Comb)). 95% CIs (in brackets).

		Hake			
Stimulation/Design		**No-stimulation**	**Ropes**	**Floats**	**LED lights**
Models	SMP	*CLogit*	*CLogit*	*CLogit*	*CLogit*
	CD	*Richard*	*Gompertz*	*Gompertz*	*Logit*
L50 **(cm)**					
SMP		37.07 (21.22–37.10)	30.03 (0.10–30.07)	36.06 (0.10–36.08)	29.99 (24.05–30.04)
CD		16.95 (16.02–17.92)	17.32 (15.43–19.53)	17.37 (16.18–18.28)	17.35 (16.20–18.40)
Comb		16.98 (16.05–17.95)	17.36 (15.45–19.59)	17.42 (16.21–18.32)	17.37 (16.23–18.44)
SR **(cm)**					
SMP		0.10 (0.10–7.42)	0.10 (0.10–19.16)	0.10 (0.10–0.10)	0.10 (0.10–0.10)
CD		4.37 (3.45–5.11)	5.88 (3.58–8.02)	5.51 (4.33–7.00)	3.71 (2.90–4.34)
Comb		4.41 (3.48–5.17)	5.96 (3.60–8.11)	5.59 (4.43–7.03)	3.74 (2.92–4.38)
C_{SMP}		0.01 (0.00–0.02)	0.01 (0.00–0.03)	0.01 (0.00–0.02)	0.01 (0.00–0.02)
Deviance		59.29	82.57	53.72	44.51
DOF		82	77	77	89
p-Value		0.972	0.311	0.980	1.000
		Horse mackerel			
Stimulation/Design		**No-stimulation**	**Ropes**	**Floats**	**LED lights**
Models	***SMP***	*CLogit*	*CLogit*	*CPogit*	*CProbit*
	CD	*Gompertz*	*Gompertz*	*Gompertz*	*Logit*
L50 **(cm)**					
SMP		28.00 (0.10–56.70)	23.04 (17.58–61.92)	24.05 (15.03–62.02)	30.01 (0.10–30.02)
CD		14.11 (13.23–14.69)	16.96 (15.61–20.13)	15.48 (14.24–16.49)	14.77 (14.48–15.09)
Comb		14.16 (13.34–14.74)	16.99 (15.65–20.13)	15.49 (14.25–16.49)	14.84 (14.54–15.18)
SR **(cm)**					
SMP		0.10 (0.10–53.69)	0.10 (0.10–6.34)	0.10 (0.10–6.67)	0.10 (0.10–43.11)
CD		2.71 (2.26–3.38)	3.94 (2.67–6.22)	3.03 (2.47–4.06)	2.61 (2.16–3.24)
Comb		2.80 (2.30–3.48)	3.99 (2.72–6.18)	3.05 (2.50–4.10)	2.70 (2.23–3.36)
C_{SMP}		0.02 (0.01–0.66)	0.01 (0.00–0.02)	0.00 (0.00–0.01)	0.03 (0.01–0.32)
Deviance		45.57	36.45	67.61	53.82
DOF		47	35	45	49
p-Value		0.532	0.401	0.016	0.295
		Blue whiting			
Stimulation/Design		**No-stimulation**	**Ropes**	**Floats**	**LED lights**
Models	***SMP***	*CGompertz*	*CGompertz*	*CGompertz*	*CGompertz*
	CD	*Richard*	*Logit*	*Richard*	*Logit*
L50 **(cm)**					
SMP		27.62 (23.14–34.76)	30.59 (0.10–38.43)	25.75 (11.77–94.93)	20.57 (0.10–25.14)
CD		20.76 (19.06–21.59)	21.36 (20.36–22.20)	22.42 (21.44–22.99)	19.31 (16.77–20.76)
Comb		21.70 (20.47–22.25)	22.33 (21.12–23.63)	23.73 (21.81–25.45)	19.74 (17.09–21.20)
SR **(cm)**					
SMP		8.99 (0.10–15.73)	15.48 (0.10–66.87)	10.93 (0.10–60.27)	6.12 (1.80–14.75)
CD		3.44 (2.67–4.41)	3.94 (2.87–4.59)	3.16 (1.87–4.35)	3.71 (2.88–4.25)
Comb		4.81 (3.26–10.56)	5.55 (3.65–7.58)	5.05 (2.56–69.53)	3.98 (3.06–4.61)
C_{SMP}		0.27 (0.21–0.38)	0.26 (0.10–0.86)	0.53 (0.46–1.00)	0.20 (0.13–0.90)
Deviance		105.10	105.10	51.84	79.07
DOF		40	40	34	31
p-Value		< 0.001	< 0.001	0.026	< 0.001

exceeding 2%. For undersized horse mackerel, the estimated values never exceeded 3%, and upper confidence limit was always below 7%. $resP_-$ and $resP_+$, which quantify how much the SMP contributes to the total escape, also demonstrated the low effect of the panel. The estimated $resP_-$ values for hake were below 1.5%, and the upper confidence limit never exceeded 3.7%. $resP_-$ and $resP_+$ for horse mackerel also show the low effect of the SMP on the total escape, and especially for sizes below MCRS, the estimated value never exceeded 3.9% with the upper confidence limit always below 8.6%. However, the contribution of the SMP to the overall escapement of legal sizes of horse mackerel was higher, reaching 17.5% (CI: 6.4–29.2%) when LED light-based stimulation was used. In contrast to hake and horse mackerel, a higher proportion of small blue whiting escaped through the SMP, with esP_- estimated to be between 19.9 and 52.6% depending on configuration.

3.3. Underwater observations

Underwater video recordings showed that the SMP and codend meshes remained open during the recorded trials (Table 2) and that the covers did not mask the meshes. Further, they showed that the stimulation devices were physically functioning as intended. With respect to fish behavior in relation to the SMP, none of the configurations seemed to affect fish behavior differently from the no-stimulation treatment. Hake individuals usually swam next to the bottom, passively drifted backwards towards the codend, and did not show any reaction to the SMP. Horse mackerel and blue whiting exhibited more active behavior, mostly swimming in the towing direction along the extension piece (close to the SMP area) until they became exhausted and drifted towards the codend. In addition, blue whiting showed more active and erratic behavior in front of the SMP; many of these individuals turned and swam quickly either towards the panel or the codend. This behavior resulted in greater physical contact with the SMP, although most of the time they were not properly oriented and therefore most of them did not manage to escape through it.

4. Discussion

The LO represents a big challenge for multi-species trawl fisheries (De Vos et al., 2016) such as the Basque bottom otter trawl fishery. It

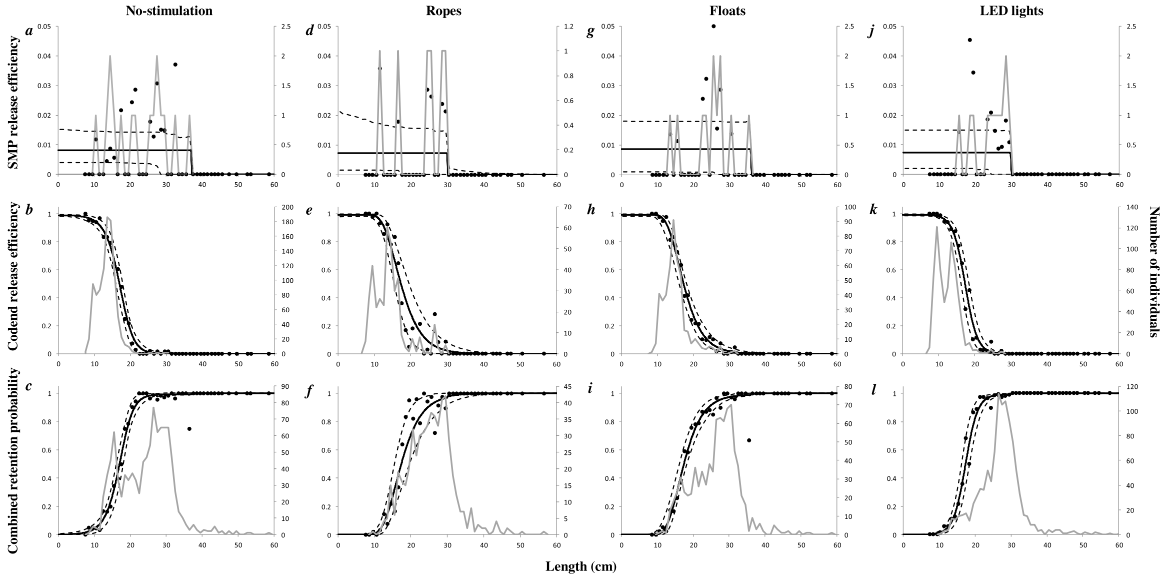

Fig. 4. Relative catch size-frequency distributions (grey lines) of hake retained in the codend (CD), codend cover (CC), and SMP cover (PC), the mean escapement curves (solid black lines) for SMP escapement (a, d, g, j), codend escapement (b, e, h, k), and combined retention (combined effect of the codend and the SMP) (c, f, i, l). All of them show 95% CIs (dashed lines). *Note that the y-axis for SMP release efficiency has a different order of magnitude in order to properly observe the data.

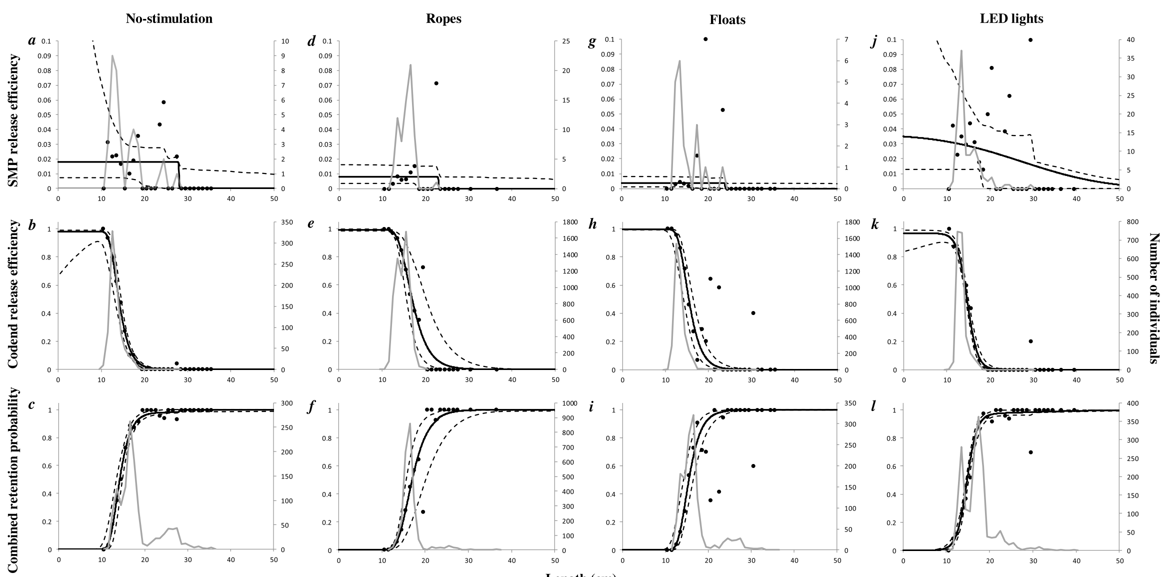

Fig. 5. Relative catch size-frequency distributions (grey lines) of horse mackerel retained in the codend (CD), codend cover (CC), and SMP cover (PC), the mean escapement curves (solid black lines) for SMP escapement (a, d, g, j), codend escapement (b, e, h, k), and combined retention (combined effect of the codend and the SMP) (c, f, i, l). All of them show 95% CIs (dashed lines). *Note that the y-axis for SMP release efficiency has a different order of magnitude to properly observe the data.

has been shown that undersized fish release efficiency through the 70 mm diamond mesh codend and the SMP is low (Rochet et al., 2014) due to low contact with the panel (Alzorriz et al., 2016). In the present study, we aimed to increase contact of fish. We attempted to stimulate escape behavior of hake, horse mackerel, and blue whiting through a panel made of 82.7 mm square meshes.

In general, the results obtained in this study showed that the stimulators, based on ropes, floats, or LED lights, barely increased the contact probability of the species tested with the SMP. For hake, escape probability was low for all stimulators tested, and it was not significantly different compared to the treatment without stimulation. Herrmann et al. (2014) and Krag et al. (2016a) reported that to improve fish escapement in non-tapered netting sections, additional stimuli are needed because in the absence of these stimuli, most fish drift towards the codend without seeking escape through the selection device. However, in the present study, despite the implementation of different stimuli, hake had very low probability of encountering the SMP. This, together with the SMP's release efficiency curves, underscores the low effectiveness of the SMP in releasing undersized individuals of this species when inserted in the upper panel of the extension piece and regardless of the presence of the stimuli. In addition, underwater observations made during the cruise demonstrated that hake did not display any active escape behavior; instead they fell back through the extension piece until reaching the aft end of the gear. This behavior and the observed preference for swimming close to the lower panel, also observed in other species (e.g. cod (*Gadus morhua*)) (Sistiaga et al., 2011, 2017), makes it difficult to improve the efficiency of the SMP (Alzorriz et al., 2016; Nikolic et al., 2015). Previous research (Grimaldo et al., 2017) also documented the low effectiveness of similar stimulators on the release efficiency of cod through a square mesh section.

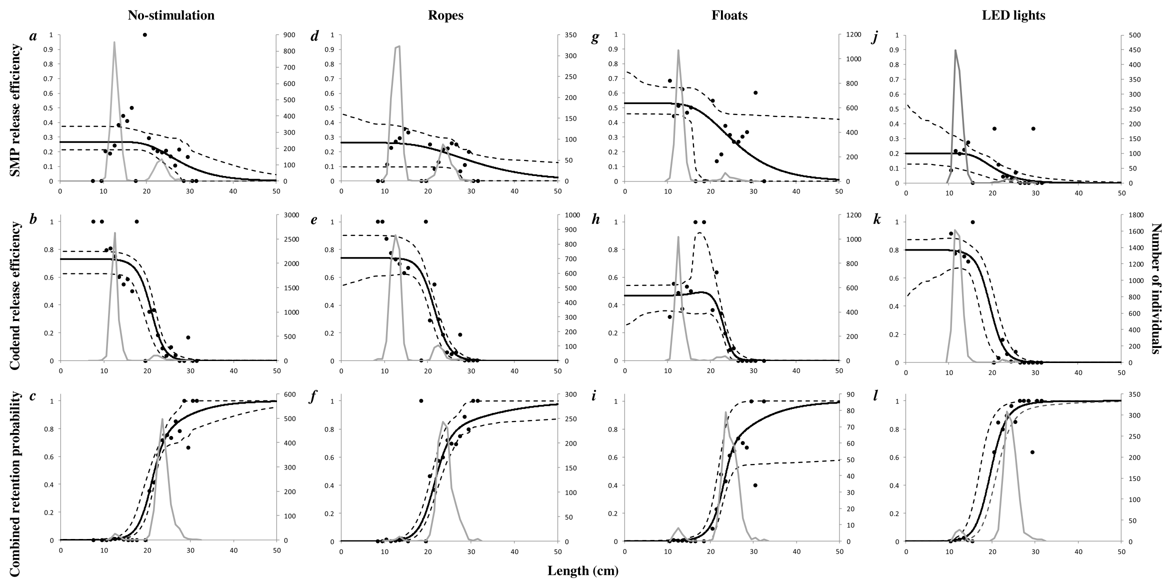

Fig. 6. Relative catch size-frequency distributions (grey lines) of blue whiting retained in the codend (CD), codend cover (CC), and SMP cover (PC), the mean escapement curves (solid black lines) for SMP escapement (a, d, g, j), codend escapement (b, e, h, k), and combined retention (combined effect of the codend and the SMP) (c, f, i, l). All of them show 95% CIs (dashed lines).

Horse mackerel showed a contact probability of between 0 and 3% for the different configurations tested. Thus, the estimated release efficiency of the SMP for this species was low and not significantly different from the no-stimulation treatment. Earlier studies (Herrmann et al., 2014; Krag et al., 2016b) showed that escape stimulation by similar floats through a SMP, placed on the upper part of the codend and the extension piece, respectively, significantly improved the escapement of cod. Grimaldo et al. (2017) also indicated that the use of mechanical stimulation based on floats could improve the release efficiency of 40 cm haddock (*Melanogrammus aeglefinus*) through a square mesh section by 50% (although these results were not statistically significant). In this study, we observed that fish tried to avoid contact with the stimulators based on ropes and floats by swimming in front of them until reaching exhaustion and then drifting towards the codend.

Blue whiting, compared to hake and horse mackerel, showed higher contact probability with the panel, which was between 20 and 26% for no-stimulation, stimulation by ropes, and LED light-based stimulation treatments. In general, and supported by underwater observations, their active swimming behaviour seemed to increase the contact probability with the SMP. In particular, when stimulation by floats was used to trigger fish escape, blue whiting showed higher contact probability (53%), and the estimated release efficiency of the SMP for individuals below 18 cm was between 47.6 and 53.1%. Compared to the treatment without stimulation, the estimated release efficiency for blue whiting between 10 and 15 cm was significantly improved, by almost 30%. However, this effect had no impact on codend size selectivity because codend selection properties would release any small individual retained in the first selection process by the panel. Therefore, any change in panel selectivity for small blue whiting would not be evident in the combined retention probability. Additionally, the assessment of the release efficiency with float stimulation was based on few hauls (3 hauls). The hauls not included were heavily subsampled, which would have highly affected the results. This resulted in a weaker experimental base for these results, which is reflected in the wider confidence bands for the size selection curves obtained. Therefore, following the protocol established, the analyses were carried out with a considerably lower number of hauls. Even if limiting the number of hauls in the analysis meant using fewer hauls than often applied for such assessment, we

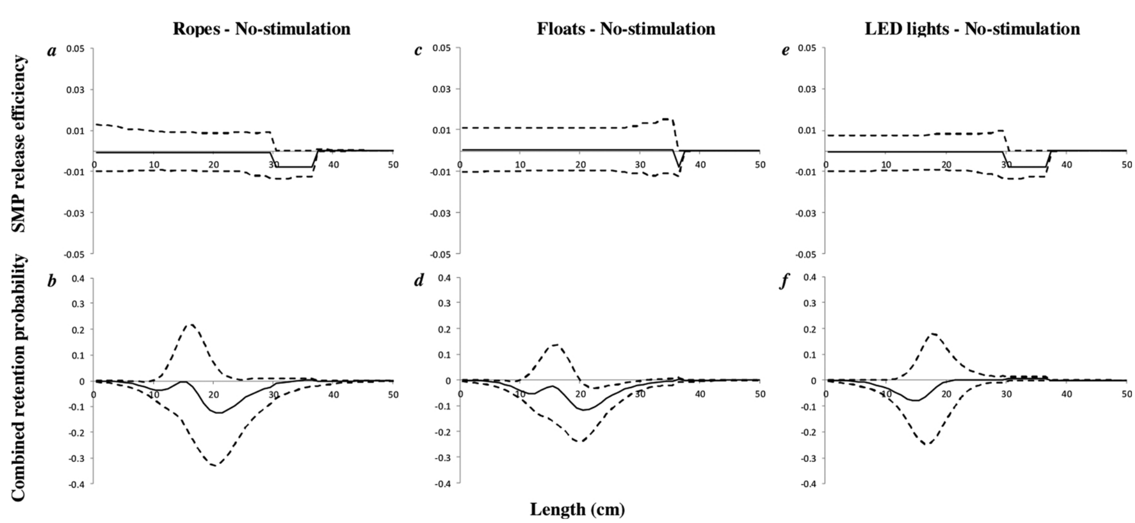

Fig. 7. Change in SMP release efficiency (a, c, e) and in combined retention (b, d, f) for hake. Dashed lines represent 95% CIs. * Note that the y-axis for SMP release efficiency has a different order of magnitude to properly observe the data.

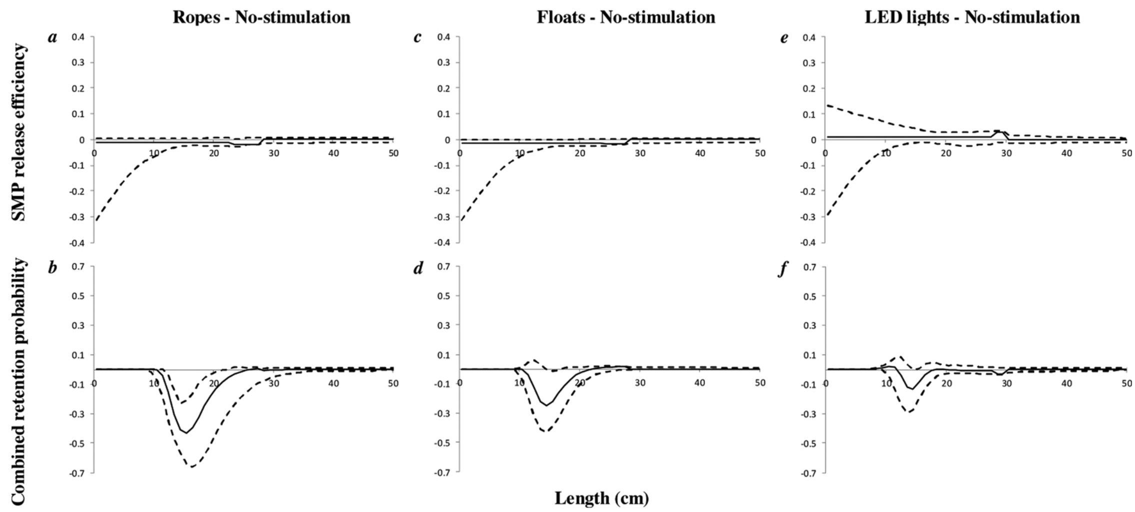

Fig. 8. Change in SMP release efficiency (a, c, e) and in combined retention (b, d, f) for horse mackerel. Dashed lines represent 95% CIs. * Note that the y-axis for SMP release efficiency has a different order of magnitude to properly observe the data.

considered this as the most correct approach. The number of hauls with these configurations was lower than we would normally recommend for making definitive conclusions. Therefore, our results for these designs should be considered as preliminary, but still relevant.

Our results also suggest that blue LED light stimulation decreased the escape probability through the SMP of blue whiting individuals between 15 and 27 cm. In general, blue LED light affected the escape probability of blue whiting negatively, although these results were only significant for a specific length range. This effect was reflected in the combined retention of the trawl, which was significantly higher for some length classes. Quality of the underwater images for the light treatment was not sufficient to analyze fish behaviour, but active behavior of this species was observed in the other three treatments when light was used to obtain underwater images (Table 2). The behavior of blue whiting could be compared with what Grimaldo et al. (2017) described for haddock when they got close to the green light stimulators placed on the extension piece of the trawl. These haddocks exhibited erratic behaviour when approaching the LED lights, which led them to hit the netting in a way that did not allow them to make contact with the SMP. This could explain the low release efficiency of blue whiting when LED lights were used compared to no-stimulation treatment. Many studies have demonstrated that visual stimulation may affect fish behaviour and the selective properties of trawl gear (Hannah et al., 2015; Larsen et al., 2018; Lomeli and Wakefield, 2014; Ryer and Olla, 2000; Walsh and Hickey, 1993). The processes through which light affects marine fish are still not completely understood because being attracted or repulsed by light depends on many factors, including species, ontogenetic development, ecological factors, light intensity, and light wavelength (Marchesan et al., 2005). In this study, lights were used during many hauls to illuminate the recordings (Table 2), which could have affected fish behaviour. However, lights were needed to check for adequate performance of the trawl and the research trials were time limited, thus we could not repeat these hauls to include non-illuminated hauls in the data analysis.

For all species and treatments, most of the escape was observed in the codend, and the contribution of the SMP was low. These results are in agreement with the observations of Brčić et al. (2016, 2018), who concluded that a SMP inserted in front of the codend had little effect on the escapement of hake, horse mackerel, and other species in a Mediterranean bottom trawl fishery. Alzorriz et al. (2016) also reported 47% escape of undersized hake through the codend, and less than 1% through the SMP. Our findings revealed no improvement in size selection for hake by inserting a SMP together with any of the stimulators and that individuals below their MCRS still had a high probability of being retained by the gear.

Previous studies on Portuguese crustacean trawl fishery (Campos and Fonseca, 2004) showed that a window made of 100 mm square meshes positioned in the upper panel of the belly section, 3.3 m before the

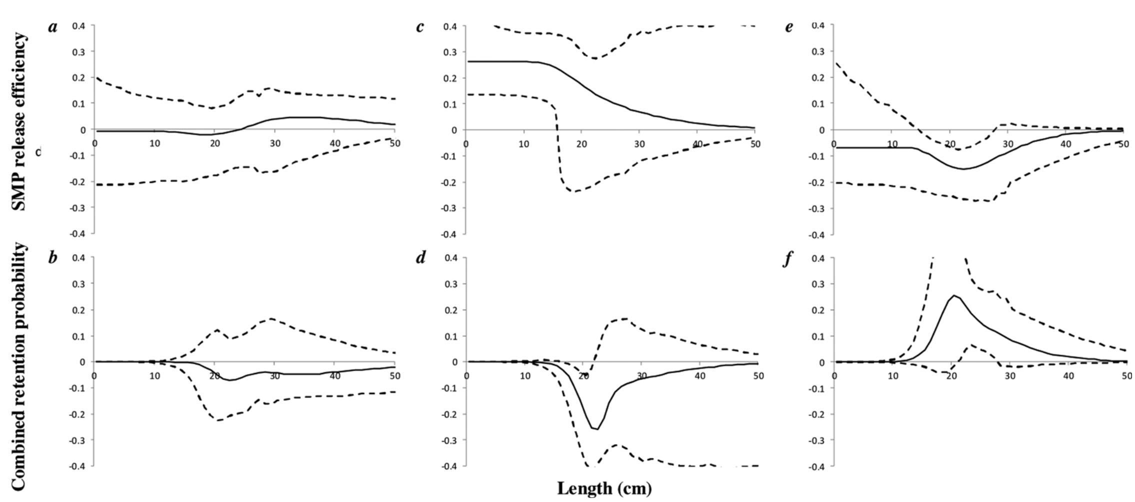

Fig. 9. Change in SMP release efficiency (a, c, e) and in combined retention (b, d, f) for blue whiting. Dashed lines represent 95% CIs. * Note that the y-axis for SMP release efficiency has a different order of magnitude to properly observe the data.

Table 5
Values of exploitation pattern indicators and their 95% CIs (in brackets) for all species in the different panel configurations. [1]MCRS for hake: 27 cm; [2] MCRS for horse mackerel: 15 cm; [3]blue whiting does not have a MCRS but it has a minimum marketable size of 30 individuals/Kg (EC, 1996), and this is equivalent to 18 cm in length according to the weight:length ratio for this species (Dorel, 1986).

Stimulation/Design	No-stimulation	Ropes	Floats	LED lights
Hake[1]				
rP_-	38.48 (34.76–41.81)	46.63 (32.94–61.78)	46.61 (36.40–55.16)	41.45 (30.31–54.30)
$rP+$	97.77 (95.61–99.45)	96.04 (87.14–100)	97.22 (94.07–98.82)	98.92 (97.33–100.00)
esP_-	0.62 (0.22–1.15)	0.57 (0.00–1.41)	0.79 (0.00–1.93)	0.58 (0.09–1.13)
$esP+$	1.49 (0.25–3.19)	0.88 (0.00–3.14)	0.93 (0.00–1.86)	0.72 (0.00–2.44)
$resP_-$	1.01 (0.36–1.86)	1.08 (0.00–3.18)	1.48 (0.00–3.61)	1.00 (0.16–1.93)
$resP+$	66.67 (12.50–100)	22.22 (0.00–100)	33.33 (0.00–88.89)	66.67 (0.00–100.00)
Horse mackerel[2]				
rP_-	27.77 (12.17–46.57)	7.87 (2.18–16.34)	10.81 (4.23–34.91)	22.12 (17.35–27.33)
rP_+	88.57 (84.04–94.69)	40.48 (16.92–64.09)	69.65 (53.35–85.19)	85.13 (74.30–90.87)
esP_-	2.19 (0.56–4.64)	0.60 (0.21–1.51)	0.34 (0.03–0.82)	2.99 (1.14–6.82)
esP_+	1.33 (0.43–2.25)	0.90 (0.43–1.75)	0.45 (0.06–1.13)	2.60 (1.21–4.31)
$resP_-$	3.04 (0.86–7.50)	0.65 (0.23–1.66)	0.38 (0.03–0.93)	3.83 (1.46–8.56)
$resP_+$	11.67 (5.31–20.75)	1.51 (0.76–4.57)	1.49 (0.17–5.88)	17.51 (6.38–29.17)
Blue whiting[3]				
rP_-	0.66 (0.26–1.57)	0.60 (0.06–1.19)	0.40 (0.00–1.09)	1.25 (0.37–4.21)
rP_+	66.29 (61.03–72.01)	61.95 (54.12–71.75)	51.63 (36.17–84.38)	89.36 (80.32–98.35)
esP_-	26.78 (20.98–37.25)	26.34 (4.87–38.81)	52.62 (45.41–63.87)	19.87 (9.93–29.94)
esP_+	19.96 (13.42–30.30)	18.35 (11.14–25.85)	29.41 (0.00–42.75)	4.69 (0.69–8.95)
$resP_-$	26.96 (21.06–37.57)	26.49 (4.92–38.87)	52.83 (45.44–64.56)	20.12 (10.26–30.54)
$resP_+$	59.20 (40.77–84.42)	48.24 (34.79–69.38)	60.81 (0.00–71.54)	44.12 (17.33–84.38)

codend, was efficient at excluding blue whiting but not horse mackerel. Graham et al. (2003) found that moving the panel closer to the codline increased the *L50* for haddock. Herrmann et al. (2014) found that the release efficiency of the SMP in the BACOMA codend largely depended on how close the panel was to the catch-accumulation zone (0–6 m from the codline). Compared to these studies, the panel distance from the codline in our study (10 m) may have been one of the reasons for the poor efficiency of the panel, as fish in the extension piece had no chance to change direction and swim up through the panel meshes even if stimulated. Other researchers also have mentioned that fish are exhausted when they reach the SMP area, so they are unable to attempt active escape (Winger et al., 2010) or may be reluctant to change swimming direction to save energy (Peake and Farrell, 2006). Besides, the towing speed during the hauls in our study was around 3 knots, whereas in real conditions a commercial trawl would tow at 4 knots, which could lead to greater exhaustion when the catch arrives in the extension piece.

Alzorriz et al. (2016) demonstrated that under commercial fishing operations, the selective properties of the trawls deployed by the Basque bottom otter trawl fleet in the Bay of Biscay did not satisfactorily release undersized individuals due to low contact. In the present study, we showed that the stimulators used to increase contact probability with the SMP were mostly ineffective, and the retention of undersized fish was still high. Hake did not react significantly to any of the stimulation treatments, whereas a significantly higher proportion of horse mackerel and blue whiting escaped through the SMP. These results indicate a clear behavioral difference compared to hake. Although this study provided greater understanding of fish behaviour inside the trawl, the contribution of the SMP to overall escape was unsatisfactory. Considering the new CFP, unwanted catches still represent a major challenge for this fishery. In order to comply with the LO, this may have a direct influence on each vessel's ability to optimize its economic revenue. Therefore, future studies should focus on maximizing SMP contact probability or improving codend release efficiency. Alternatively, future studies could also consider investigating the applicability of other bycatch reduction devices like sorting grids in this fishery.

Declaration of Competing Intere

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Acknowledgements

We are grateful to the crew of *Emma Bardan* for their valuable assistance during the cruise. We also thank the two anonymous reviewers for the comments that helped to improve this manuscript. Finally, we are thankful to the MAPAMA for funding the research and lending the *RV Emma Bardan*.

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Paper II

“Release efficiency and selectivity of four different square mesh panel configurations in the Basque mixed bottom trawl fishery”

Scientia Marina 84(1)
March 2020, 39-47, Barcelona (Spain)
ISSN-L: 0214-8358
https://doi.org/10.3989/scimar.04975.17A

Release efficiency and selectivity of four different square mesh panel configurations in the Basque mixed bottom trawl fishery

Elsa Cuende [1], Luis Arregi [1], Bent Herrmann [2,3], Manu Sistiaga [4], Mikel Basterretxea [1]

[1] AZTI-Tecnalia, Marine Research Division, Txatxarramendi ugartea w/n, Sukarrieta, 48395, Spain.
(EC) (Corresponding author) E-mail: elsacuende@gmail.com. ORCID iD: https://orcid.org/0000-0002-5787-5612
(LA) E-mail: larregi@azti.es. ORCID iD: https://orcid.org/0000-0001-6273-3654
(MB) E-mail: mbasterretxea@azti.es. ORCID iD: https://orcid.org/0000-0001-7684-4398
[2] SINTEF Ocean, Fishing Gear Technology, Willemoesvej 2, Hirtshals, 9850, Denmark.
[3] The Arctic University of Norway, UiT, Breivika, Tromsø, N-9037, Norway.
(BH) E-mail: Bent.Herrmann@sintef.no. ORCID iD: https://orcid.org/0000-0003-1325-6198
[4] Institute of Marine Research, Postboks 1870 Nordnes, Bergen, 5817, Norway.
(MS) E-mail: Manu.Sistiaga@hi.no. ORCID iD: https://orcid.org/0000-0002-0750-0900

Summary: Reduction of discards from the Basque mixed bottom trawl fishery is a challenge. To improve the selective properties of the gear used by the fleet and supplement codend size selection, a square mesh panel (SMP) installed in the upper panel of the trawl was introduced in 2006. However, recent studies have shown that the release efficiency of this SMP is low due to lack of contact between the fish and the SMP. In this study, we tested the release efficiency of the SMP for four different gear configurations. We tested the effect of adding LED lights at two different positions and altering panel size and panel position in the trawl. The analyses were focused on two species: hake (*Merluccius merluccius*) and blue whiting (*Micromesistius poutassou*). The results showed that the position of LED lights did not significantly affect the SMP's release efficiency for any species. However, increasing panel size had a significant positive effect on the release efficiency of blue whiting, and placing the SMP in the lower panel improved the release efficiency of hake. These results highlight the challenge of simultaneously improving the selective properties of gear for species with different behaviour, especially in mixed demersal fisheries.

Keywords: square mesh panel; LED lights; trawl fishery; release efficiency; hake; blue whiting.

Eficiencia de escape y selectividad de cuatro configuraciones diferentes aplicadas a un panel de malla cuadrada en la pesquería multiespecífica de arrastre del País Vasco

Resumen: La reducción de descartes en la pesquería de arrastre del País Vasco supone un problema importante. En 2006, se introdujo en la reglamentación la posibilidad de usar un Panel de Malla Cuadrada (SMP) en la zona anterior al copo para mejorar la selectividad de la red. Sin embargo, estudios recientes manifiestan que la eficiencia de escape de los peces es baja debido a la falta de contacto selectivo entre el pez y el panel. En este estudio, analizamos la eficiencia de diferentes configuraciones del SMP. Se analizó el efecto de luces LED colocadas en distintas posiciones, el efecto del tamaño del SMP y su localización. Estudiamos la merluza (*Merluccius merluccius*) y la bacaladilla (*Micromesistius poutassou*). La posición de las LED demostró no tener ningún efecto significativo sobre la eficiencia de escape del SMP para ninguna de las dos especies. Sin embargo, aumentar el área del panel tuvo un efecto significativo en la eficiencia de escape de la bacaladilla, mientras que el cambio de posición del SMP incrementó la eficiencia de escape de la merluza a través del SMP. Estos resultados muestran el reto que supone mejorar la selectividad de un arte de pesca simultáneamente para especies demersales con comportamientos diferentes.

Palabras clave: panel de malla cuadrada; luces LED; pesca de arrastre; eficiencia de escape; merluza; bacaladilla.

Citation/Como citar este artículo: Cuende E., Arregi L., Herrmann B., Sistiaga M., Basterretxea M. 2020. Release efficiency and selectivity of four different square mesh panel configurations in the Basque mixed bottom trawl fishery. Sci. Mar. 84(1): 39-47. https://doi.org/10.3989/scimar.04975.17A

Editor: P. Sartor.

Received: July 4, 2019. **Accepted:** November 12, 2019. **Published:** January 28, 2020.

INTRODUCTION

The landing obligation established under the new Common Fisheries Policy (EU 2013) aims to eliminate the discard of commercial species and represents a big challenge for mixed fisheries with large quantities of discards (de Vos et al. 2016). The Basque demersal bottom trawl fishery operating in the ICES VIIIabd area is one of such fisheries. Total catch includes more than 100 different marine species, and the fishery is subject to large quantities of discards (~60–65% of the total catch in the period 2011-2013; Rochet et al. 2014).

According to the regulations specified by the European Commission (EC 2006), the vessels participating in this fishery usually use a trawl net with a 70 mm diamond mesh codend combined with a 100 mm square mesh panel (SMP) (2 m long, 1 m wide) inserted in the upper panel of the extension piece of the trawl. However, recent studies have shown that most undersized individuals that escape the gear do so through the codend rather than through the panel (Nikolic et al. 2015, Alzorriz et al. 2016).

Mesh size modifications in the codend are often not well received by fishermen because they may lead to potential loss of economically valuable fish (Bahamon et al. 2006). On the other hand, SMPs can be an alternative measure to increase the escape of some species without excessively affecting profitability (Brčić et al. 2016). Several studies have investigated the functioning and release efficiency potential of SMPs, but the release efficiency of SMPs has often been estimated to be low due to the low probability of contact of the fish with the panel (Herrmann et al. 2014, Alzorriz et al. 2016, Brčić et al. 2018). There have been attempts to improve the fish-panel contact probability by inserting stimulating devices in the gear. Stimulators are designed to trigger fish escape behaviour, but the results obtained so far have shown varying degrees of success (e.g. Glass and Wardle 1995, Herrmann et al. 2014, Grimaldo et al. 2017). Mechanical stimulators have been shown to reduce the retention rate of some juvenile fish species (e.g. Kim and Whang 2010), and in some cases light-based stimulators have been able to induce fish escape behaviour through the escape path (e.g. Hannah et al. 2015, Lomeli et al. 2018).

The main goal of the present study was to determine whether the release efficiency of an SMP installed at the top panel of the extension piece of the trawl could be improved by applying different modifications: i) adding white LED lights at different positions of the panel, ii) changing the size of the panel, and iii) changing the position of the panel in the trawl. This study focused on hake (*Merluccius merluccius*) and blue whiting (*Micromesistius poutassou*), which are two common gadoids in the northeast Atlantic and are important species in this fishery (Rochet et al. 2014).

MATERIALS AND METHODS

Sea trials and data collection

Sea trials were carried out on board the R/V *Emma Bardan* (29 m length overall; 900 kW) from 1 to 15 June 2018 in the Bay of Biscay (ICES division VIIIb) (Fig. 1). All hauls were carried out during daylight.

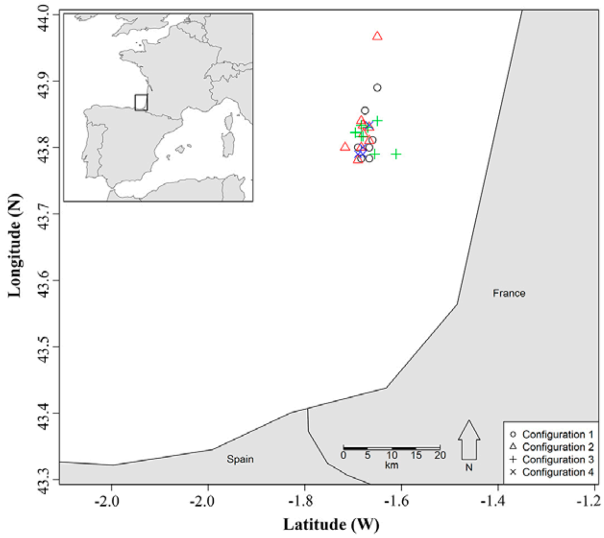

Fig. 1. – Sampling area and positions of the experimental hauls. Different symbols represent the configurations tested during each haul. Conf. 1: a standard SMP inserted in the upper panel with 10 white LED lights placed longitudinally over it. Conf. 2: the same as Conf. 1, but with 10 white LED lights placed longitudinally in the lower panel in front of the SMP. Conf. 3: a large SMP inserted in the upper panel. Conf. 4: a standard SMP inserted in the lower panel. Standard SMP: mesh size (M), 82.7 mm; area (A), 2.64 m^2. Large SMP: (M), 80.0 mm; (A), 4.77 m^2.

A four-panel bottom trawl (GOC73; Bertrand et al. 2000) was used. This trawl was built according to the standard bottom trawl survey manual for the Mediterranean (Anonymous 2016). The towing rig was spread with a set of Morgère doors (Morgère WH S8 type, 2.6 m^2, 350 kg), 100 m sweeps, and a light rockhopper ground gear (with 3 × 40 kg chain + 15 kg chain on the bosom). The trawl had a headline of 35.7 m and a fishing line of 40.0 m. While fishing, the trawl had a horizontal opening of 16.0 m and a vertical opening of between 2.7 and 3.2 m. We inserted an SMP into the extension piece of the trawl, 1 m in front of the joint between the codend and the extension piece (Fig. 2). The SMP was placed either in the upper or the lower panel and was of different sizes depending on the configuration tested (Fig. 2). Configurations 1 and 2 were designed to determine the release efficiency of a standard SMP (mesh size 82.7 mm, area 2.64 m^2) with white LED lights attached in the upper and lower panel of the extension piece, respectively. Configuration 3 was designed to determine the release efficiency of a larger SMP (mesh size 80.0 mm, area 4.77 m^2) in the upper panel of the extension piece, while configuration 4 tested the release efficiency of the standard SMP in the lower panel of the extension piece. In every case, codend release efficiency and combined retention probability were also estimated. A total of 28 experimental hauls were conducted, the towing speed was between 3.0 and 3.3 knots, and depths varied between 108 and 122 m.

The codend (CD) used together with the panel was 7.0 m long (72.8 mm mesh size, 4 mm polyamide (PA) double twine). The SMP cover (PC) was 13 m long

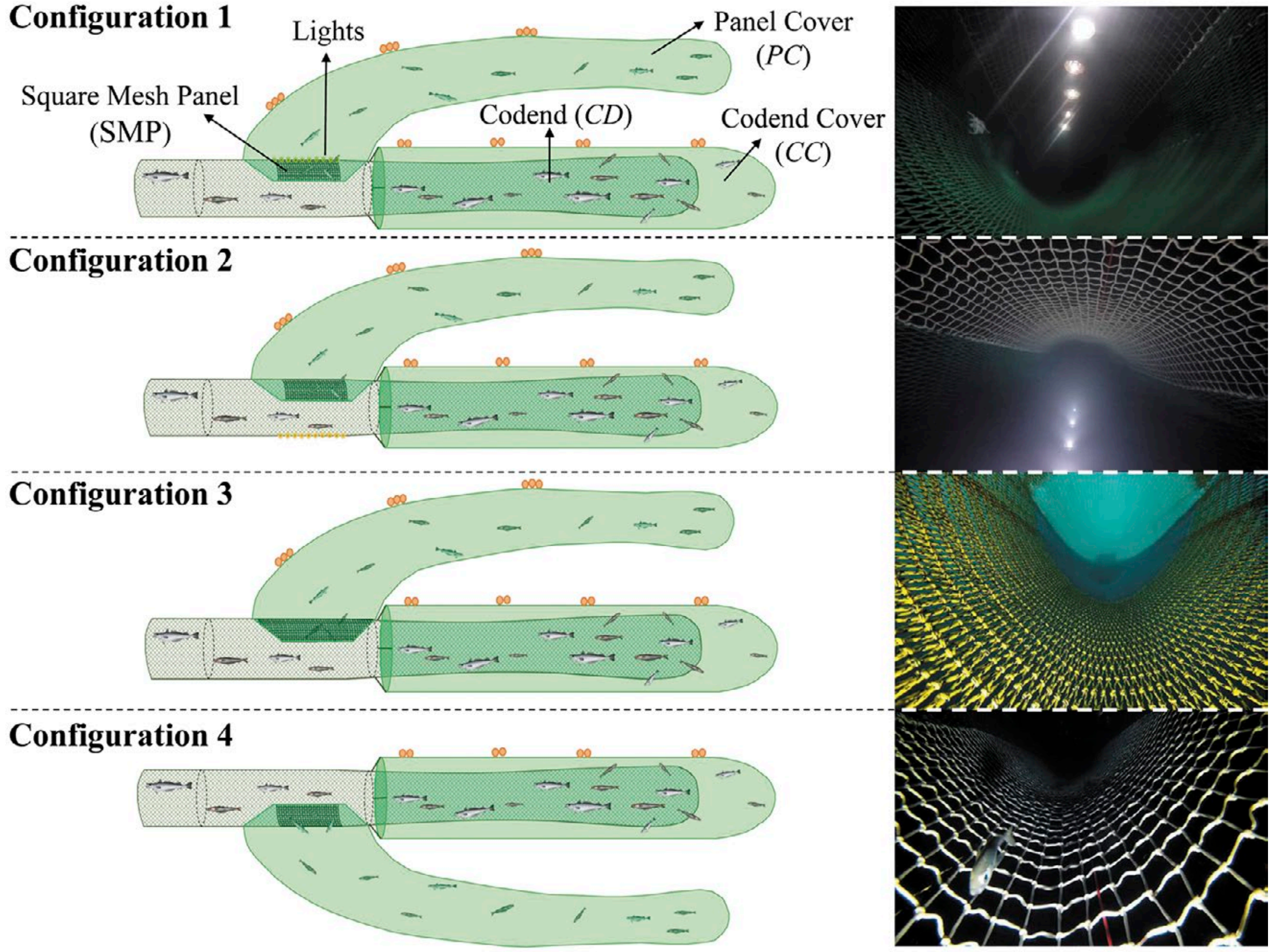

Fig. 2. – Representation of the four gear configurations tested (see explanations in Fig. 1).

(26.1 mm mesh size, 1.2 mm PA twine), and the codend cover (CC) was 9 m long (26.5 mm mesh size, 1.3 mm PA twine). Each experimental haul was carried out with one configuration at a time. Hake and blue whiting individuals caught were measured to the nearest centimetre below (Table 1). The minimum conservation reference size (MCRS) for hake is 27 cm total length (TL). For blue whiting, which does not have an MCRS, its marketable size limit is estimated to be 18 cm TL. This TL is based on a regulation that establishes a maximum of 30 individuals of blue whiting per kilo for commercialization (Dorel 1986, EC 1996).

Selectivity model

The number of fish of length l retained in the three compartments (CD, PC and CC) can be modelled using a multinomial distribution with length-dependent probability of being retained in the codend $r_{\text{comb}}(l)$; escaping through the SMP $e_{\text{SMP}}(l)$; and escaping through the codend $e_{\text{codend}}(l)$. The combined retention can be modelled as follows, where l represents fish length:

$$r_{\text{comb}}(l) = 1 - e_{\text{SMP}}(l) - e_{\text{codend}}(l) \quad (1)$$

First, fish arrive inside the extension piece where the SMP is located, and they can either actively contact the SMP (first selection process) or simply continue to drift towards the codend. We assumed that the probability for fish to contact the panel could be modelled with the length-independent parameter C_{SMP}. C_{SMP} quantifies the fraction of fish that contact the device, assuming they enter the zone of the device in the trawl and are therefore subjected to a size-dependent probability of escaping through it. This leads to the following model for $e_{\text{SMP}}(l)$:

$$e_{\text{SMP}}(l) = C_{\text{SMP}} \times (1 - rc_{\text{SMP}}(l, \boldsymbol{v}_{\text{SMP}})), \quad (2)$$

where $rc_{\text{SMP}}(l, \boldsymbol{v}_{\text{SMP}})$ is the selectivity model for fish making contact with the SMP and having a suitable orientation to achieve a size-dependent probability of passing through the SMP mesh, and $\boldsymbol{v}_{\text{SMP}}$ are the parameters in the model $rc_{\text{SMP}}(l, \boldsymbol{v}_{\text{SMP}})$. We assumed that $rc_{\text{SMP}}(l, \boldsymbol{v}_{\text{SMP}})$ can be described by one of the standard S-shaped size selection models for trawl gears. We considered four S-shaped size selection curves: Logit, Probit, Gompertz and Richard. Further information about these models, their respective parameters $\boldsymbol{v}$, and estimation of the selectivity parameters L50 and SR (L50 is the length at which a fish has a 50% chance of being retained by the SMP, whereas SR is the difference between L75 and L25) can be found in Wileman et al. (1996).

Table 1. – Summary of data collected for hake and blue whiting retained in the SMP cover (PC), codend (CD) and codend cover (CC). The raised number of fish measured is given in brackets.

	Configuration no.	1	2	3	4
Hake	No. hauls	7	9	8	4
	Length range (TL, cm)	7-48	7-59	7-60	6-53
	nPC	1 (1)	9 (9)	48 (48)	820 (820)
	nCD	215 (215)	381 (381)	807 (807)	244 (244)
	nCC	1011 (1011)	1656 (2769)	1909 (1909)	1856 (1856)
Blue whiting	No. hauls	7	4	6	3
	Length range (cm)	12-33	19-32	12-32	9-30
	nPC	158 (158)	70 (70)	430 (1071)	7 (7)
	nCD	1259 (1986)	562 (871)	616 (1260)	290 (548)
	nCC	205 (205)	47 (47)	57 (57)	196 (196)

To model the size-dependent codend retention probability $rc_{codend}(l,\boldsymbol{v}_{codend})$, we assumed that every fish entering the codend came into contact with the codend meshes and that $rc_{codend}(l,\boldsymbol{v}_{codend})$, like $rc_{SMP}(l,\boldsymbol{v}_{SMP})$ could be modelled by a Logit, Probit, Gompertz or Richard model. The estimation of codend escape involves solely the fish that have not escaped through the SMP. The above considerations led to the following model for $e_{codend}(l)$:

$$e_{codend}(l) = (1 - rc_{codend}(l,\boldsymbol{v}_{codend}))\times(1 - e_{SMP}(l,C_{SMP},\boldsymbol{v}_{SMP})) \quad (3)$$

Model estimation

The values of C_{SMP}, $\boldsymbol{v}_{SMP}$, and $\boldsymbol{v}_{codend}$ for selection models (1)-(3) were obtained for each species and gear configuration using maximum likelihood estimation (MLE) by pooling the experimental data over the hauls *j* (*1* to *m*) with the specific gear configuration and minimizing:

$$-\sum_{l}\sum_{j=1}^{m}\left\{\frac{nCD_{lj}}{qCD_j}\times\ln\left(r_{comb}(l,C_{SMP},\boldsymbol{v}_{SMP},\boldsymbol{v}_{codend})\right)+ \right.$$
$$+\frac{nPC_{lj}}{qPC_j}\times\ln\left(e_{SMP}(l,C_{SMP},\boldsymbol{v}_{SMP})\right)+ \quad (4)$$
$$\left.+\frac{nCC_{lj}}{qCC_j}\times\ln\left(e_{codend}(l,C_{SMP},\boldsymbol{v}_{SMP},\boldsymbol{v}_{codend})\right)\right\}$$

where for each haul *j* and length class *l*, nCD_{lj}, nPC_{lj} and nCC_{lj} are the numbers of individuals length-measured in the CD, PC and CC, respectively, and qCD_j,

Table 2. – Based on Equations (1)-(3), selectivity results for the two species, the different configurations, and compartments (square mesh panel (SMP); codend (CD), and combined effect of the codend and the SMP (Comb)). Estimated selectivity parameters, 95% CIs (in brackets), and fit statistics are provided. DOF, degrees of freedom; Dev, deviance.

Hake	Configuration no. 1	2	3	4
Model				
rc_{SMP}	Logit	Logit	Logit	Gompertz
rc_{codend}	Richard	Gompertz	Gompertz	Richard
L50 (cm)				
SMP	11.95 (0.10-11.96)	16.05 (11.79-16.08)	32.07 (31.04-32.10)	18.76 (1.20-23.70)
CD	18.06 (16.46-20.19)	20.42 (17.14-24.38)	15.71 (14.52-17.05)	22.27 (19.21-26.00)
Comb	18.06 (16.46-20.19)	20.42 (17.14-24.38)	15.79 (14.61-17.13)	22.87 (19.78-26.60)
SR (cm)				
SMP	0.10 (0.10-0.91)	0.10 (0.10-2.43)	0.10 (0.10-0.10)	6.69 (0.10-12.30)
CD	4.88 (2.67-6.24)	7.92 (4.98-11.82)	4.99 (3.91-6.34)	7.89 (4.63-11.78)
Comb	4.88 (2.67-6.24)	7.92 (4.98-11.81)	5.15 (4.06-6.52)	7.75 (4.94-11.04)
C_{SMP}	0.00 (0.00-0.01)	0.00 (0.00-0.01)	0.02 (0.01-0.03)	0.33 (0.10-0.94)
Dev	21.82	62.24	102.44	121.27
DOF	66	69	81	70
p-value	1.00	0.71	0.05	0.00

Blue whiting	Configuration no. 1	2	3	4
Model				
rc_{SMP}	Logit	Gompertz	Gompertz	Logit
rc_{codend}	Gompertz	Gompertz	Gompertz	Logit
L50 (cm)				
SMP	77.74 (29.30-200.00)	29.62 (20.19-72.18)	32.39 (29.81-197.57)	29.00 (0.10-200.00)
CD	19.51 (14.87-22.23)	21.07 (0.51-21.97)	18.33 (11.28-22.23)	23.76 (20.67-25.54)
Comb	19.85 (15.57-22.40)	21.29 (9.26-22.21)	23.96 (17.01-160.65)	23.80 (20.77-25.57)
SR (cm)				
SMP	3.32 (0.10-6.10)	0.90 (0.10-20.79)	1.99 (0.10-48.72)	0.10 (0.10-8.37)
CD	5.11 (2.76-9.09)	3.03 (1.98-13.71)	4.50 (1.16-6.73)	4.11 (2.49-7.81)
Comb	5.84 (3.11-10.44)	3.51 (2.43-13.62)	14.26 (8.85-176.98)	4.16 (2.50-7.87)
C_{SMP}	0.07 (0.05-0.09)	0.07 (0.04-1.00)	0.45 (0.26-0.66)	0.01 (0.00-0.02)
Dev	28.93	97.03	25.81	12.70
DOF	29	23	23	27
p-value	0.47	0.00	0.31	0.99

qPC_j, and qCC_j are their respective subsampling factors (ratio of length measured to total number of fish caught in each compartment). In total, 16 models were considered based on the combination of the four S-shaped functions considered for $rc_{SMP}(l)$ and $rc_{codend}(l)$. The model showing the lowest Akaike information criterion value (AIC; Akaike 1974) was selected. MLE using expression (4) with (1) to (3) requires pooling experimental data over hauls. This results in stronger data for average size-selectivity estimation but does not consider explicit variation in selectivity between hauls (Fryer 1991). To account for the effect of both between-haul variation and the uncertainty in individual hauls when estimating uncertainty in size selection, we applied a double bootstrap method (Herrmann et al. 2012). We estimated the 95% Efron percentile confidence intervals (95% CIs) (Efron 1982) for $e_{SMP}(l)$, $e_{codend}(l)$ and $r_{comb}(l)$ curves by carrying out 1000 bootstrap iterations.

Evaluation of the ability of the models to describe the experimental data was based on inspecting the fit statistics (i.e. the p-value and the model deviance versus the degrees of freedom (DOF)) following the procedures described by Wileman et al. (1996). The p-value expresses the likelihood of obtaining at least as big a discrepancy as that observed between the fitted model and the observed experimental data by coincidence. In cases with poor fit statistics (p-value<0.05; deviance>>DOF), the residuals were inspected to determine whether the poor result was due to structural problems when describing the experimental data using the model or to over-dispersion in the data (Wileman et al. 1996). All analyses were performed using the software tool SELNET (Herrmann et al. 2012).

To infer the effect of the different configurations on the length-dependent SMP escape probability, we compared the selectivity curves estimated between configurations (SMP release efficiency and combined selectivity). We first compared the effect on the release efficiency through the SMP of white LED lights placed at different positions in the extension piece (Configuration 1 vs. 2). We then compared the effect of increasing the SMP's area relative to the effect of the standard SMP placed on the lower panel of the extension piece (Configuration 3 vs. 4).

RESULTS

Table 1 shows the number of hake and blue whiting captured and the length measured in each of the configurations and compartments. A number of other species were caught as well: horse mackerel (*Trachurus trachurus*), mackerel (*Scomber scombrus*), megrim

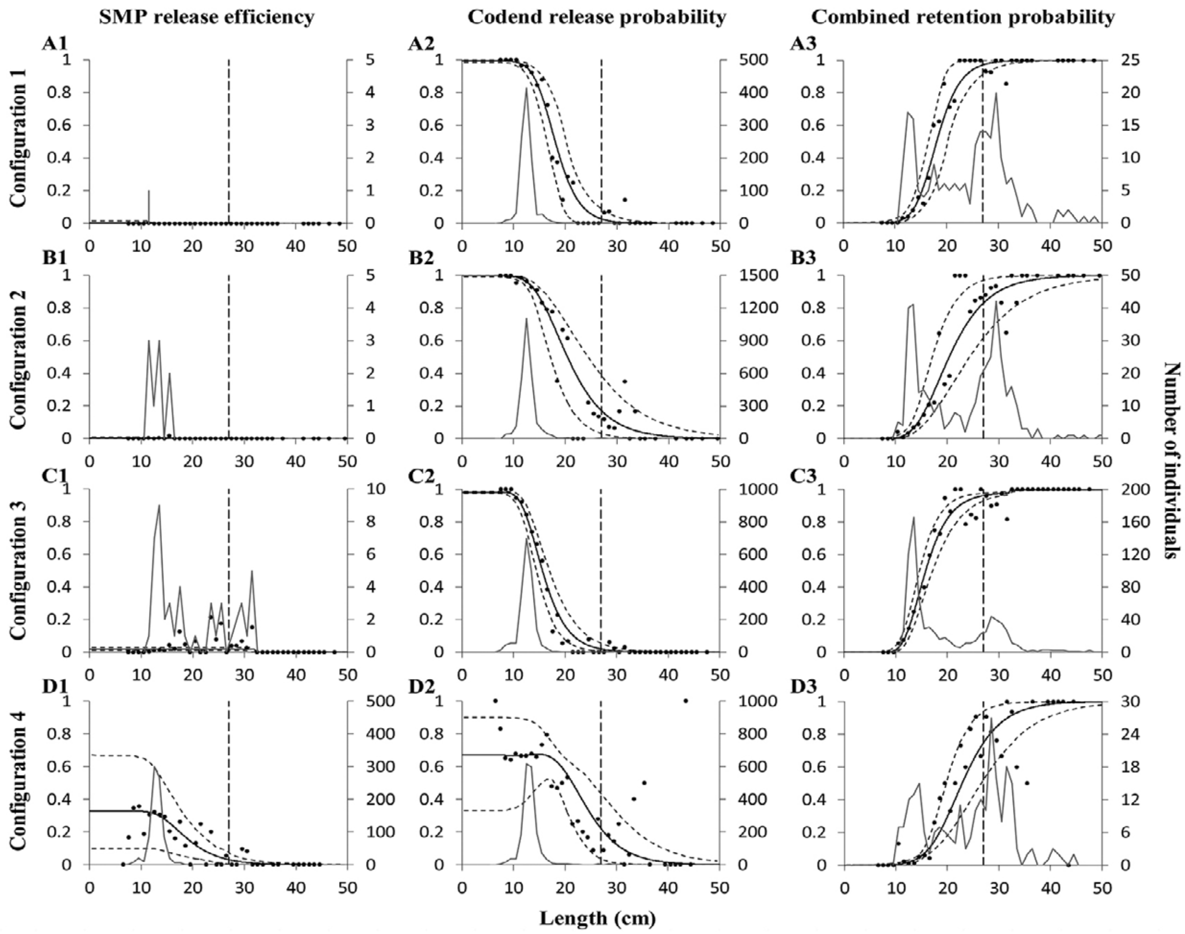

Fig. 3. – Escape probability through the SMP panel and the codend, and probability of being retained in the codend for hake in the different configurations tested. Grey lines, raised catch size-frequency distributions; solid circles, mean experimental rates per size class; solid black lines, mean escapement curves for SMP (A1-D1), codend (A2-D2) and combined retention (A3-D3). All of them show 95% CIs (dashed lines). Vertical stippled lines show the MCRS of hake: 27 cm TL.

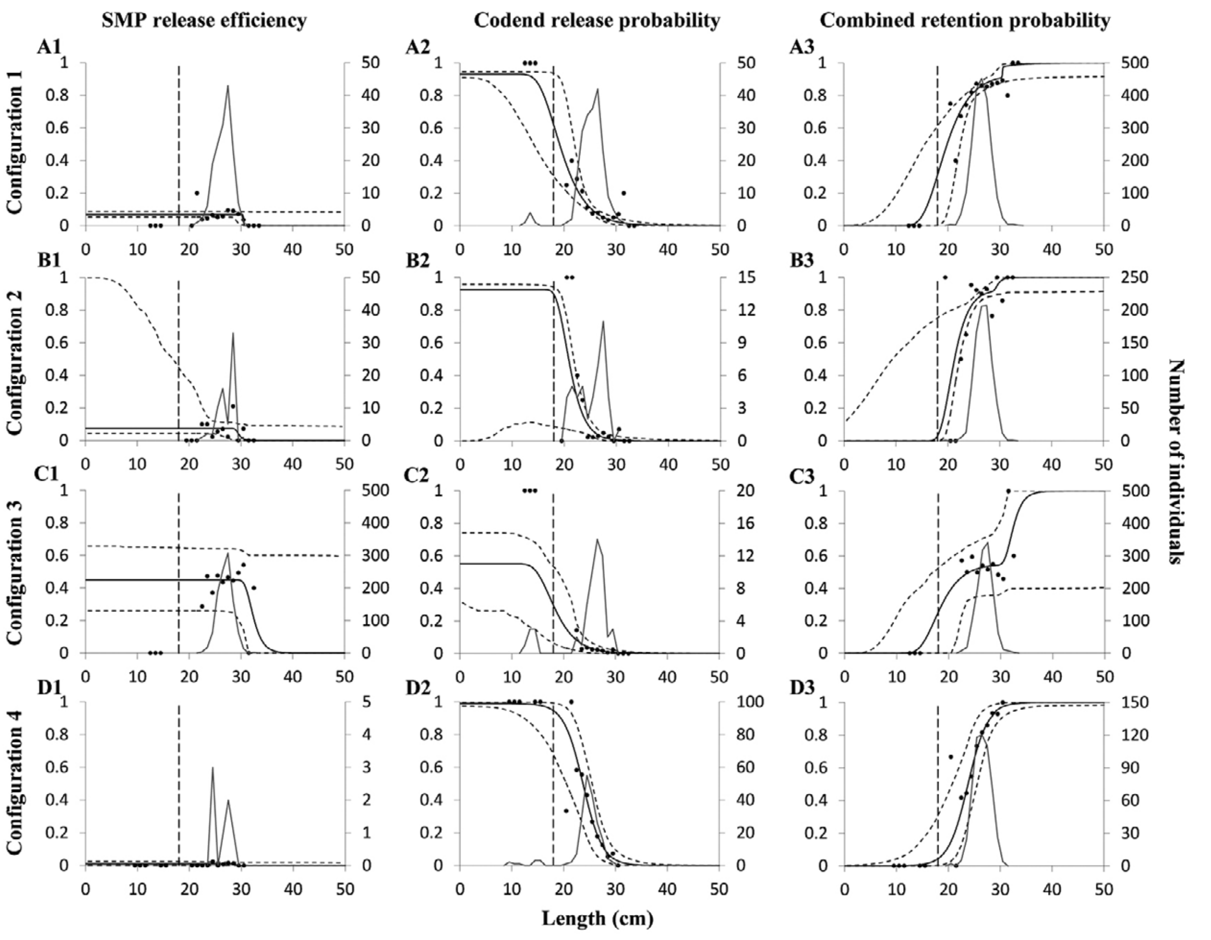

Fig. 4. – Escape probability through the panel and the codend, and probability of being retained in the codend for blue whiting in the different configurations tested. Grey lines, raised catch size-frequency distributions; solid circles, mean experimental rates per size class; solid black lines, mean escapement curves for SMP (A1-D1), codend (A2-D2) and combined retention (A3-D3). All of them show 95% CIs (dashed lines). Vertical stippled lines show the estimated minimum marketable size of blue whiting: 18 cm TL.

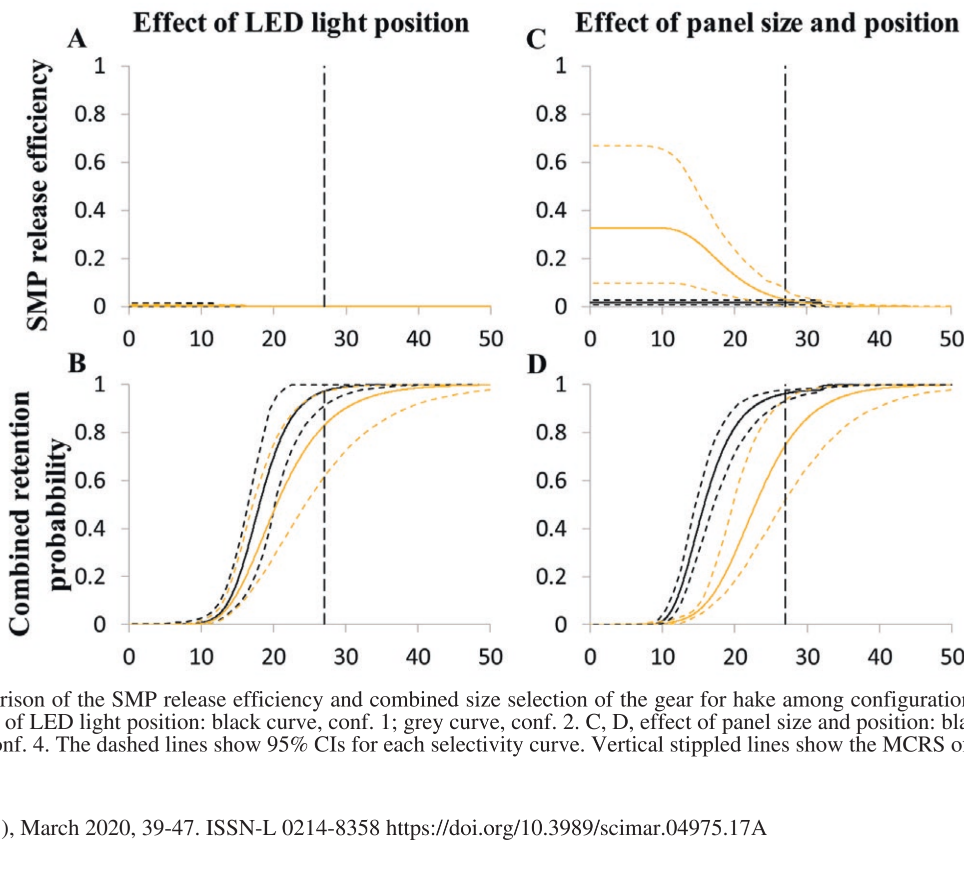

Fig. 5. – Comparison of the SMP release efficiency and combined size selection of the gear for hake among configurations applied in each test. A, B, effect of LED light position: black curve, conf. 1; grey curve, conf. 2. C, D, effect of panel size and position: black curve, conf. 3; yellow curve, conf. 4. The dashed lines show 95% CIs for each selectivity curve. Vertical stippled lines show the MCRS of hake: 27 cm TL.

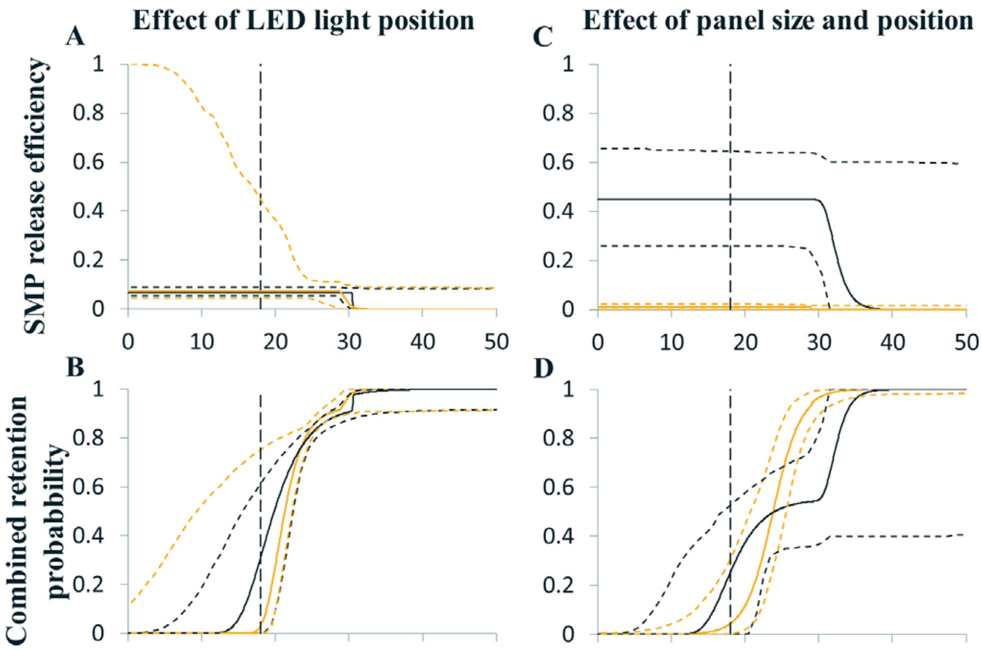

Fig. 6. – Comparison of the SMP release efficiency and combined size selection of the gear for blue whiting among configurations applied in each test. A, B, effect of LED light position: black curve, conf. 1; grey curve, conf. 2. C, D, effect of panel size and position: black curve, conf. 3; yellow curve, conf. 4. The dashed lines show 95% CIs for each selectivity curve. Vertical stippled lines show the estimated minimum marketable size of blue whiting: 18 cm TL.

(*Lepidorhombus* spp.) and boarfish (*Capros aper*). However, the numbers of these species caught were too low for selectivity analysis.

Table 2 summarizes the model combinations for SMP release (Equation 2) and codend release (Equation 3) resulting in the lowest AIC value for each configuration tested and the selectivity parameters estimated. Because the p-value was greater than 0.05 in most cases, the fit statistics showed that the models were able to describe the experimental data well for both species. The p-values lower than 0.05 obtained for hake when the SMP was placed in the lower panel and for blue whiting when lights were in the lower panel were attributed to over-dispersion in the data.

The release efficiency of hake and blue whiting through the SMP was low (Figs 3 and 4), except for hake when configuration 4 was applied and for blue whiting when configuration 3 was tested (Figs 3D1 and 4C1). This was also shown in the C_{SMP} values obtained (Table 2), which were estimated to be 0.33 for hake in configuration 4 and 0.45 for blue whiting in configuration 3. Figures 3A1-3, B1-3 and 4A1-3, B1-3 also show that LED lights, no matter the position, did not affect the escape probability through the SMP for either species.

Comparing both the SMP release and the combined SMP and codend retention probability curves between configurations 1 and 2 and between configurations 3 and 4 (Figs 5 and 6) enabled us to investigate the effect of each design change. No matter where the lights were located, the release of hake and blue whiting through the SMP remained very low due to the low contact probability and showed no significant differences between configurations (Figs 5A and 6A). The escape mainly happened through the codend (Figs 3A2-D2 and 4A2-D2). The release efficiency of hake below 24 cm TL was significantly higher when the standard SMP was placed in the lower panel than with the rest of the configurations applied (Fig. 5C). This finding may be related to the behaviour of this species (Alzorriz et al. 2016, Santos et al. 2016). On the other hand, the release efficiency of blue whiting was significantly higher when the large SMP was installed in the upper panel (Fig. 6C). However, this effect had almost no impact on the combined retention probability of the SMP and codend because codend size selection would release any small individual retained during the first selection process by the SMP (Fig. 6D). The combined retention was significantly lower only for larger individuals (between 26 and 30 cm TL) that did not escape through the codend.

DISCUSSION

Earlier studies by Alzorriz et al. (2016) and Brčić et al. (2016, 2018), which were carried out in the Atlantic Ocean and the Mediterranean Sea, respectively, showed that few individuals of hake escaped through SMPs located in front of the codend and on the top panel of the trawl. These low escape rates were attributed mainly to the low contact probability between the fish and the SMP, which resulted in few fish being size-selected by the panel. This low contact for hake was also found in the present study (the proportion of fish that contacted the SMP placed in the top panel of the trawl was not higher than 2% (CI: 0-3%) for any of the three different configurations tested). When the SMP was inserted in the lower panel of the trawl, the release efficiency of the SMP was significantly improved. Specifically, the release efficiency of the standard SMP placed in the lower panel for hake was significantly higher than that of the large SMP placed in the upper panel for individuals up to 24 cm TL (Fig. 5C). However, for the combined size selection, the effect of placing the SMP in the lower panel would only affect hake between 11 and 28 cm TL because hake below 11 cm TL would be released by the codend meshes (Fig. 5D). As in the present study, Santos et al. (2016) also studied the effect of changing the position of a 100 mm SMP. In their case, they tested the release efficiency of 10 m long SMPs integrated into the sides of the trawl in the last tapered section of the belly. The system was supplemented by a pentagon-shaped device that was mounted in the belly to guide fish towards the SMPs located on the sides. Their results showed that the contact probability of hake for SMPs inserted on the sides of the trawl far exceeded that of an equivalent SMP installed on the top panel of the gear. Thus, the results obtained by Santos et al. (2016) together with the results obtained in our study encourage testing positions other than the top panel of the trawl for SMPs that aim to release undersized individuals of hake.

The results of the present study also showed that hake and blue whiting responded differently to the modifications applied to the SMP. The contact with the SMP estimated when the SMP was located at the top panel of the trawl was significantly higher for blue whiting than for hake. Furthermore, when the large SMP was inserted in the upper panel, the probability of contact of blue whiting individuals with the SMP increased from values below 7% for the rest of the configurations to 45% (CI: 26–66%) (Fig. 4C1; Table 2), whereas the probability of contact of hake with the same configuration was estimated to be 2% (CI: 1–3%) (Fig. 3C1; Table 2). This result clearly demonstrates that the behavioural differences between hake and blue whiting in the aft part of the trawl can be substantial.

When white LED lights were installed on the SMP or in the panel right below the SMP, the release efficiency through the SMP was not significantly improved for either hake or blue whiting. Grimaldo et al. (2017) tested whether green LED lights could improve the release efficiency of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) through a square mesh section. No significant differences were found for cod, whereas the results for haddock only indicated an effect for the smaller individuals. Despite cod and haddock having different behavioural patterns in the aft part of a trawl (Engås et al. 1998, Ferro et al. 2007, Sistiaga et al. 2016), somewhat like hake and blue whiting, the results in the present study showed no difference in the behavioural response of hake and blue whiting to LED lights.

As in several previous studies, such as those on the Norwegian bottom trawl gadoid fishery in the Barents Sea (Engås et al. 1998) and the mixed whitefish trawl fishery in the North Sea (Ferro et al. 2007), our results highlight species-related behavioural differences in the aft part of the trawl. In some cases, these behavioural differences have been used to sort different species inside the trawl (Engås et al. 1998). Considering the behavioural differences between blue whiting and hake reported here and the poor contact of hake with the SMP installed on the top panel reported in other studies (Alzorriz et al. 2016, Brčić et al. 2016, 2018), it can be speculated whether the Basque mixed bottom trawl fishery is suited for species-specific selective measures in the aft part of the trawl. The results of this study support the hypothesis that modifications applied to the SMP can influence the release efficiency of hake and blue whiting in different ways, mainly determined by the specific behaviour of each species inside the trawl. However, they also illustrate the challenge of improving the selective properties of a gear in a mixed fishery simultaneously for more than one species. Moreover, this study demonstrated that fish behaviour is an important issue that should be considered when designing and implementing selectivity devices.

ACKNOWLEDGEMENTS

We would like to thank the editor and two anonymous reviewers for their valuable comments, which have certainly improved the manuscript. We thank the Spanish Ministry of Agriculture, Fisheries, Food and Environment for funding the research and for use of the R/V *Emma Bardan*, and we thank the crew of the *Emma Bardan* for their valuable assistance during the study.

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Paper III

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

Paper IV

“Optimizing size selectivity and catch patterns for hake (*Merluccius merluccius*) and blue whiting (*Micromesistius poutassou*) by combining square mesh panel and codend designs”

PLOS ONE

RESEARCH ARTICLE

Optimizing size selectivity and catch patterns for hake (*Merluccius merluccius*) and blue whiting (*Micromesistius poutassou*) by combining square mesh panel and codend designs

Elsa Cuende[1]*, **Manu Sistiaga**[2,3], **Bent Herrmann**[4,5,6], **Luis Arregi**[1]

1 Marine Research, AZTI Basque Research and Technology Alliance (BRTA), Sukarrieta, Bizkaia, Spain, **2** Fish Capture Division, Institute of Marine Research, Bergen, Norway, **3** Department of Marine Technology, Norwegian University of Science and Technology, Trondheim, Norway, **4** Fisheries and New Biomarine Industry, SINTEF Ocean, Fishing Gear Technology, Hirtshals, Denmark, **5** The Norwegian College of Fishery Science, UiT The Arctic University of Norway, Tromsø, Norway, **6** Fisheries Technology, DTU Aqua, Denmark Technical University, Hirtshals, Denmark

* ecuende@azti.es

Citation: Cuende E, Sistiaga M, Herrmann B, Arregi L (2022) Optimizing size selectivity and catch patterns for hake (*Merluccius merluccius*) and blue whiting (*Micromesistius poutassou*) by combining square mesh panel and codend designs. PLoS ONE 17(1): e0262602. https://doi.org/10.1371/journal.pone.0262602

Editor: Andreas C. Bryhn, Swedish University of Agricultural Science, SWEDEN

Received: August 31, 2021

Accepted: December 29, 2021

Published: January 20, 2022

Data Availability Statement: All relevant data are within the manuscript.

Funding: Secretaria General de Pesca (MAPA) - The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

Abstract

Gear modifications in fisheries are usually implemented to obtain catch patterns that meet management objectives. In the Basque bottom trawl fishery, gear regulations include the use of a square mesh panel (SMP) placed at the top panel of the extension piece of the trawl to supplement diamond mesh codend selectivity. However, the catch patterns obtained with this combination have raised concern among scientists and authorities. This study combines new data on different SMP and codend designs with existing data from the literature to produce new results that are applied to predict the size selectivity and catch patterns of different gear combinations for a variety of fishing scenarios. A systematic approach based on the concept of treatment trees was outlined and applied to depict the effect of individual and combined gear design changes on size selectivity and catch patterns for hake (*Merluccius merluccius*) and blue whiting (*Micromesistius poutassou*). This approach led to identification of the gear combination with the most appropriate exploitation pattern for these two species and improved the readability and interpretation of selectivity results. The results demonstrated that changes both in SMP and, especially, codend designs have a significant effect on hake and blue whiting size selectivity and catch patterns. Therefore, we believe that further research should prioritize codend size selectivity, and additional selection devices may be added once codend designs with good selective properties are achieved.

Introduction

Reducing the capture of non-target species and undersized individuals of commercial species is one of the major challenges of fisheries management [1, 2]. In the trawl fisheries of the

European Union (EU), considerable effort has been devoted in recent years to reduce discards and comply with the recently reformed Common Fisheries Policy (CFP). The strategies used to meet the new management objectives include the increased use of bycatch, a decrease or relocation of fishing effort and the application of more selective fishing gears [3]. Following the last of these strategies, extensive research has been conducted on towed fishing gears, especially aiming at the development of alternative gear designs to improve catch patterns (i.e., the composition of species and sizes in the catch) in specific fisheries (e.g., [4, 5]).

In several multispecies trawl fisheries, the applied gear designs have been modified to meet changes in management objectives such as quota availability, capture prohibition or discard bans [6–8]. For example, in the multispecies bottom trawl fishery of northern Spain (Basque Country), several fishing regulations were implemented in recent decades to stimulate the recovery of hake (*Merluccius merluccius*) [9–12]. In 2006, a 2 m long, 1 m wide, 100 mm mesh size square mesh panel (SMP) positioned in the upper panel of the trawl's extension piece was introduced in the regulation to supplement diamond mesh codend selectivity [13]. Combinations of SMPs and diamond mesh codends have been widely used in crustacean trawl fisheries (e.g., [14, 15]) because they can support the release of undersized roundfish while preventing the loss of crustaceans such as *Nephrops*, which usually enter the trawl closer to the lower netting panel [16, 17]. However, in several fish directed fisheries the performance of those gear designs has been unsatisfactory regarding reduction in captures of undersized fish of commercial species [18–20].

The release of fish through SMPs can be more problematic than through sorting grids or codend meshes because SMPs function by relying on fishes' swimming ability and active contact with the SMP [21–24]. Some gear has been designed with the aim of improving fish contact with the SMP (e.g. [21, 25]), but low contact rates remain a problem. Contact probability can vary between species depending on SMP size and position in the trawl [21, 26]. Cuende et al. [24] showed that the release efficiency of hake through an SMP placed in the bottom panel of the extension piece was significantly higher than that of a larger SMP placed in the top panel of the extension piece, while for blue whiting (*Micromesistius poutassou*) the opposite result was achieved.

Codends can also be modified in multiple ways to affect species and size catch patterns. Mesh size, shape, twine material, twine thickness and codend circumference influence species and size selectivity, both due to differences in behavior and the fish's ability to physically penetrate the codend meshes [27–29]. In bottom trawls, diamond meshes in the codend are normally only partially open and do not support the release of fish sizes that theoretically could escape through them at higher opening angles [30–32]. To mitigate this problem, some fisheries have implemented the use of codends entirely or partly constructed from square meshes [33], which keep an open shape during trawling [30, 34]. Different studies have demonstrated that compared to diamond mesh codends, square mesh codends can reduce discards, maintaining target catch efficiency [35, 36].

Individually, both SMPs and codends have limitations regarding size selection and consequently on obtainable catch patterns. In addition, the literature covering the size selectivity potential of different SMP and codend designs typically tests only a few gear types, partly for logistic reasons and partly to ensure that there are sufficient hauls to estimate the selection of each gear with reasonable precision. However, studies combining results from previous research have become more common in this field in recent years [16, 37–39], and have proven to be a suitable tool for exploring a broad range of selective gear options for use in a fishery without the time and cost outlay associated to experimental trials [16, 38, 40, 41].

In this study, we aim at identifying which SMP and codend design combination leads to the best catch patterns for hake and blue whiting. For this purpose, the selective properties of different SMPs and codend designs were estimated individually so that the selectivity of different SMP and codend combinations for different population scenarios could later be modeled. These two species are usually captured together by the different trawl fisheries operating in the Bay of Biscay and their condition as target or bycatch species varies depending on the fishery, quota availability and market preferences [7]. Thus, flexibility for the size selective properties of the gear for these species is required. To provide detailed information about the contribution of different SMP and codend designs to the overall size selectivity and catch pattern of the species studied, a systematic approach based on treatment trees was used. Treatment trees tool uses a tree-like structure to depict the effect of different treatments and their consequences using the same procedure as decision trees [42–44]. The growing need to depict several results systematically has recently encouraged the use of this approach in different scientific fields (e.g. [42–44]), including research on fishing gear [45, 46].

Therefore, this study was designed to answer the following research questions:

1. Considering the different designs investigated, what is the optimal SMP and codend combination with respect to size selectivity and catch patterns for hake and blue whiting?
2. Is the use of treatment trees appropriate for investigating and illustrating the effect of multiple gear changes on selectivity and catch patterns systematically and comprehensively?

Materials and methods

SMP and codend designs

This study considered trawl gears with different SMP and codend designs to improve size selectivity for hake and blue whiting. Regarding SMP, the following designs were considered: (i) small SMP located at the top panel of the extension piece (SMP_{TS}), which is included in current regulation of the fishery; (ii) large SMP located at the top panel of the extension piece (SMP_{TL}); (iii) small SMP located at the bottom panel of the extension piece (SMP_{BS}); (iv) large SMP located at the bottom panel of the extension piece (SMP_{BL}) and (v) absence of SMP in the trawl. Earlier studies showed that the SMP_{TS} performs unsatisfactorily for some species due to lack of contact between fish and the SMP_{TS} [19, 23]. We therefore considered different SMP designs meant to optimize the release efficiency of hake and blue whiting. The second design considered was a larger SMP placed at the upper panel, potentially increasing the chance for contact with the panel. Underwater observations in earlier studies showed that hake prefer swimming close to the lower panel [19, 23, 47], whereas blue whiting has an erratic behavior in the SMP area, swimming quickly either towards the SMP or the codend [23]. Thus, the third and fourth designs consisted respectively of the small SMP in (i) and a larger-size panel placed at the bottom panel of the trawl. Considering that hake individuals, besides entering the trawl close to the lower panel, do not actively swim inside it [23], we tested a SMP_{BL} that was bigger than SMP_{TL} in case (iv). The aim was to potentially offer more chances to hake individuals to attempt escape. Finally, for completeness and simplicity regarding onboard operations, an extension piece with no SMP was considered. The SMPs (single-braided 4mm polyamide in all cases) were inserted 1 m in front of the joint between the codend and the extension piece and were of different sizes depending on the gear design tested (Fig 1). The SMP_{TS} and SMP_{BS} were 2 m long, 1 m wide and had a mesh size of 82.70 mm ± 1.95 mm (mean ± SD). The SMP_{TL} was 2.81 m long, 1.70 m wide and had a mesh size of 80.00 ± 2.02 mm (mean ± SD). The SMP_{BL} was 3.56 m long, 1.90 m wide and had a mesh size of 77.30 ± 2.57 mm (mean ± SD).

Regarding the codend used in this fishery (70 mm mesh size, diamond mesh), it has been demonstrated that it retains undersized hake [19]. However, greatly increasing its mesh size to

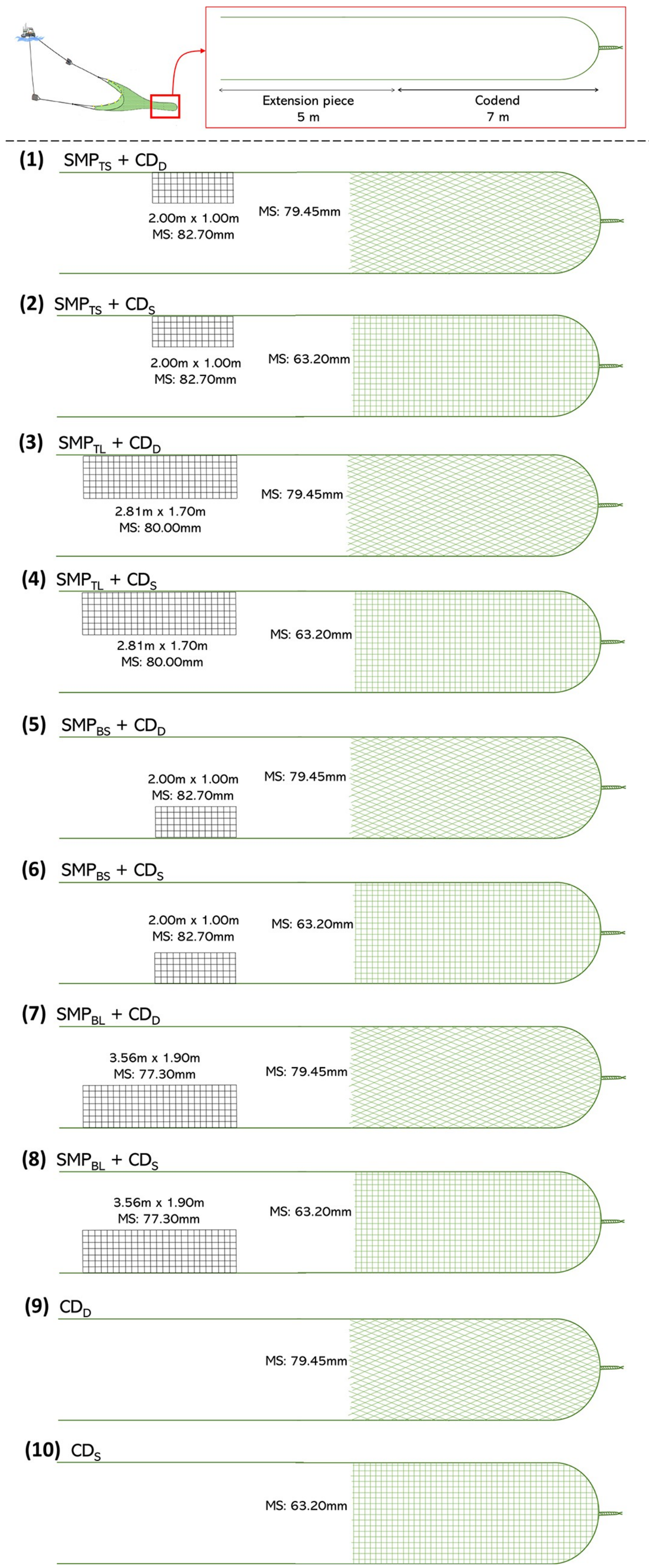
Extension piece
5 m
Codend
7 m
(1) SMP$_{TS}$ + CD$_{D}$
2.00m x 1.00m
MS: 82.70mm
MS: 79.45mm
(2) SMP$_{TS}$ + CD$_{S}$
2.00m x 1.00m
MS: 82.70mm
MS: 63.20mm
(3) SMP$_{TL}$ + CD$_{D}$
2.81m x 1.70m
MS: 80.00mm
MS: 79.45mm
(4) SMP$_{TL}$ + CD$_{S}$
2.81m x 1.70m
MS: 80.00mm
MS: 63.20mm
(5) SMP$_{BS}$ + CD$_{D}$
2.00m x 1.00m
MS: 82.70mm
MS: 79.45mm
(6) SMP$_{BS}$ + CD$_{S}$
2.00m x 1.00m
MS: 82.70mm
MS: 63.20mm
(7) SMP$_{BL}$ + CD$_{D}$
3.56m x 1.90m
MS: 77.30mm
MS: 79.45mm
(8) SMP$_{BL}$ + CD$_{S}$
3.56m x 1.90m
MS: 77.30mm
MS: 63.20mm
(9) CD$_{D}$
MS: 79.45mm
(10) CD$_{S}$
MS: 63.20mm

Fig 1. Ten trawl gear configurations included in the study that resulted from combining different SMP and codend designs considered. MS: mesh size.

https://doi.org/10.1371/journal.pone.0262602.g001

release small fish would potentially lead to escape of commercial sizes of hake and probably other fish species not considered in this study. Therefore, in this study a regular diamond mesh codend design (CD_D) with slightly bigger mesh size that the commercial one was tested. The CD_D was 7.0 m long, double-braided 4 mm polysteel, forming 79.45 ± 2.01 mm (mean ± SD) meshes (Fig 1). The fishery, besides a variety of roundfish species, also includes important flatfish species. Since diamond mesh codends are typically more selective for flatfish than for roundfish species [48–50] a square mesh codend design (CD_S) was also considered (Fig 1). The design guides made by Tokaç et al. [51] showed that a 60 mm mesh size with an opening angle of 90˚ would result on a *L*50 of approximately 25 cm for hake. However, in order to get a compromise between releasing undersized hake and not losing other important species for the fishery, the CD_S tested in this study was 7.0 m long, double-braided 3.5 mm polyethylene, forming 63.20 ± 1.73 mm (mean ± SD) meshes. The CD_S was constructed by turning the meshes in codend 45˚ (square meshes), and made of polyethylene twine, which is more deformable than polysteel [52] and facilitates fish escape (Fig 1).

Combining the five SMP designs with the two codend designs considered led to ten different gear combinations: (1) SMP_{TS} + CD_D; (2) SMP_{TS} + CD_S; (3) SMP_{TL} + CD_D; (4) SMP_{TL} + CD_S; (5) SMP_{BS} + CD_D; (6) SMP_{BS} + CD_S; (7) SMP_{BL} + CD_D (8) SMP_{BL} + CD_S; (9) CD_D; and (10) CD_S (Fig 1).

Experimental design and sea trials

Three gear designs were hence tested at sea: (i) SMP_{BS} + CD_D; (ii) SMP_{BL} + CD_D; and (iii) CD_S (Fig 2). From experimental designs (i) and (ii), selectivity data for the SMP_{BS}, SMP_{BL} and CD_D were obtained, whereas selectivity data for the CD_S was obtained from design (iii). The selectivity data of SMP_{TS} and SMP_{TL} for hake and blue whiting was obtained from the sea trials conducted by Cuende et al. [23] and Cuende et al. [24], respectively. These two studies were carried out in 2017 and 2018 respectively, during same fishing period and similar fishing ground and depth. Using information from the experimental sea trials in Cuende et al. [23, 24], the selectivity of all ten gear combinations was subsequently modeled.

The sea trials in the current and previous studies [23, 24] included here were carried out on board the research vessel *Emma Bardan* (29 m length overall; 900 kW). The gear used in all experiments was a four-panel bottom trawl of the type GOC73 [53]. This trawl is built according to the standard bottom trawl survey manual for the Mediterranean [54]. The headline, sidelines, 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 m^2; 350 kg), 100 m sweeps, and a light rockhopper ground gear (with 3 × 40 kg chain + 15 kg chain on the bosom). While fishing, the trawl had a horizontal opening of approximately 16 m and a vertical opening between 2.7 and 3.2 m. Furthermore, all trials were carried out in the same period of the year (June) and in a similar area, within ICES divisions 8c and 8b, in Spanish and French waters (Fig 3).

Data was collected using the covered codend method [58]. For hauls where the gear design included SMPs, a dual-covered method was applied [59, 60]. In this case a cover was installed both over the SMP and the codend, and the data included the number of fish in the panel cover (*PC*), in the codend cover (*CC*) and in the codend (*CD*). In the gear configurations without SMP, a single cover was attached to the codend and the number of fish in the *CD* and *CC* were obtained (Fig 2). The same methodology was followed in Cuende et al. [23, 24] for SMP_{TS} and SMP_{TL}.

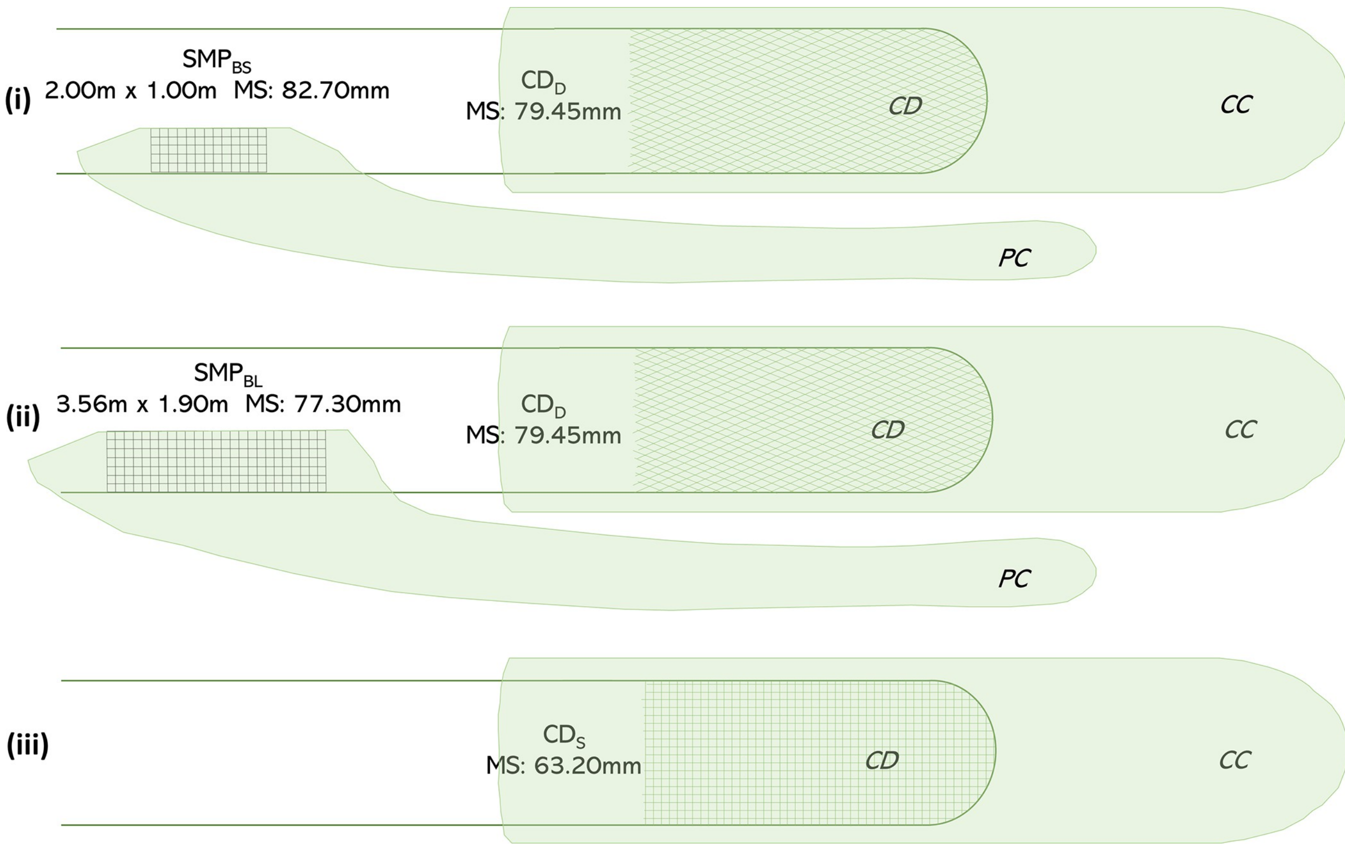

Fig 2. Experimentally tested gears with the covers used to collect fish. MS: mesh size.

https://doi.org/10.1371/journal.pone.0262602.g002

The *PC* over the SMP$_{BS}$ was 13.0 m long, with diamond meshes of 26.10 ± 0.91 mm (mean ± SD) (1.3 mm polyamide twine); the *PC* over the SMP$_{BL}$ was 13.6 m long, with diamond meshes of 41.80 ± 0.85 mm (mean ± SD) (1.8 mm polyamide twine). Both were built based on the design by [61] and were equipped with nine floats (N-50/8 type; 135 mm diameter; 0.76 kg buoyancy each) on the top and leaded rope on the bottom to ensure expansion. The gear specifications for the SMP$_{TS}$ and SMP$_{TL}$ designs are available at Cuende et al. [23] and Cuende et al. [24], respectively. The *CC*s for CD$_D$ and CD$_S$ were 9 m long and made of 26.2 ± 0.41 mm (mean ± SD) (1.3 mm PA twine) and 33.70 ± 1.35 mm (mean ± SD) diamond meshes (3 mm polyamide twine), respectively. To ensure expansion of the covers and prevent obstruction of the codend meshes, nine pairs of floats (N-25/5 type; 100 mm diameter; 0.300 kg buoyancy each), eight kites (four per panel) and four chains (1 kg each) were respectively attached to the top, sides and bottom of the *CC*s. After each haul, the hake and blue whiting captured were measured to the nearest centimeter below. When the catch exceeded a maneuverable quantity in terms of the available time and crew for measuring the fish, randomly selected subsamples of the catch were taken, and the subsample ratio was calculated.

A flaw in the experimental design resulted in obvious differences in the mesh sizes used for SMP$_{BS}$ and SMP$_{BL}$ *PC*s and CD$_D$ and CD$_S$ *CC*s. Given that, we could not rule out that some of the smallest hake and blue whiting individuals might escape through the cover meshes. According to predictions made by Tokaç et al. [51], a 40 mm diamond mesh would be able to release hake between approximately 8 and 17 cm depending on mesh opening angle. Similarly, and based on the predictions for blue whiting in Cuende et al. [62], the same mesh size and

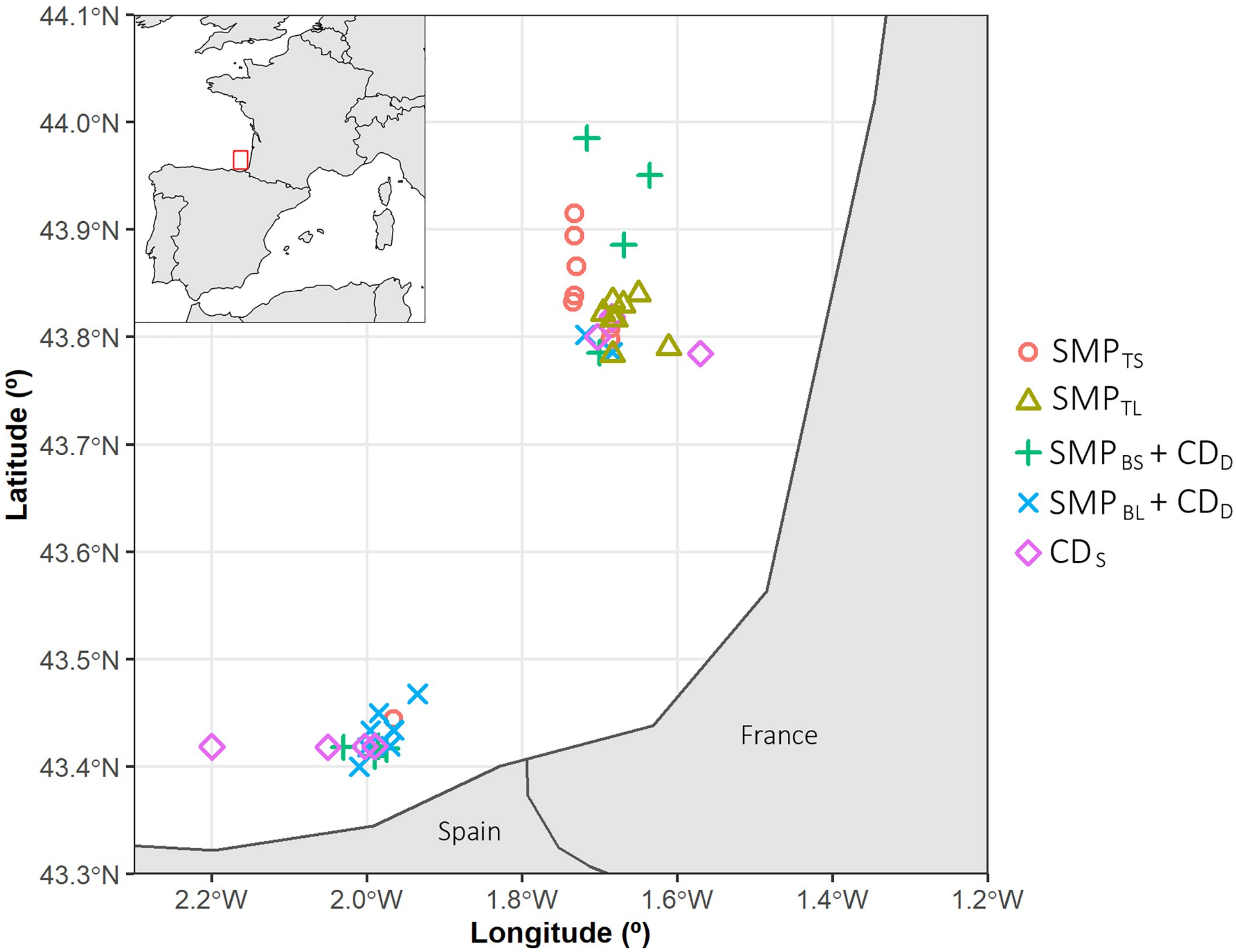

Fig 3. Sampling area and positions of the experimental hauls. Positions for SMP_{TS} and SMP_{TL} are also included [23, 24]. We used "ggplot2" [55] (under version 3.3.5) and "rnaturalearth" [56] (under version 0.1.0) within the R statistical environment [57] (R version 4.0.4) for mapping.

https://doi.org/10.1371/journal.pone.0262602.g003

mesh opening angles would release individuals ranging between 8 and 20 cm. Using data from length classes that could potentially escape through the covers could cause bias in the estimation of selection curves. For that reason, only individuals above 20 mm in the *PC* and above 15 mm length in the *CC* were considered in the analysis.

Models used for SMP and codend size selection estimation. The selectivity models applied were specific for the SMPs and codends independently, meaning that even though some hauls included data for SMP and codend size selection, the data collected for each gear compartment was analyzed separately. Regarding the diamond mesh codend, since the codend used together with SMP_{BS} and SMP_{BL} was the same, the codend data for those hauls was analyzed together, resulting in a larger and more robust dataset.

To estimate the retention probability ($r_{SMP}(l)$) for SMP_{BS} and SMP_{BL}, the fraction of fish escaping through the SMP was compared to the fraction that did not escape through it. Assuming that the fate of each fish is independent of that of other fish, the number of individuals of a specific length class *l* present in the *PC* (*nPC*) was compared to the sum of the individuals present in the *CD* and *CC* (*nCD* + *nCC*). The experimental data in the analysis was thus treated as two-compartment data and described using a binomial distribution with length-dependent probabilities of being retained by the SMP $r_{SMP}(l)$.

A fish entering SMP zone can be size-selected if it contacts the panel and its body size, shape, and orientation allows it to pass through the meshes. For the fish that contact the SMP we therefore assume that the length-dependent retention probability can be sufficiently well modeled by a *logit* function [58], defined by the parameters $L50_{SMP}$ (length at which a fish contacting the panel has a 50% chance of escaping through the SMP) and SR_{SMP} (difference between the lengths at which a fish contacting the panel has 75% and 25% chances of escaping through the SMP). However, because some fish may not come into contact with the SMP, the size selection process was modeled based on a *CLogit* size selection model [63], which has shown to be sufficiently flexible to describe the process [22, 64]. The *CLogit* model estimates the available size selection for the SMP through the parameter C_{SMP}, which quantifies the probability that a fish entering the SMP zone will contact the SMP and be subject to a size-dependent probability of escaping through it (selectivity contact). We assumed that the likelihood of C_{SMP} can be modeled by a single length independent number that ranges between 0.0 and 1.0. If C_{SMP} is equal to 1.0, all fish contact the SMP, whereas if C_{SMP} is equal to 0.0, none do. Therefore, the length-dependent SMP retention probability, $r_{SMP}(l)$, can be modeled by:

$$r_{SMP}(l, C_{SMP}, L50_{SMP}, SR_{SMP}) = CLogit(l, C_{SMP}, L50_{SMP}, SR_{SMP}) = 1.0 - C_{SMP} + C_{SMP} \times logit(l, L50_{SMP}, SR_{SMP}) \quad (1)$$

where

$$logit(l, L50, SR) = \frac{exp(ln(9) \times (l - L50)/SR)}{1.0 + exp(ln(9) \times (l - L50)/SR)} \quad (2)$$

For codend retention probability ($r_{CD}(l)$), the fraction of fish in the *CD* was compared to the fraction of fish in the *CC*. We assumed that the retention likelihood could be modeled using a binomial distribution with length-dependent probabilities for being retained in the codend ($r_{CD}(l)$) by a *logit* model with parameters $L50_{CD}$ and SR_{CD}:

$$r_{CD}(l, L50_{CD}, SR_{CD}) = Logit(l, L50_{CD}, SR_{CD}) \quad (3)$$

Estimation of SMP and codend size selection. The parameters C_{SMP}, $L50_{SMP}$, SR_{SMP}, $L50_{CD}$, and SR_{CD} were estimated simultaneously on a haul-by-haul basis. We used a maximum likelihood estimation (MLE) method, pooling the experimental data over the hauls *j* (*1* to *m*) for each specific gear and minimizing the following expression [23, 24]:

$$-\sum_{l}\sum_{j=1}^{m}\left\{\left(\frac{nCD_{lj}}{qCD_j}+\frac{nCC_{lj}}{qCC_j}\right)\times \ln(r_{SMP}(l, C_{SMP}, L50_{SMP}, SR_{SMP})) + \frac{nPC_{lj}}{qPC_j}\times \ln(1.0 - r_{SMP}(l, C_{SMP}, L50_{SMP}, SR_{SMP}))\right\} \quad (4)$$

whereas codend size selectivity was estimated by:

$$-\sum_{l}\sum_{j=1}^{m}\left\{\frac{nCD_{lj}}{qCD_j}\times \ln(r_{CD}(l, L50_{CD}, SR_{CD})) + \frac{nCC_{lj}}{qCC_j}\times \ln(1.0 - r_{CD}(l, L50_{CD}, SR_{CD}))\right\} \quad (5)$$

For each haul *j* and length class *l*, nCD_{lj}, nPC_{lj}, *and* nCC_{lj} are the numbers of individuals length-measured in the *CD*, *PC*, and *CC*, respectively; and qCD_j, qPC_j, and qCC_j are their respective subsampling factors (ratio of length-measured to total number of fish in each compartment). The summation is over the length classes (each 1 cm wide).

The models were validated based on p-value estimations and model deviance versus degrees of freedom [58]. If the p-value was < 0.05 and deviance was much greater than the degrees of freedom, the residuals were inspected to determine whether the discrepancy between model and experimental data was the result of over-dispersion. On the other hand, a p-value > 0.05 means that it cannot be ruled out that the difference observed between the model and the data is coincidental.

The confidence intervals (CIs) for the average size selection were estimated using a double bootstrap method. This approach is identical to the one described in Millar and Fryer [65] and Herrmann et al. [66], and takes both within-haul and between-haul variation into consideration. Each of the 1,000 bootstrap repetitions conducted resulted in a 'pooled' set of data used to estimate the Efron percentile [67] 95% CIs for the selection curve and its parameters [68]. We applied the software tool SELNET [68] for the size selection analysis and used the double bootstrap method implemented in this tool to obtain CIs for the size selection curve and the corresponding parameters.

Size selection models for combined SMP and codend designs

To estimate the retention probability of the different gear combinations (SMP_{TS} + CD_D; SMP_{TS} + CD_S; SMP_{TL} + CD_D; SMP_{TL} + CD_S; SMP_{BS} + CD_D; SMP_{BS} + CD_S; SMP_{BL} + CD_D; SMP_{BL} + CD_S; CD_D and CD_S), a sequential combination of the different SMP and codend designs was modeled. The combined retention probability of the specific gear combination ($r_{comb}(l)$) was modeled using the following generic model [22, 23, 60]:

$$r_{comb}(l, C_{SMP}, L50_{SMP}, SR_{SMP}, L50_{CD}, SR_{CD}) = r_{SMP}(l, C_{SMP}, L50_{SMP}, SR_{SMP}) \times r_{CD}(l, L50_{CD}, SR_{CD}) \quad (6)$$

Due to the differences in minimum fish length included in the analyses (20 mm for *PC* and 15 mm for *CC*), the selectivity in the different compartments was analyzed separately. Therefore, although SMP_{BS} + CD_D and SMP_{BL} + CD_D combinations were experimentally tested, their combined retention was also modeled by Eq (6).

Comparison between different gear designs

To investigate whether and how the different gear designs perform with respect to each other, we quantified (a) changes in absolute selectivity, by using the delta selectivity [69]; (b) catch profile, by estimating the structure of the population caught; and (c) potential consequences for the fishery, using exploitation pattern indicators [70].

Treatment trees. To investigate the effect of the gear modifications implemented on size selectivity and catch profile of hake and blue whiting, treatment trees were used. Delta selectivity was estimated by subtracting the predicted, species-specific, absolute selectivity of two gear designs to identify size ranges where there was a significant change in selectivity [69]. The pooled delta selectivity for each gear combination were arranged in a tree-like structure, starting with a reference gear design, which was connected stepwise to the remaining gear designs. The reference gear design established was the one used by the fleet today, SMP_{TS} + CD_D. Every step forward changed to a gear design (treatment gear design) where a unique modification was implemented (Fig 4). That modification could be increasing SMP size, changing SMP position, removing SMP or changing codend mesh geometry (Fig 4).

In each step (Fig 4), the delta selectivity curves and size selectivity for the treatment gear, baseline gear and reference gear designs were shown with the corresponding CIs. Delta selectivity curves showed the difference in the retention probability between a gear design with an implemented modification (treatment gear) and its baseline gear design. To infer the difference in retention probability, the following generic delta curve ($\Delta r(l)$) was applied:

$$\Delta r(l) = r_{treatment}(l) - r_{baseline}(l) \quad (7)$$

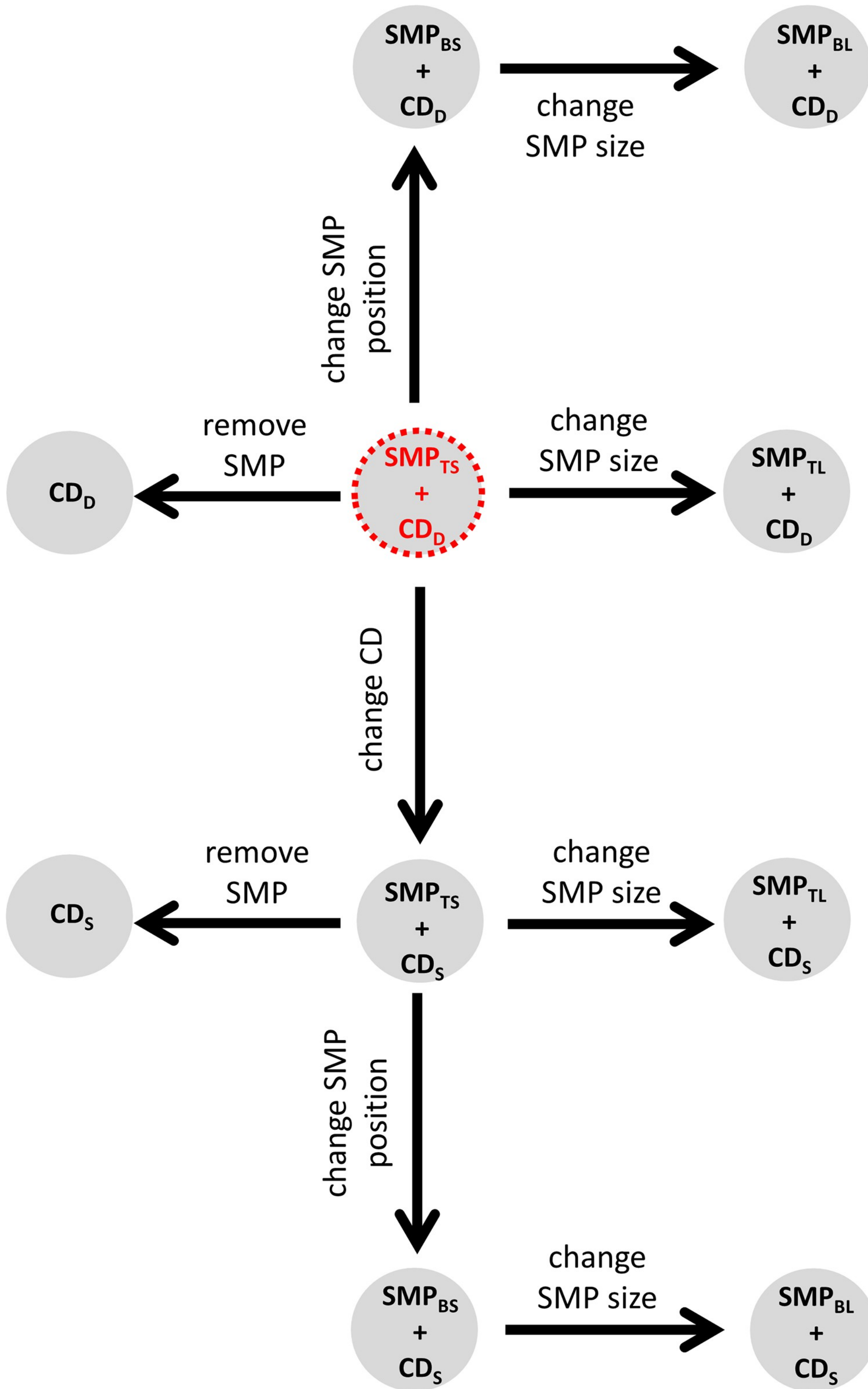

Fig 4. Treatment tree diagram. Arrows represent the delta comparisons carried out. Red circle indicates the reference gear design.

https://doi.org/10.1371/journal.pone.0262602.g004

where $r_{treatment}(l)$ is the retention probability value of a specific gear which has implemented a modification on its design, and $r_{baseline}(l)$ is the retention probability value of the baseline gear design in each pairwise comparison.

Efron 95% CIs for $\Delta r(l)$ were obtained based on the two bootstrap populations of results (1,000 bootstrap repetitions in each) for both $r_{treatment}(l)$ and $r_{baseline}(l)$. As the bootstrap resampling was random and independent for the two groups of results, it is valid to generate the bootstrap population of results for the difference based on (7) using the two generated bootstrap files [66]:

$$\Delta r(l)_i = r_{treatment}(l)_i - r_{baseline}(l)_i \; i \in [1 \ldots 1000], \tag{8}$$

where *i* denotes the bootstrap repetition index. Significant differences in size selection between gears were obtained if the 95% CIs for the delta curves had length classes that did not overlap 0.0.

Following the same approach, a treatment tree was applied to depict catch profiles of the treatment and the reference gear designs. Each step in the tree showed differences in the fish population retained by the treatment gear compared to the reference gear design (Fig 4). To estimate the differences in the fish population retained, the size selection curves predicted for each design combination were applied to the population of hake and blue whiting entering the fishing gear by:

$$nr_l = nPop_l \times r_{comb}(l) \tag{9}$$

Efron 95% CIs for the average populations retained were estimated using a double bootstrap method. The population applied throughout this process was the population entering the gear during the experimental fishing with SMP_{BS} + CD_D. In this gear design, *PC* and *CC* mesh sizes were suitable for retaining the whole length class ranges of hake and blue whiting and the individuals fished covered a wide range of sizes. Therefore, SMP_{BS} + CD_D was assumed to be representative of the population fished during the trials with the remaining gear designs. These treatment trees show the mean population retained of the treatment gear (with CIs) and the population retained by the reference gear design.

Exploitation pattern indicators. To investigate how applying the different design combinations considered would affect the catch pattern in the fishery, we estimated the value of three exploitation pattern indicators, nP^{-}, nP^{+} and *nDiscard*, for each gear design. These indicators are often used in fishing gear size selectivity studies to supplement assessment solely based on selectivity curves [22, 25, 38, 71–73]. Specifically, the percentage of individuals retained below (nP^{-}) and above (nP^{+}) the species-specific minimum conservation reference size (MRCS) was estimated, as well as the discard ratio (*nDiscard*), which quantifies the fraction of hake and blue whiting below MCRS in the total catch (in %). MCRS for hake is 27 cm. For blue whiting, which does not have an MCRS, we used its estimated marketable size limit, 18 cm length. That length is based on a regulation that establishes a maximum of 30 individuals of blue whiting per kilo for commercialization [74, 75].

Since these indicators are affected by the populations fished, which may vary depending on factors such as fishing period and area, we analyzed the catch patterns of the different design combinations considered for different population scenarios. The different populations corresponded to selectivity data obtained in different fishing areas in the Bay of Biscay (ICES 8abd) and Western Iberian waters (ICES 9a) in different years (in between 2011 and 2019). The exploitation indicators calculated for those scenarios were used to discuss the most promising gear design for the fishery under study.

The indicators were estimated for the ten combined gear designs considered by:

$$
\begin{aligned}
nP^{-} &= 100 \times \frac{\sum_{l<MCRS}\{r_{comb}(l) \times nPop_l\}}{\sum_{l<MCRS}\{nPop_l\}}, \\
nP^{+} &= 100 \times \frac{\sum_{l>MCRS}\{r_{comb}(l) \times nPop_l\}}{\sum_{l>MCRS}\{nPop_l\}}, \\
nDiscard &= 100 \times \frac{\sum_{l<MCRS}\{r_{comb}(l) \times nPop_l\}}{\sum_{l}\{r_{comb}(l) \times nPop_l\}}
\end{aligned}
\tag{10}
$$

Indicators nP^{-}, nP^{+} and *nDiscard* were estimated with uncertainties for each species and population scenario, using the bootstrap set for $r_{comb}(l)$ and $nPop_l$, specifically, by first calculating the values for the indicators based on the result of each bootstrap repetition for $r_{comb}(l)$ and $nPop_l$ in (10) to obtain a bootstrap set for the indicator values. Efron 95% CIs were estimated for each of the indicators based on the resulting bootstrap set.

To visualize and categorize multiple exploitation pattern indicator results, a traffic light system procedure was implemented, using red, yellow and green colors. Specifically, the colors express indicator values regarding how 'favorable' or 'poor' they are with respect to regulations. In simple terms, data in green color represents satisfactory/safe outcomes, while data in red represents dangerous outcomes. The conditions in-between are transitional outcomes represented in yellow. The change in colors is gradual, from green to yellow and from yellow to red depending on the value of the indicator. For example, an ideal fishery where nP^{-} and *nDiscard* are low (close to 0) and nP^{+} is high (close to 100) would be represented by a green color, intermediate values would shift to a yellow/orange color, while very high nP^{-} and *nDiscard* or low nP^{+} would be indicated by red.

Results

Overview of sea trials

During the sea trials, selectivity data for SMP_{BS}, SMP_{BL}, CD_D and CD_S was obtained for hake and blue whiting from a total of 33 and 32 experimental hauls, respectively. Specifically, eight experimental hauls with SMP_{BS} were carried out, nine with SMP_{BL}, seventeen with CD_D and eight with CD_S were carried out for hake. For blue whiting, eight experimental hauls with SMP_{BS}, nine with SMP_{BL}, sixteen with CD_D and seven with CD_S were carried out. The towing speed was between 2.9 and 3.0 knots, and towing depths varied between 99 and 126 m. The two covers enabled separate collection and measurement of the individuals retained by the *CD*, *CC*, and *PC* per haul and length class. Length-measured individuals included 11,665 hake and 10,463 blue whiting. In general, the models used seemed to explain the experimental data adequately, which was confirmed by the fit statistics (p-value > 0.05) (Table 1). The poor p-value associated to SMP_{TS} for blue whiting was probably due to overdispersion in the data created by heavy subsampling ratios [23], as the experimental data and the fitted escape probability curve showed no clear deviation patterns.

The number of hauls, individuals measured and haul characterization for experimental trials including SMP_{TS} and SMP_{TL} designs are available in Cuende et al. [23, 24]. Selectivity parameters and fit statistics for these gear designs are also included in Table 1.

Size selectivity of individual SMP and codend designs

The selectivity parameters shown in Table 1 demonstrate that the contact probability resulted on the highest values for hake when the SMP_{BL} was used. It was estimated that 38% (CI: 27%–100%) of the hake contact the SMP_{BL} while not more than 5% contact the remaining SMP designs. The

Table 1. Selectivity parameters for hake and blue whiting for the different SMP and codend designs considered in the study.

	SMP_{TS}	SMP_{TL}	SMP_{BS}	SMP_{BL}	CD_D	CD_S
Hake						
*L*50	37.07 (21.22–37.10)	32.07 (31.04–32.10)	35.03 (0.10–35.09)	31.33 (15.02–34.73)	15.68 (12.47–17.51)	23.49 (22.82–24.46)
SR	0.10 (0.10–7.42)	0.10 (0.10–0.10)	0.10 (0.10–27.08)	6.51 (0.10–19.72)	7.92 (5.07–11.84)	4.36 (3.73–4.92)
C_{SMP}	0.01 (0.00–0.02)	0.02 (0.01–0.03)	0.05 (0.02–1.00)	0.38 (0.27–1.00)	-	-
p-Value	0.972	0.05	0.8735	0.6995	0.4420	0.8543
Dev	59.29	102.44	14.73	23.66	36.57	25.46
DOF	82	81	22	28	36	34
Blue whiting						
*L*50	27.62 (23.14–34.76)	32.39 (29.81–197.57)	28.97 (0.10–56.51)	0.10 (0.10–1.00)	22.88 (20.76–24.12)	27.06 (26.70–27.44)
SR	8.99 (0.10–15.73)	1.99 (0.10–48.72)	0.10 (0.10–4.60)	27.73 (0.10–40.50)	4.37 (3.60–5.61)	3.32 (2.85–3.84)
C_{SMP}	0.27 (0.21–0.38)	0.45 (0.26–0.66)	0.00 (0.00–1.00)	0.18 (0.01–1.00)	-	-
p-Value	<0.001	0.31	0.9793	0.6226	0.1159	0.3349
Dev	105.10	25.81	4.21	8.99	21.70	19.96
DOF	40	23	12	11	15	18

Selectivity parameters estimated, 95% CIs (in brackets) and fit statistics are shown. Selectivity parameters and fit statistics from trials in Cuende et al. [23, 24] are also shown.

https://doi.org/10.1371/journal.pone.0262602.t001

contact probability values for blue whiting were highest when the SMP designs were located at the top panel, being of 45% (CI: 26%–66%) when SMP_{TL} was used and of 27% (CI: 21%–38%) with SMP_{TS}. Regarding codend selectivity, CD_S released smaller individuals than CD_D, since CD_S design showed a higher *L*50 value and lower *SR* value than CD_D for both species.

The size selection curves for hake show a flat shape for the designs consisting of an SMP at the top panel (SMP_{TS} and SMP_{TL}), and changes in the pattern occur when the SMP's position is moved to the bottom panel, especially when the SMP_{BL} is used (Fig 5). The patterns observed are the opposite for blue whiting, as the SMP designs at the bottom panel (SMP_{BS} and SMP_{BL}) do not have any effect on its escape probability, whereas when it is placed at the top panel, the retention probability of smaller length classes is reduced to 73.26% and 55.08% for SMP_{TS} and SMP_{TL}, respectively (Fig 6).

Regarding codend size selectivity, CD_S increases the size at which the codend starts retaining fish with respect to CD_D for both hake and blue whiting (Figs 5 and 6). For example, *L*25 of CD_D for hake is 12 cm and increases to 21 cm for CD_S; similarly, it increases from 21 cm to 25 cm for blue whiting.

Treatment trees

The treatment tree for hake shows that regardless of codend design, changing the SMP position from the top panel to the bottom panel as well as increasing its size significantly decreases the retention probability compared to the reference gear design (SMP_{TS} + CD_D). However, changing codend geometry from CD_D to CD_S has a greater effect on the gear's retention probability by decreasing it to a maximum of 61.97% (CI: 51.76–73.70%) for hake of 20 cm (Fig 7). The size selection curves in the treatment tree reveal that all gear designs including the CD_S release more undersized hake, especially when combined with the SMP_{BL}. They also show that the retention probability curves for the gear designs with CD_D are less steep than when combined with CD_S (have higher *SR*), which result in a lower retention probability for hake. CIs for gears combined with CD_S are narrower than for those with CD_D (Fig 7).

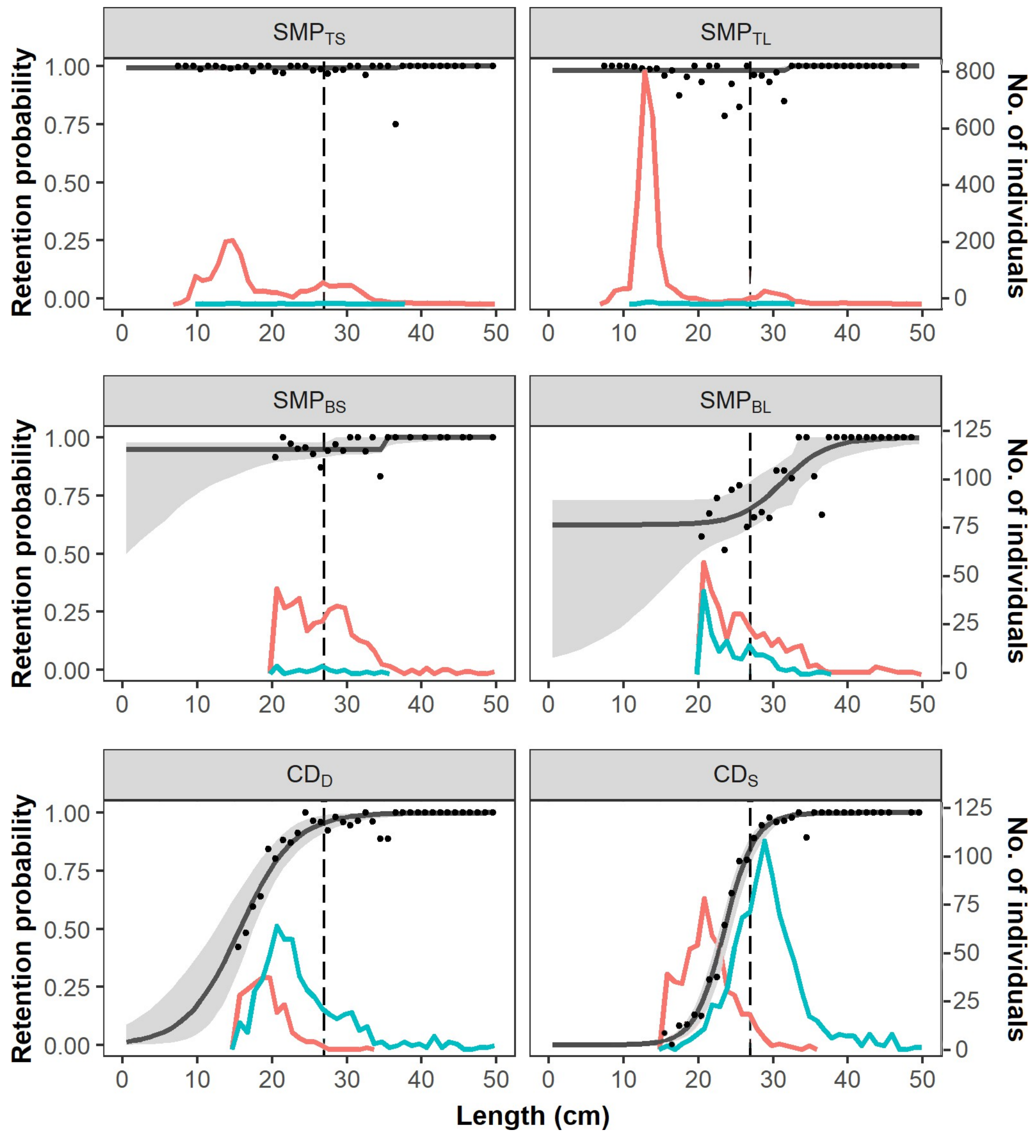

Fig 5. Length-dependent retention probabilities for hake. Retention probability curves (black line) with corresponding CIs (grey bands) and experimental rates (black dots) for the different SMP and codend configurations for hake. Vertical dashed lines show the MCRS for hake: 27 cm. The number of individuals escaped (red lines) and retained (blue lines) by each design are also shown.

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Regarding blue whiting, either removing the SMP or changing its position to the bottom panel would retain significantly more individuals above their marketable size. For example, using CD_D and CD_S without any SMP can retain up to 13.10% (CI: 5.98%–25.72%) and 8.86% (CI: 0.00%–21.03%) more individuals of 26 and 29 cm, respectively (Fig 8). Similarly, in gears composed by CD_D and $CD_{S,}$ changing the position of the SMP from SMP_{TS} to SMP_{BS} retain up to 13.06% (CI: 6.71%–23.44%) and 8.76% (CI: 0.00%–21.02%) more individuals of 25 and 29 cm, respectively. Conversely, increasing the size of the SMP increases the escape of commercial-size individuals. Also, SMP_{TS} + CD_S would significantly affect the retention probability of blue whiting by releasing up to 43.75% (CI: 30.52%–57.09%) more individuals of 24 cm than the SMP_{TS} + CD_D gear design. Additionally, the size selection curves show that all gear designs considered would mostly fish individuals above the respective marketable size since

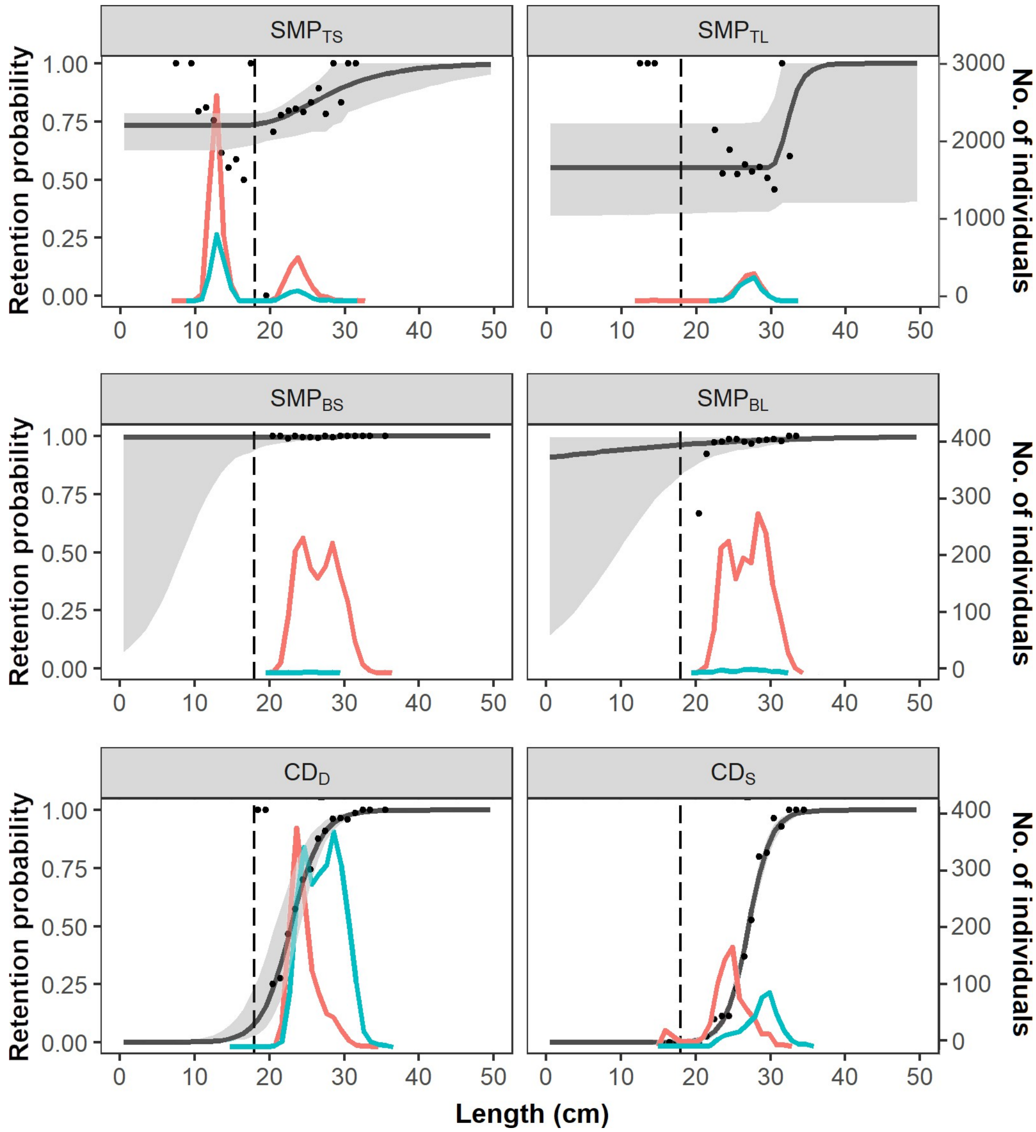

Fig 6. Length-dependent retention probabilities for blue whiting. Retention probability curves (black line) with corresponding CIs (grey bands) and experimental rates (black dots) for the different SMP and codend configurations for blue whiting. Vertical dashed lines show the minimum marketable size for blue whiting: 18 cm. The number of individuals escaped (red lines) and retained (blue lines) by each gear are also shown.

https://doi.org/10.1371/journal.pone.0262602.g006

the retention probability of individuals below 18 cm is lower than 6% of the total catch in every case. Designs with CD_S release 100% of individuals below 18 cm and achieve high retention probabilities (above 50%) for fish >25 cm (Fig 8).

The catch profiles showed that the proportion of catch composed of undersized individuals (i.e. < MCRS) can vary significantly when using the different gear designs (Figs 9 and 10). For hake, the designs with CD_S catch larger individuals, while CD_D, even though some SMP designs (like SMP_{BL}) can release a higher proportion of undersized fish, mostly retains undersized fish (Fig 9). For blue whiting the plots show that the catch pattern of every gear design is composed by individuals above their minimum marketable size. In this case, those gear combinations with CD_D retain higher proportion of fish above MCRS that the gears combined with CD_D (Fig 10).

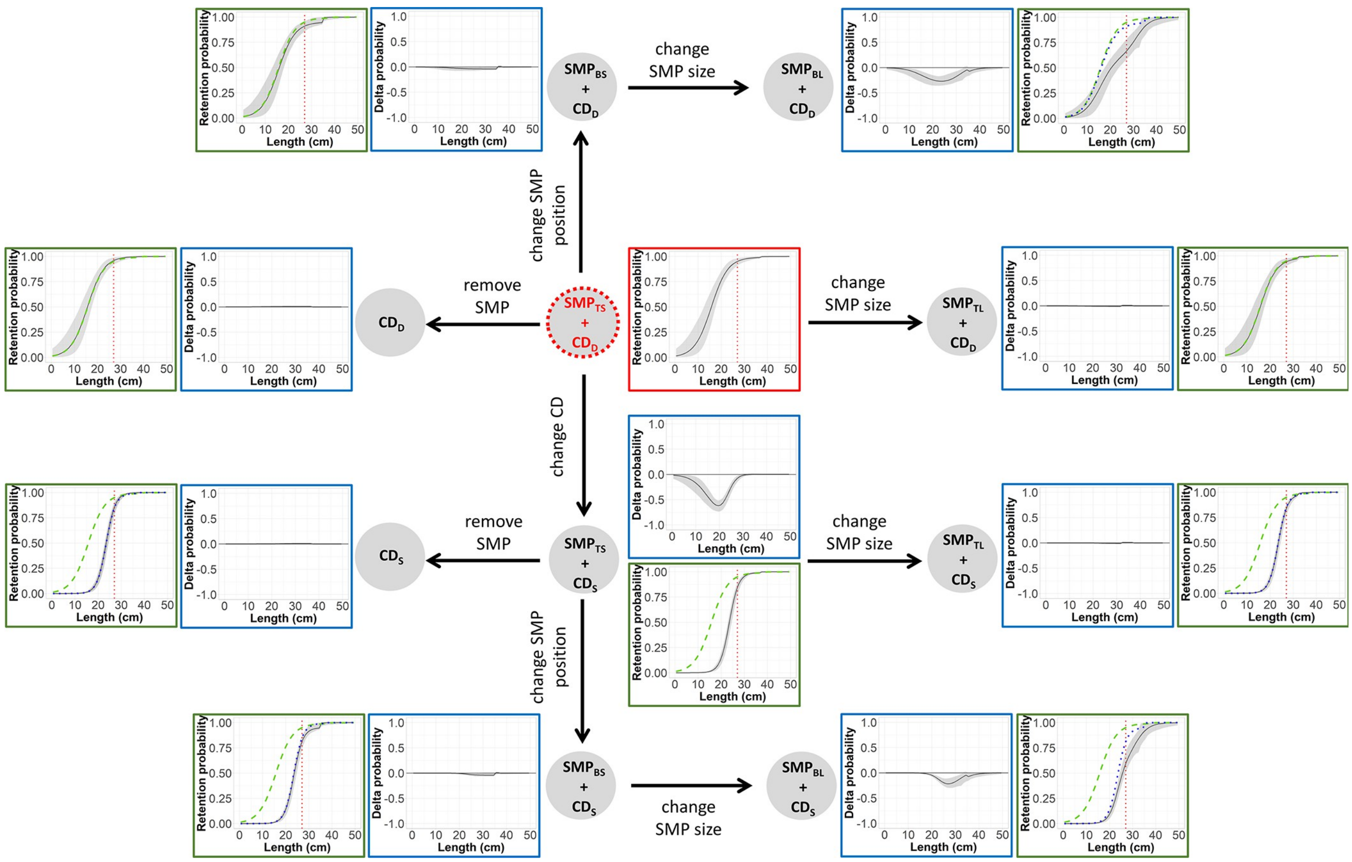

Fig 7. Size selection treatment tree for hake. Delta comparisons (blue boxes) carried out (represented by arrows), which include delta curves for each modification applied in the gear (black line) with its corresponding CIs (grey bands), are shown. Each step also includes selectivity plots (green boxes) showing: selection curves for the treatment gear design (black line) with CIs, baseline gear design (blue dots) and reference gear design (green dashed lines). Vertical red dotted lines correspond to the MCRS: 27 cm.

https://doi.org/10.1371/journal.pone.0262602.g007

Exploitation pattern indicators

To identify the most favorable design regarding catch patterns, the indicators nP^{-}, nP^{+} were estimated for all gear designs and population scenarios considered. The highest proportion of undersized hake was always retained when the population structure largely comprised individuals close to the MCRS. For example, for those populations composed mainly of hake below 20 cm (Fig 11*A*, 11*C*), nP^{-} and nP^{+} show greenish colors for almost all designs, meaning that they have a low probability of retaining them. However, when the population includes individuals closer to the MCRS but still below 27 cm, the retention of sized individuals remains high while yellow-red colors are expressed for undersized individuals in most of the gear designs (Fig 11*B*, 11*D*–11*G*). In general, although the catch of individuals above MCRS is higher when any SMP design is used together with CD_D, *nDiscard* shows lower values when these are combined with CD_S. For blue whiting, the results show mostly yellow-red colors for the capture of individuals above 18 cm, meaning low efficiency in retaining these individuals. When the blue whiting population is composed of individuals above the respective marketable size but larger than 22 cm (Fig 11*C*), the indicators nP^{+} and *nDiscard* show better values for all gear designs, especially for SMP_{BS} + CD_D and CD_S.

When the exploitation of both species is considered together, the gear designs with fewer undersized retention are those combined with CD_S. However, CD_S also has a higher release of

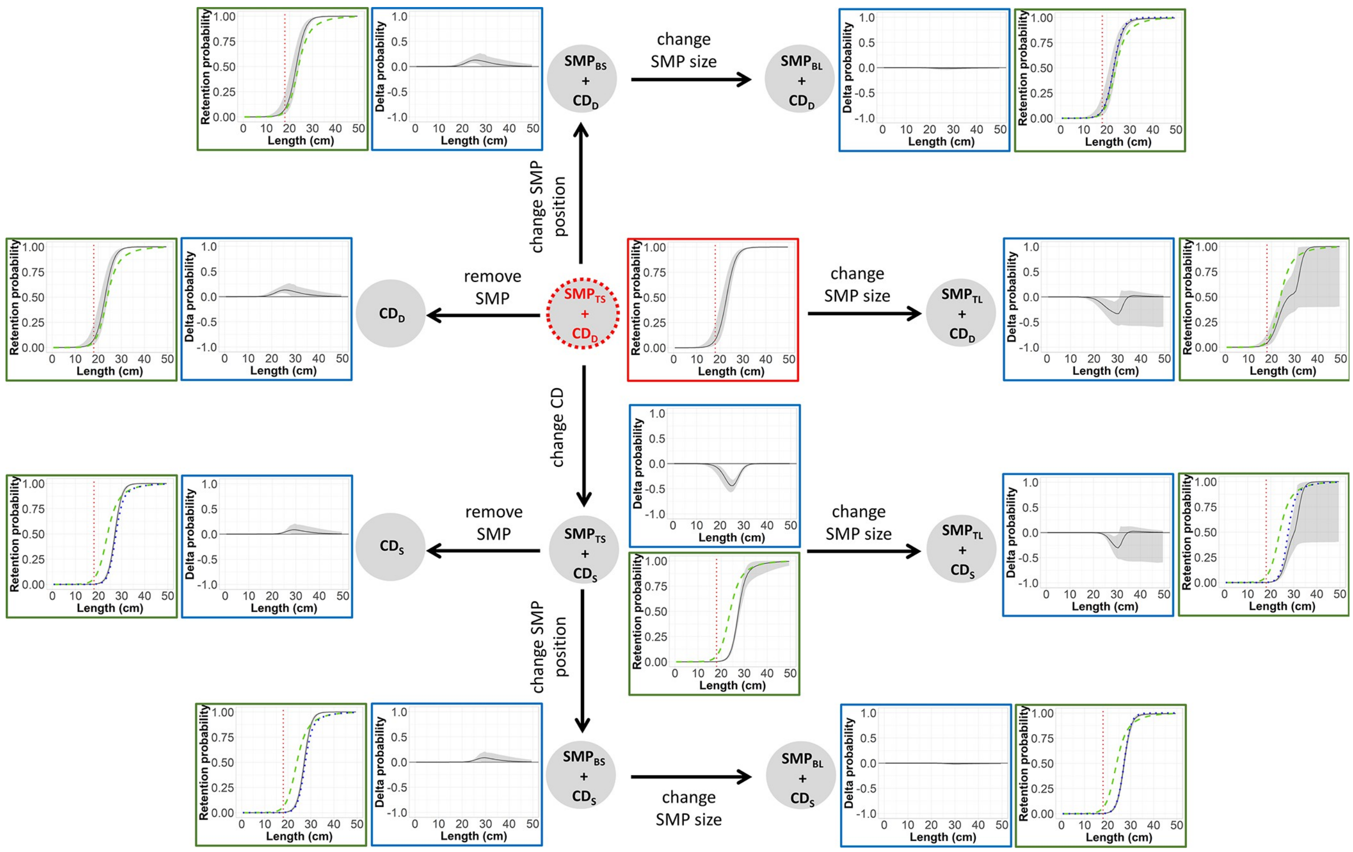

Fig 8. Size selection treatment tree for blue whiting. Delta comparisons (blue boxes) carried out (represented by arrows), which include delta curves for each modification applied in the gear (black line) with corresponding CIs (grey bands), are shown. Each step also includes selectivity plots (green boxes) showing: size selection curves for the treatment gear design (black line) with CIs, baseline gear design (blue dots) and reference gear design (green dashed lines). Vertical red dotted lines correspond to the minimum marketable size: 18 cm.

https://doi.org/10.1371/journal.pone.0262602.g008

individuals above MCRS, which could make the fishing activity less efficient. These results show that the exploitation pattern of hake and blue whiting can be greatly influenced by making small changes in the gear design.

Discussion

Adapting the selectivity of fishing gears is an important strategy to achieve desired catch patterns and meet management objectives. The diversity of unwanted species and sizes caught in fisheries has led to the development of a vast array of gear designs and consequently to a great deal of literature focusing on the effect of those designs on size and species selectivity [4, 76, 77]. The approach used in this study makes best use of existing knowledge on size selectivity in the Basque bottom trawl fishery and leads to new insights about the potential for its improvement. This approach allowed us to quickly inspect a number of potential gear modifications based on few experimental trawl designs and data already available. Specifically, the gear combinations implemented led to the identification of ten potentially applicable gear designs that could help the fishery meeting the management requirements (e.g. European Landing Obligation [78]).

The effect of multiple gear modifications on the size selectivity and catch patterns of hake and blue whiting was systematically illustrated using treatment trees. This tool presented all

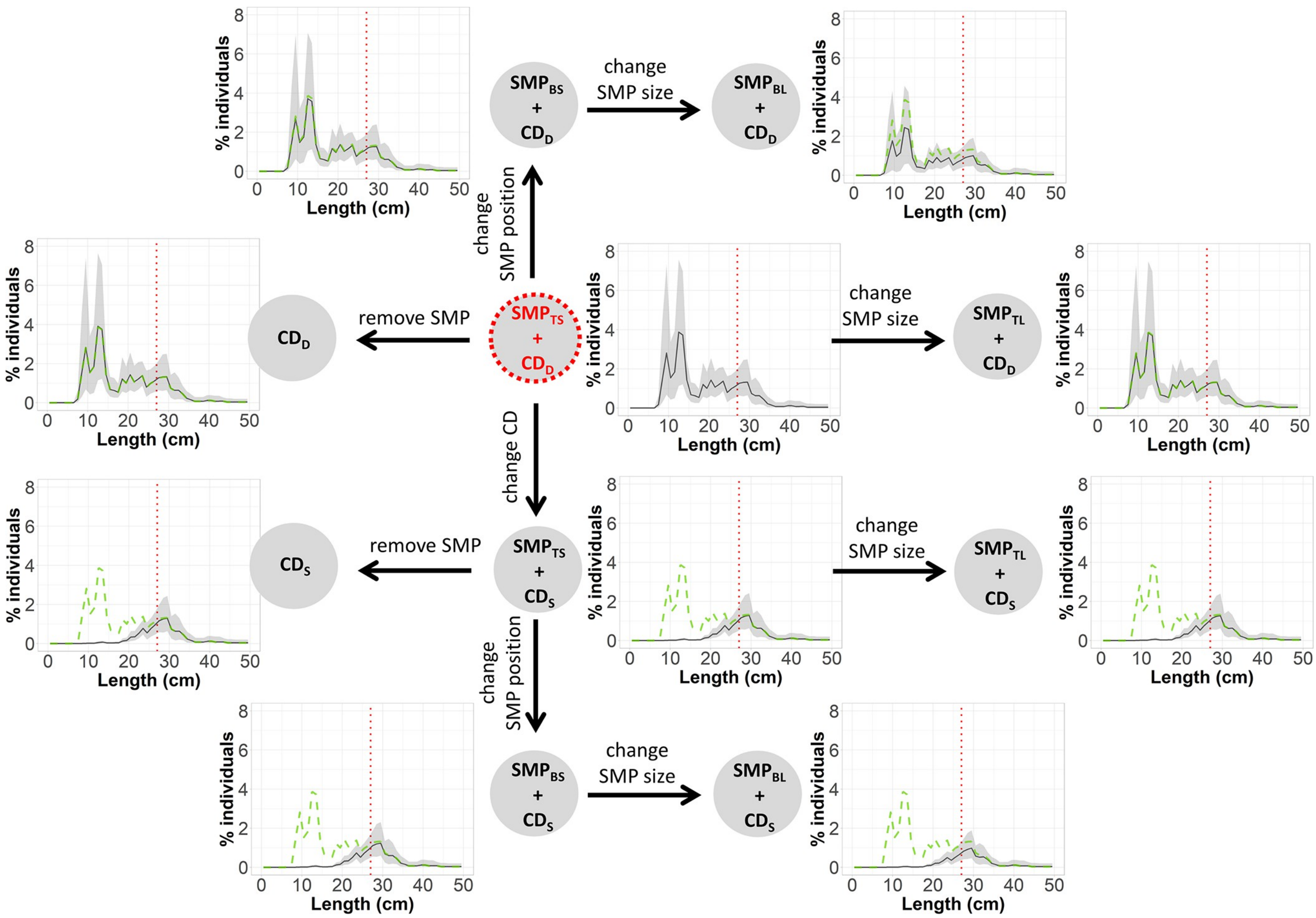

Fig 9. Treatment tree of the population structure fished for hake with the different gear designs. Includes the fished population structure (black line) for each gear design and CIs (grey bands) and the population structure fished by the reference gear design (SMP_{TS} + CD_D) (green dashed lines). Vertical red dotted lines correspond to the MCRS: 27 cm.

https://doi.org/10.1371/journal.pone.0262602.g009

the gear designs by graphically illustrating predicted retention probabilities, delta estimates among designs and catch profiles of different population scenarios, and provided detailed information about the contribution of the different components of the gear to its overall performance.

Treatment trees for hake demonstrated that changing the position of the panel to the lower netting, along with increasing its size (SMP_{BL}), decreased the retention probability of undersized individuals. These results are in line with those of Cuende et al. [24], who showed that panel position could be a key factor to improve the release of undesired and non-target hake, since positioning the SMP in the lower panel could favor the escape of species that swim closer to the lower panel of the trawl [23]. In contrast, the 60 mm mesh size located in the lower panel used by Nikolic et al. [47] in the Bay of Biscay's *Nephrops* fishery did not show to have any effect on hake catches. However, their study was based on data that included total catches and mean lengths, and the population fished was unknown. Therefore, we believe that our results cannot be directly compared to those. The results in this study showed that if only the position (SMP_{BS}) or size (SMP_{TL}) of the SMP was changed, the contact probability between the fish and the SMP was not improved compared to the SMP_{TS} design. However, the escape probability comparison between SMP_{BL} and SMP_{TL} should be interpreted carefully because

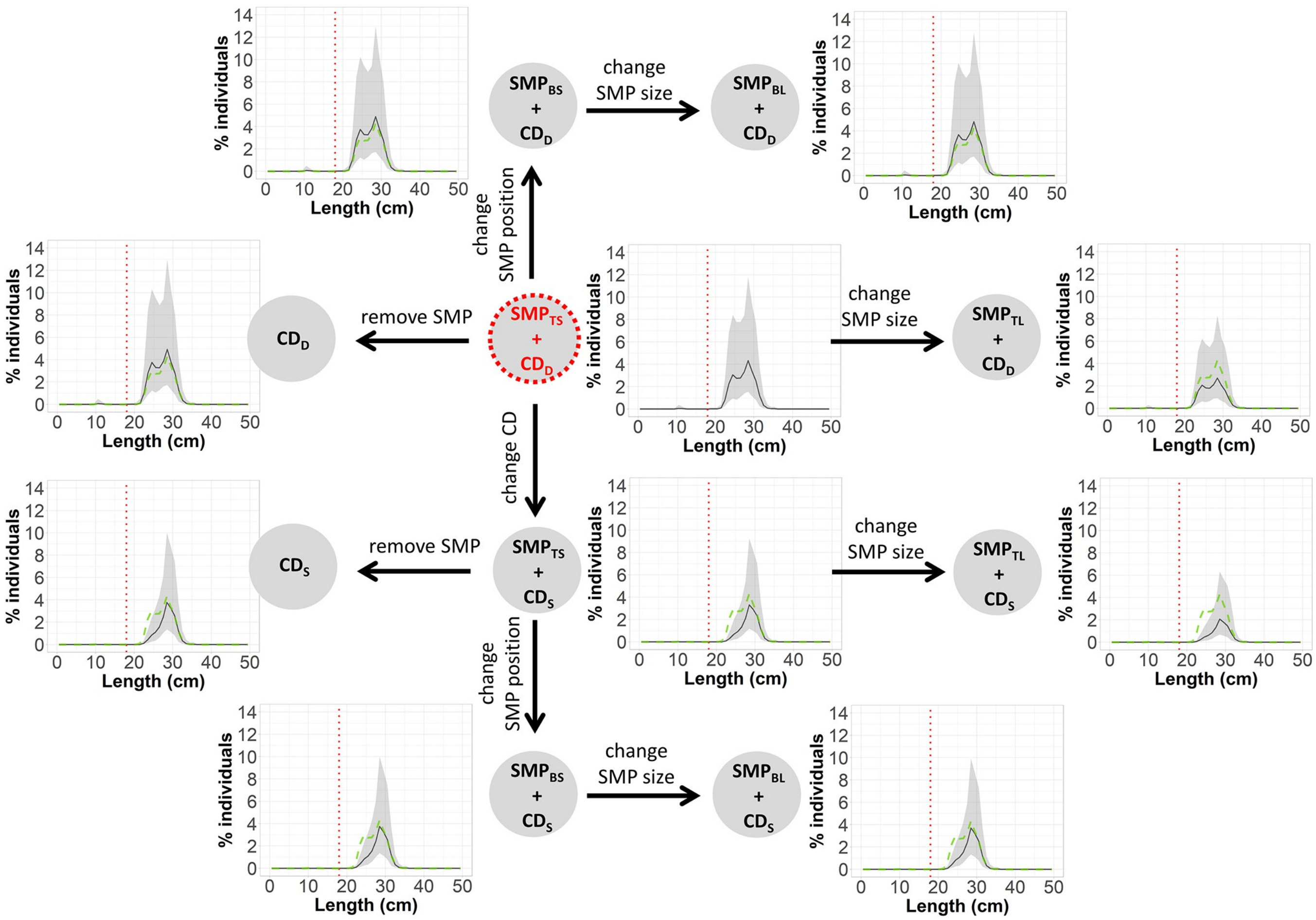

Fig 10. Treatment tree of the population structure fished for blue whiting with the different gear designs. Includes the fished population structure (black line) for each gear design and CIs (grey bands) and the population structure fished by the reference gear design (SMP_{TS} + CD_D) (green dashed lines). Vertical red dotted lines correspond to the minimum marketable size: 18 cm.

https://doi.org/10.1371/journal.pone.0262602.g010

SMP_{BL} had a bigger dimension than SMP_{TL}. The results demonstrate that increasing hake chances to contact the different SMPs (placed at the top and the bottom panel, respectively) is only significantly effective when placed at the bottom.

Regarding codend mesh geometry, CD_S significantly increased the escape probability of hake, and this increased even more when combined with SMP_{BL}. According to the catch profile, the hake population retained by any design with CD_S would mostly be that above its MCRS, due to the release of undersized individuals. Here, we highlight that contrary to diamond meshes, where all mesh bars are under tension due to the forces acting on the gear, for square meshes tension is present only in the two longitudinal mesh bars [34], which favors mesh shape distortion outwards during an escape attempt. In our case, this may have been further facilitated due to differences in mesh material as, CD_S was constructed of polyethylene, a material less resistant to deformation than polysteel used in CD_D [52]. Besides, *L*50 of hake for CD_D showed to be low (15.68 (CI: 12.47–17.51)) when compared to results reported by Alzorriz et al. [19] (20.29 (CI: 17.64–24.08)) who used a diamond mesh size of 75.80 mm. Apart from mesh size, other factors such as catch size [31, 32, 79], netting orientation and twine thickness [29], or the number of meshes in the circumference [28] can affect codend size selectivity because they can alter codend shape. Although several characteristics of the codend used

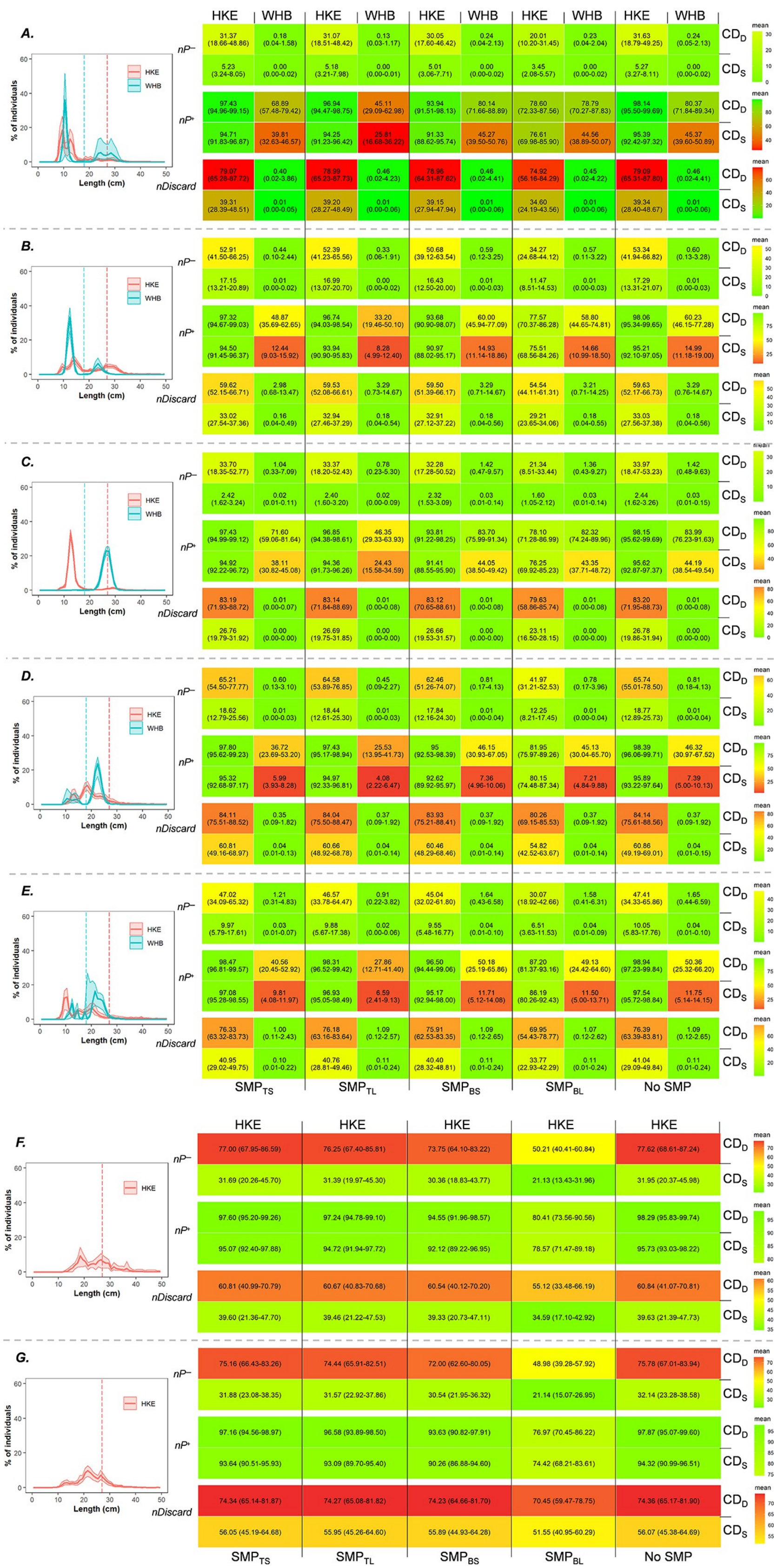
A.
B.
C.
D.
E.
F.
G.
HKE
WHB
nP−
nP+
nDiscard
CD_D
CD_S
% of individuals
Length (cm)
SMP_TS
SMP_TL
SMP_BS
SMP_BL
No SMP

Fig 11. Diagram of the exploitation pattern indicators for every gear combination and species following a traffic light system. A to G rows show different fish populations. In the left side, population structures for hake (HKE) and blue whiting (WHB) are shown, with vertical dashed lines representing the MCRS of hake (27 cm) and the estimated minimum marketable size of blue whiting (18 cm). In the right side, the traffic light diagrams show the indicators values (%), with green indicating 'satisfactory' and red 'unsatisfactory'.

https://doi.org/10.1371/journal.pone.0262602.g011

by Alzorriz et al. [19] and the used in this study were similar (mesh size and twine thickness), other differed. For example, Alzorriz et al. [19] made experimental trials on a fishing vessel, used a larger trawl, had longer towing times and probably, bigger catches. Although we cannot explain the differences found between these studies with certainty, we speculate that the differences in the experimental design mentioned may be the cause of the differences found. Conversely to hake, the delta plots in the treatment tree for blue whiting showed that any gear design that included an SMP at the bottom panel of the trawl increased the escape probability for this species (SMP_{BS} + CD_D, SMP_{BL} + CD_D, SMP_{BS} + CD_S or SMP_{BL} + CD_S). Similar to other gadoids (e.g. haddock (*Melanogrammus aeglefinus*) or whiting (*Merlangius merlangus*)), which have a vertical preference of swimming in the upper part of the trawl [80], blue whiting showed higher escape probability through the SMP_{TS} and SMP_{TL} together with any codend design, including a fraction of commercial-size individuals. These results agree with previously reported data on the suitability of SMP designs placed at the top panel to release non-target blue whiting in trawl gears [62, 81, 82].

Since the meshes in SMP_{BL} *PC* and CD_S *CC* were too big to rule out that some of the smallest hake and blue whiting individuals could have escaped through the cover meshes, we cannot conclude on the outcome for individuals below 20 cm for SMP_{BS} and SMP_{BL}, and below 15 cm for CD_D and CD_S. For hake, there is experimental data around the MCRS (both below and over 27 cm length), and therefore, the interpretation of the results for the sizes around MCRS can be trusted. In case of blue whiting, whose marketable size limit is 18 cm, the experimental data included in the analyses for SMP_{BS} and SMP_{BL} are over this size and therefore, the results around 18 cm should be interpreted with care.

Exploitation pattern indicators were also estimated for hake and blue whiting, providing quantitative information about the suitability of the gear for a specific fishing situation [83, 84]. The configurations analyzed in this study show different exploitation patterns for hake and blue whiting depending on the population scenario fished. These results highlighted potential strategies for fishing vessels operating in this area. Comparison of the exploitation indicators of the different gear between both species reveals that in some population scenarios fishing interest focused on hake may conflict with other target species with lower MCRS or minimum marketable size, such as blue whiting. However, the results in this study show that this mismatch could be resolved by taking advantage of differences in escape behavior between species. For instance, since only hake individuals are released by the SMP_{BL}, blue whiting would almost exclusively be size-selected by meshes in the codend. For example, in scenario (a), around 45% of legal-size blue whiting are estimated to be retained with SMP_{BL} + CD_S, opposite to SMP_{TS} + CD_S and SMP_{TL} + CD_S gear designs, which were respectively estimated to retain around 40% and 26% less blue whiting above its minimum marketable size. These low values, especially when using SMP_{TL}, could be seen as poor capture efficiency for blue whiting, although non-desired catches of this species in some fisheries often respond to market preferences [7]. In the Cantabrian Sea fisheries, for example, from the year 2000 on the single bottom trawl métier targeting blue whiting practically disappeared as a consequence of increased pair trawl effort in the area [85, 86]. The preference for blue whiting in bottom trawls operating in the Bay of Biscay may be conditioned by the more efficient pair trawls in ICES 8c, which target blue whiting. Additionally, whereas pair trawlers return to port almost every 24 hours, bottom trawlers in the Bay of Biscay (8abd) return every 6 days, which may imply retaining blue whiting during the last couple of days of the cruise to ensure the fish quality and freshness required by the market.

So far, the effort invested on attempting to open new paths towards sustainable exploitation patterns in these fisheries by means of the use of supplementary selection devices (e.g., SMPs) has shown that avoiding unwanted catches without losing target catch remains a problem. The results in this study state that SMP_{BL} + CD_S can favor catch patterns for hake because most undersized hake can be released for the majority of population scenarios. However, our data also show that the strongest effect on the catches are obtained when a square mesh codend is used, suggesting that simple codend adjustments may provide the opportunity to improve the size selectivity for hake and blue whiting. Although fishermen are often reluctant to codend modifications, especially in mixed fisheries, bioeconomic simulations anticipated detrimental effects in the short-term for the Basque trawling fisheries under full compliance of the Landing Obligation as well as in mid-term when applying any kind of exemption or flexibility to the law (current situation) [87, 88]. Therefore, we believe that further research should prioritize codend size selectivity, and additional selection devices may be added once codend designs with good selective properties are achieved.

Finally, graphics are becoming increasingly important for scientists to effectively communicate their findings to broad audiences. We believe that the treatment trees used in this study greatly improves the readability and interpretation of selectivity results and therefore, may aid the identification of promising and compatible gear designs, thus helping the industry in the pursuit of individual catch goals. The exploitation pattern indicators proved to be the fastest measure to determine which gear design could represent a viable option for a case-study fishery and the traffic-light procedure implemented categorized multiple exploitation indicators, providing by overview easily understandable results for managers and stakeholders. We therefore find the approach used in this study a powerful tool to periodically evaluate the performance of fishing gears in different fisheries around the world, which could potentially support and speed up the decision-making process made by fishing commissions, states or stakeholders.

Acknowledgments

We thank Mikel Basterretxea for his contribution on conceiving, developing and setting-up of the experiments at sea, to Jose Maria Ferarios and for his help during sea trials and to Nekane Alzorriz for providing data on fish populations. We also thank the crew of the RV Emma Bardan for their valuable assistance during the cruise. Finally, we thank the Editor of the journal and the three anonymous reviewers, who helped improving the quality of the manuscript. This paper is contribution n˚ 1088 from AZTI, Marine Research, Basque Research and Technology Alliance (BRTA).

Author Contributions

Conceptualization: Elsa Cuende, Manu Sistiaga, Bent Herrmann.

Data curation: Elsa Cuende.

Formal analysis: Elsa Cuende.

Funding acquisition: Luis Arregi.

Investigation: Elsa Cuende, Manu Sistiaga, Luis Arregi.

Methodology: Elsa Cuende, Bent Herrmann, Luis Arregi.

Project administration: Luis Arregi.

Resources: Luis Arregi.

Software: Bent Herrmann.

Supervision: Manu Sistiaga, Bent Herrmann, Luis Arregi.

Validation: Manu Sistiaga, Bent Herrmann.

Visualization: Elsa Cuende.

Writing – original draft: Elsa Cuende.

Writing – review & editing: Manu Sistiaga, Bent Herrmann.

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Paper V

"Species separation efficiency and effect of artificial lights with a horizonal grid in the Basque bottom trawl fishery"

Ocean and Coastal Management 221 (2022) 106105

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Species separation efficiency and effect of artificial lights with a horizonal grid in the Basque bottom trawl fishery

E. Cuende[a,*], B. Herrmann[b,c,d], M. Sistiaga[e,f], M. Basterretxea[a], A. Edridge[g], E.K. Mackenzie[g], R.J. Kynoch[g], G. Diez[a]

[a] AZTI, Marine Research, Basque Research and Technology Alliance (BRTA), Txatxarramendi ugartea z/g, 48395, Sukarrieta, Bizkaia, Spain
[b] SINTEF Ocean, Fishing Gear Technology, Willemoesvej 2, 9850, Hirtshals, Denmark
[c] The Arctic University of Norway, UiT, Breivika, N-9037, Tromsø, Norway
[d] DTU Aqua, Denmark Technical University, Hirtshals, Denmark
[e] Institute of Marine Research, Postboks 1870 Nordnes, Bergen, 5817, Norway
[f] Norwegian University of Science and technology, Otto Nielsens veg 10, N-7491, Trondheim, Norway
[g] Marine Scotland Science, Marine Laboratory, 375 Victoria Road, Aberdeen, AB11 9DB, UK

A R T I C L E I N F O

Keywords:
Species separation
Fish behaviour
Grid
Artificial light
Turbidity

A B S T R A C T

Achieving effective size selectivity for different species within a fishing gear is a major challenge in mixed fisheries. Fish behaviour may be exploited to separate species into separate codends where different selective properties can then be applied. Within the Basque bottom trawl fishery such a set-up has never been tested despite species with different behaviours being present. In this study, we investigate if species separation can be achieved through the use of a horizontal grid, where species typically found close to the seabed are intended to pass through the horizontal grid into the lower codend, while maintaining other species in an upper codend. Furthermore, the effect of artificial light on grid passage probability was estimated. Results were obtained for five fish species of commercial interest in the Basque bottom trawl fishery. Less than 25% of the individuals of all species analysed passed through the grid and were retained in the lower codend, and no significant differences were found when the grid was illuminated. The specific conditions under which the Basque bottom trawl fishery is conducted, i.e., high turbidity levels, high towing speed, may have influenced the performance of the gear in this fishery. Consequently, the design was found to have limited potential to improve species and size selection in the Basque bottom trawl fishery.

1. Introduction

During the last decade, many new trawl designs have been developed in an attempt to improve selectivity in commercial fisheries i.e., reduce the bycatch of unwanted species while maintaining high catch efficiency for the target species and sizes (Kennelly and Broadhurst, 2021). Selectivity in fishing gears is generally governed by a sorting process that has both a mechanical and a behavioural component (Broadhurst, 2000). The mechanical part is determined by whether or not a fish can physically pass through the selective device (e.g. netting meshes or spaces between bars in a grid), whereas the behavioural part determines how fish distribute inside the trawl gear and their reaction to specific selection devices. Research on fish behaviour relative to selectivity of fishing gears flourished in the 80s and 90s and has increased substantially in recent years (e.g. Campbell et al., 2010; Ferro et al., 2007; ICES, 2019, 2021; Krag et al., 2009a, 2014, 2017; Løkkeborg et al., 2010; Madsen et al., 2006; Melli et al., 2018, 2019). Research has shown that an understanding of fish behaviour facilitates the development of more efficient species or size selective trawl gears (Løkkeborg et al., 2010; Wardle, 1986).

The catch process by which fish enter and are retained in a trawl involves a complex sequence of events and corresponding fish behaviours (Winger et al., 2010). During the catch process, fish behaviour can differ in the pre-trawl zone, between trawl doors and trawl mouth, and

* Corresponding author.
E-mail addresses: ecuende@azti.es (E. Cuende), Bent.Herrmann@sintef.no (B. Herrmann), Manu.Sistiaga@hi.no (M. Sistiaga), mbasterretxea@azti.es (M. Basterretxea), Alexius.Edridge@gov.scot (A. Edridge), Emma.Mackenzie@gov.scot (E.K. Mackenzie), Robert.Kynoch@gov.scot (R.J. Kynoch), gdiez@azti.es (G. Diez).

https://doi.org/10.1016/j.ocecoaman.2022.106105
Received 11 January 2022; Received in revised form 22 February 2022; Accepted 23 February 2022

inside the trawl and the codend. These differences have previously been used to select different fish species and sizes (Fryer et al., 2017; Krag et al., 2009b; Løkkeberg et al., 2010; Melli et al., 2018). In particular, species specific differences in vertical distribution inside the trawl have been used to reduce unwanted catches, i.e. by separating species that enter the gear low down from species that distribute themselves higher in the gear (Fryer et al., 2017; Karlsen et al., 2019; Krag et al., 2009a, 2009b; Larsen et al., 2021). Karlsen et al., (2015) for example, separated fish from Norway lobster (*Nephrops norvegicus*) using a horizontally divided codend and by encouraging fish to swim upwards with a frame at the entrance of the lower codend.

The Basque bottom trawl multispecies fishery includes more than 100 different species (Rochet et al., 2014). Hake (*Merluccius merluccius*), megrim (*Lepidorhombus* spp.) and anglerfish (*Lophius* spp.) are main target species whereas horse mackerel (*Trachurus trachurus*), mackerel (*Scomber scombrus*) or blue whiting (*Micromesistius poutassou*) are important as choke species (Schrope, 2010). In between some of these fish species distinct behaviours inside trawl gear have been documented. Previous studies have revealed that hake tends to swim close to the lower netting in the trawl and is more likely to pass through devices placed in the lower panel than the top panel (Cuende et al., 2020a; 2020b). Similarly, megrim, like most flatfish, enter the trawl close to the seabed and remain there (Main and Sangster, 1981, 1982; Ryer, 2008; Thomsen, 1993). On the other hand, horse mackerel, mackerel and blue whiting, distribute more uniformly and show a more active swimming behaviour inside the trawl gear (Cuende et al., 2020a; 2020b). Thus, the range of behaviours in this fishery highlight its potential for bycatch and target species separation.

In this study we aim to separate species that typically enter the trawl gear close to the seabed (hake and megrim) from those distributed more uniformly within the trawl (horse mackerel, mackerel and blue whiting). While hake and megrim are target species throughout the whole year, horse mackerel, mackerel and blue whiting are usually considered target or bycatch species depending on their quota availability and market preferences (Rochet et al., 2014). Therefore, the effective separation of these species through a modified gear design would allow subsequent size selectivity processes to be applied to the relevant species groups and could support fishers to maintain target catch while releasing by-catch. It was proposed that a passage section inserted in the lower panel in the aft of the trawl would facilitate the access of those species swimming close to the lower panel (e.g. hake and megrim) to an additional lower codend. Contrary, those species with a more uniform distribution in the gear would continue to the upper codend. The separation of the different fish species would allow more specific size selectivity processes to be applied in the different codends.

The diversity of morphologies present in this fishery requires a passage suitable both for flat- and roundfish species. Since square meshes are more suited for the release of roundfish rather than flatfish due to fish morphology (Halliday et al., 1999; Robertson, 1989; Walsh et al., 1992), a horizontal passage section with rectangular gaps (with a grid-like shape) was used, as it is better suited for the passage of both targeted roundfish and flatfish species. However, these gaps were oriented longitudinally to the trawl body, which may reduce flatfish escape chances since they may not allow the body shape of flatfish to pass in natural swimming orientation (Herrmann et al., 2013). Therefore, to compensate and maximize its possibilities to pass through the passage section, wide bar-spacing was provided.

The passage device (hereafter referred to as grid) also provides a rigid structure that facilitates the attachment of devices such as lights and maintain the shape of the escape gaps. Previous studies have shown that artificial lights can improve the selective properties of trawl gears for some species (e.g. Hannah et al., 2015; Lomeli et al., 2018; Lomeli and Wakefield, 2019; O'Neill and Summerbell, 2019). Melli et al., (2018) confirmed their potential as behavioural stimulators and their role in vertical separation efficiency. Therefore, in this study we aim to test the effect of artificial light, with a wavelength of 450 nm (visible as blue) on species separation when attached on the grid.

The present study was designed to answer the following research questions:

1) Can a horizontal grid be used for species separation?
2) Is fish passage probability through the grid species- and/or length-dependent?
3) Can artificial light be utilised to improve fish passage through a grid into the lower codend?

2. Material and methods

2.1. Gear design

Sea trials were carried out on board the commercial fishing vessel Kalamendi (43m length overall; 353 kW) from 28 June to 4 July 2021. The fishing was carried out in ICES division 8a (Fig. 1). Towing occurred during day and night, at depths that varied between 89 and 124 m and towing speed over ground ranged from 3.9 to 4.2 knots. Each tow lasted 2.5 h approximately, counting from when the vessel reached a constant towing speed to the beginning of gear hauling-back.

The gear used in the experiments was a two-panel bottom trawl with a 120 m long fishing line. The trawl was rigged with a set of Morgère doors (Morgère EXOCET EX07 type, 3.84 m^2; 988 Kg each), 385 m sweeps, and a light rockhopper ground gear (with 400 Kg chain).

The trawl configuration tested was attached to the aft part, just behind the body of the trawl net and was composed by three sections (Fig. 2). The trawl configuration tested an 80 mm two-panel netting section split into two compartments (i.e. upper and lower extension and codend) with an 80 mm horizontal separator panel that kept both extensions separated (Fig. 2). This section was made of 76.5 meshes long x 120 meshes round and constructed of 4 mm single PE twine (Fig. 2). Ahead of this section, a guiding panel was installed forcing fish to swim into the upper extension and over the horizontal separator panel where a grid (described below) was installed, just below the main flow of fish. For fish to end up in the lower compartment they need to pass through the grid (Fig. 2). The horizontal separation contained an internal supporting hoop (internal radius 78 cm) to keep the netting spread (Figs. 2 and 3c).

The grid in the passage section was designed as an octagon with rectangular gaps (Fig. 3a). The grid was 25 mm thick high-density polyurethane with dimensions 1.20 m × 0.75 m. It had a horizontal

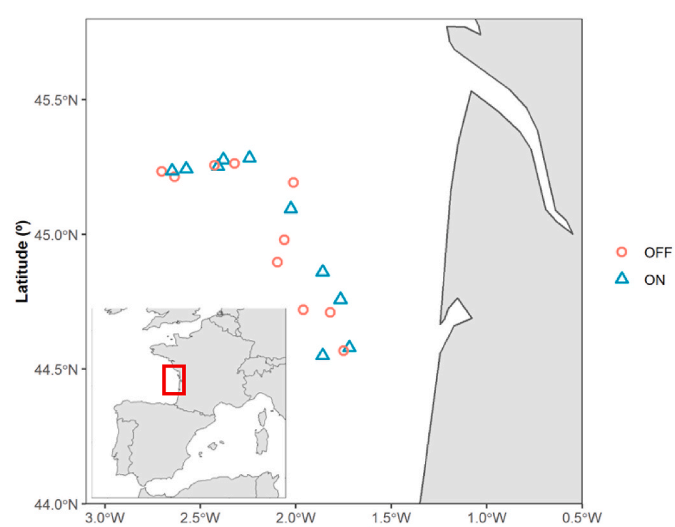

Fig. 1. Sampling area and fishing position for all hauls conducted during the cruise. Red circles represent hauls with lights switched off and blue triangles with lights switched on.

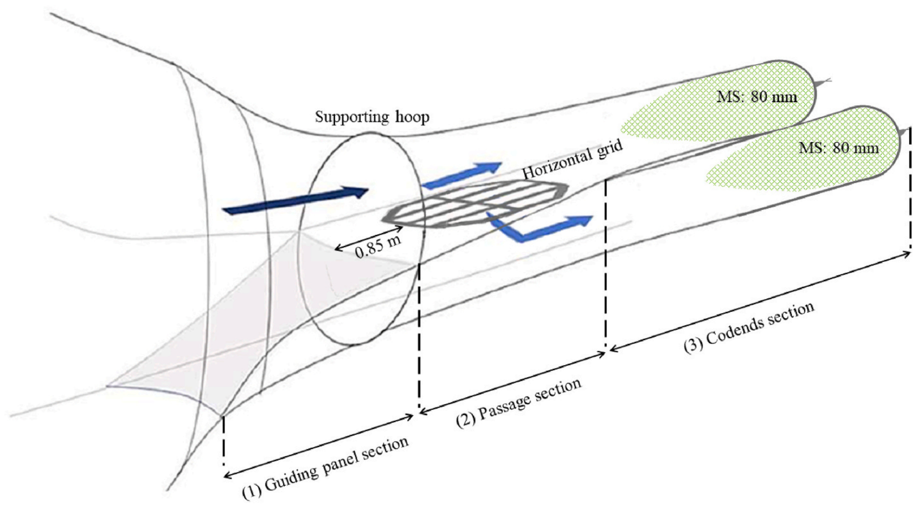

Fig. 2. Gear diagram and specification of different sections. MS: mesh size.

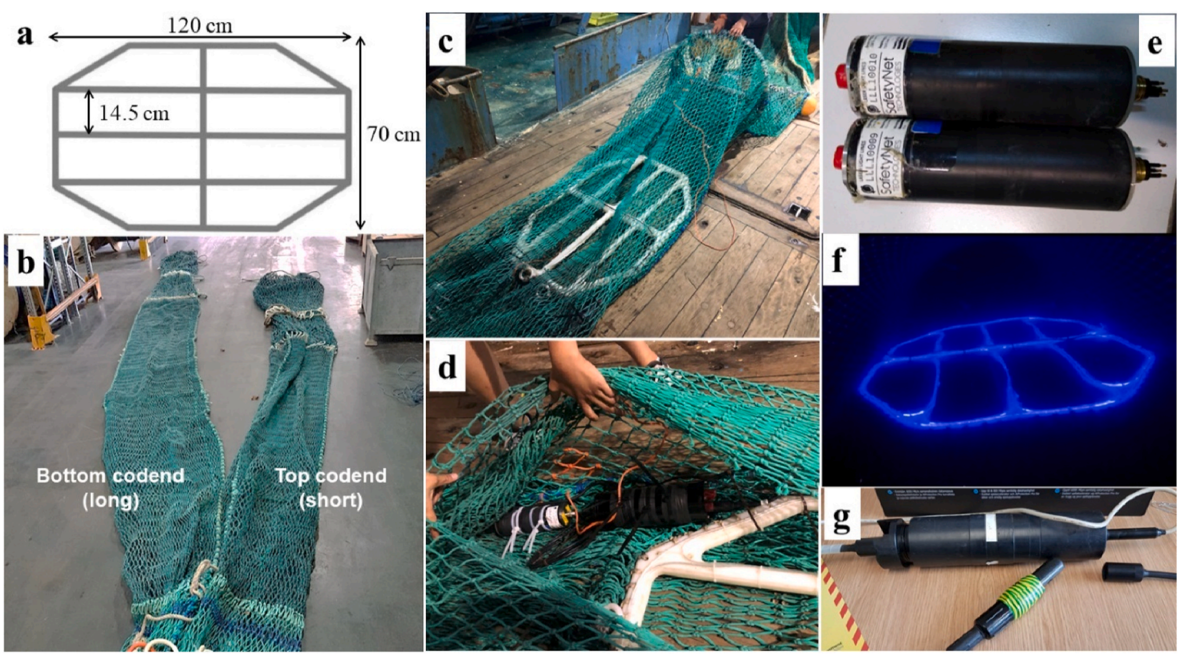

Fig. 3. (a) Technical characteristics of the grid used; (b) Gear picture, the grid and upper (short) and lower (long) codends are shown; (c) passage section and the internal supporting hoop; (d) battery housing and LDP attached to the gear; (e) LDPs; (f) underwater picture of the illuminated grid and (g) turbidity sensor.

bar dividing the grid in half and vertical bars on both halves at 0.145 m apart (to permit passage of legal sizes of all species under study). The grid was placed 0.85 m after the end of the guiding panel (Fig. 2).

The fishery studied here allows the use of a 100 mm codend mesh size or a 70 mm codend mesh size together with a 100 mm square mesh panel (SMP). The sea trials were carried out on commercial fishing grounds where catch of large-sized target individuals was expected. Therefore, as compromise between the mandatory codend mesh sizes and to ease the fishing operation onboard (by fishing smaller bulks), the upper and lower codends were made of 80 mm nominal mesh size. The upper codend was made of 4 mm single twine, 120 meshes round, 73 meshes long, and had an average mesh size of 81.75 (±2.57 SD) mm. The lower codend was made of 4 mm single twine, 120 meshes round, 102 meshes long (longer than upper codend to facilitate the fishing operation) and had a mesh size of 81.25 (±1.97 SD) mm (Fig. 3b). Both codends were rigged with 160 mm mesh size lifting/strengthening bags 17 meshes long x 30 meshes width constructed from 5 mm double PE twine.

The light source used to illuminate the grid was a 20 m long multi-strand side-emitting fibre optic cable, connected to a laser diode pod (LDP) at each end (SafetyNet Technologies Ltd) (Fig. 3de). Each of the two LDP emit coherent light from a laser diode at a wavelength of 450 nm, at 340 mW of optical power and were powered by an external 12V Li-Ion battery pack (Fig. 3d). Since lower wavelengths of the visible spectrum are faster absorbed than higher wavelengths, a 450 nm wavelength (visible as blue light) was selected for the experiments in this study (Carleton et al., 2020). Additionally, this may allow comparison of results with Cuende et al., (2020a) (Fig. 3f). We used a single trawl with the grid illuminated (hereafter treatment design) and without illumination (hereafter baseline design) in an alternating order.

Turbidity levels inside the gear were measured during trawling in every haul, as recommended by the International Council for the Exploration of the Sea (ICES) to improve comparability of results between light studies (ICES, 2018). Turbidity was measured with a

Seapoint turbidity meter and recorded by an Aquatec AQUAlogger 210 series Data Logger (Fig. 3g). Underwater recordings were conducted when the artificial lights attached on the grid were switched on. By synchronising video camera and turbidity logger recording timers, we aimed to associate turbidity measures to specific video frames. Since the turbidity meter was positioned ~1.5 m from the video camera, we calculated the mean turbidity (±SD) of each video frame by accounting on the 5 s before and after the targeted video frame. Besides, quantiles Q10, Q25, Q50, Q75 and Q90 were calculated to estimate the towing time percentage (10%, 25%, 50%, 75% and 90%) during which the turbidity did not exceed a certain level.

The species included in the data analysis were hake, megrim, anglerfish, horse mackerel and mackerel due to their importance as target and bycatch species. Despite being an important species for the fishery, blue whiting was not included in the study because there were not enough catches. After each haul, all the catch in upper and lower codends was sorted by species and all individuals were measured to the nearest centimetre using a measuring board.

2.2. Modelling the length-dependent probability for capture in the lower codend

Previous studies working with behaviour-based selectivity have shown a size-dependent entry pattern of fish in trawls (Karlsen et al., 2019; Melli et al., 2018). Therefore, we conducted an analysis to determine for each species the length-dependent probability for being captured in the lower codend conditioned capture $PL(l)$, i.e., the probability for passage through the grid. We used the numbers and length measurements of the fish caught in upper and lower codend, respectively. The analysis was carried out independently for each species and gear configurations (with and without the LDP turned on) following the description below.

The expected probability for a fish of length l to be captured in the lower codend will be:

$$PL_l = \frac{\sum_{j=1}^{h} nL_{lj}}{\sum_{j=1}^{h} \left\{ nL_{lj} + nU_{lj} \right\}} \tag{1}$$

where nL_{lj} and nU_{lj} are the number n of fish of the species investigated caught per length class l in respectively, lower (L) and upper (U) codend in haul j and h is the total number of hauls with the specific gear configuration. The functional description of the capture probability in the lower codend was obtained using maximum likelihood estimation by minimising Equation (2):

$$-\sum_{j=1}^{h}\sum_{l}\left\{ nL_{lj} \times ln[PL(l,\boldsymbol{v})] + nU_{lj} \times ln[1.0 - PL(l,\boldsymbol{v})] \right\} \tag{2}$$

In Equation (2), $\boldsymbol{v}$ represents the parameters describing the capture probability curve defined by $PL(l, \boldsymbol{v})$, that spans the value range [0.0; 1.0]. Equations (1) and (2) together is similar in form to what is often used for modelling and estimating the length-dependent catch comparison rate between two fishing gears (Krag et al., 2014). Therefore, we adapted the same approach for modelling $PL(l, \boldsymbol{v})$ as is often applied for catch comparison studies based on binominal count data (Herrmann et al., 2017):

$$PL(l,\boldsymbol{v}) = \frac{exp[f(l, v_0, \ldots, v_k)]}{1 + exp[f(l, v_0, \ldots, v_k)]} \tag{3}$$

In Equation (3), f is a polynomial of order k with coefficients $v_0 - v_k$, so that $\boldsymbol{v} = (v_0,\ldots,v_k)$. The values of the parameters $\boldsymbol{v}$ describing $PL(l, \boldsymbol{v})$ are estimated by minimising Equation (2). We considered f of up to an order of 4. Leaving out one or more of the parameters $v_0 \ldots v_4$, at a time resulted in 31 additional candidate models for the capture probability function $PL(l, \boldsymbol{v})$. Among these models, the capture probability was estimated using multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017). The ability of the combined model to describe the experimental data was based on the p-value, which is calculated based on the model deviance and degrees of freedom (Herrmann et al., 2017; Wileman et al., 1996). This p-value quantifies the probability to obtain at least as big a discrepancy between the fitted model and experimental data as observed by coincidence. For the applied model to describe the experimental data at an acceptable level, this p-value should be > 0.05 (see Wileman et al., 1996). We used a double bootstrapping method (1000 bootstrap repetitions) to estimate the 95% confident intervals (CIs) for the capture probability curve following the description in (Lomeli et al., 2019).

The average probability of being retained in the lower codend integrating the Minimum Conservation Reference Size (MCRS), $PL_{average}$, was quantified by calculating the values for a number of indicators. Specifically, based on the population size structure caught during the trials, the average value for the capture probability in the lower codend of individuals below MCRS ($PL-$), above MCRS (PL_+) and of the total catch (PL_{total}) were estimated:

$$PL_{average} = \frac{\sum_l \sum_{j=1}^{h} nL_{lj}}{\sum_l \sum_{j=1}^{h} \left\{ nL_{lj} + nU_{lj} \right\}} \tag{4}$$

where the outer summations include the size classes in the catch during the experimental fishing period. The equation (4) used, both summed-over undersized fish ($PL-$), target sized fish (PL_+) and all fish (PL_{total}), respectively. In contrast to the length-dependent evaluation of the capture probability curve for the lower codend $PL(l,\boldsymbol{v})$, $PL_{average}$ is specific for the population structure encountered during the experimental trials and cannot be extrapolated to other scenarios in which the size structure of the specific fish species may be different. The MCRS values for each species were: hake: 27 cm; megrim: 20 cm; horse mackerel: 15 cm; and mackerel 20 cm. Anglerfish has a minimum marketable weight of 500 gr (without guts) per individual (EC, 1996), which is equivalent to 32 cm length according to Dorel (1986). We used the statistical software SELNET (Herrmann et al., 2012) to analyse the catch data and ggplot2 (Wickham, 2016) for graphical output in R statistical software (R Core Team, 2021).

2.3. Inferring the effect of artificial light on probability for capture in the lower codend

The difference in $PL(l,\boldsymbol{v})$ between using treatment and baseline designs was obtained species-wise by estimating the difference in the probability of ending up in the lower codend between treatment and baseline designs ($\Delta PL(l) = PL_{light}(l) - PL_{base}(l)$). Where $PL_{base}(l)$ and $PL_{light}(l)$ represent $PL(l,\boldsymbol{v})$ obtained by using (3) in (2) for two different gear configurations compared. 95% CIs for $\Delta PL(l)$ was obtained based on the two bootstrap populations for both $PL_{light}(l)$ and $PL_{base}(l)$ by the method described in Larsen et al., (2018).

3. Results

3.1. Overview of sea trials

A total of 20 valid hauls were conducted, 10 hauls with the baseline design and 10 hauls with the treatment design. Sufficient data for analysis were collected for hake, megrim, anglerfish, horse mackerel and mackerel, although some species were not present in all hauls (Table 1). In total, 24,008 individuals comprising all species were included in the analysis, from which 20,343 entered the upper codend while 3665 individuals went through the grid and ended up in the lower codend. Although most individuals entered the upper compartment, the level of separation differed among the species (Table 1).

Underwater recordings of the light on the grid were not visible from the video camera for long periods while towing, this was due to the

Table 1
Overview of the hauls conducted during the experimental sea trials and the numbers of hake, anglerfish, megrim, horse mackerel and mackerel in the upper (*nU*) and lower (*nL*) codends.

Haul no.	Light	Depth (m)	Tow starting time	Tow ending time	Hake		Anglerfish		Megrim		Horse mackerel		Mackerel	
					nU	nL	nU	nL	nU	nL	nU	nL	nU	nL
1	ON	102.8	8:20	10:20	171	88	118	4	95	7	837	78	81	0
2	OFF	102.8	11:00	13:30	234	48	–	–	115	10	750	98	84	13
3	ON	102.0	14:10	16:40	292	67	74	4	103	12	1603	163	23	0
4	OFF	112.8	17:20	19:50	241	35	90	10	221	28	824	137	244	4
5	OFF	115.4	0:25	2:55	255	58	102	17	76	16	25	8	–	–
6	ON	116.2	3:50	6:20	155	31	116	29	84	16	75	6	6	1
7	OFF	109.5	10:45	13:30	559	100	53	8	200	43	2126	326	73	3
8	ON	90.3	14:10	16:30	310	113	54	13	134	64	475	181	15	1
9	ON	114.5	21:15	23:45	147	30	135	56	186	46	387	67	27	1
10	OFF	111.2	0:35	3:05	82	29	160	80	131	65	–	–	–	–
11	OFF	117.0	7:45	10:15	350	60	124	19	396	138	440	48	111	1
12	ON	106.2	11:05	13:35	–	–	96	32	–	–	598	63	94	0
13	ON	112.8	22:15	0:45	63	11	180	44	190	48	12	7	–	–
14	OFF	112.0	1:35	4:05	114	12	190	27	213	19	–	–	–	–
15	OFF	109.5	8:55	11:25	370	111	93	20	270	82	398	78	16	0
16	ON	109.5	12:10	14:40	339	90	117	29	272	101	346	61	25	1
17	ON	92.8	20:05	22:35	246	59	69	12	156	51	150	16	9	0
18	OFF	92.8	23:25	1:55	179	26	82	11	53	21	30	11	–	–
19	ON	98.6	20:15	22:45	218	47	110	17	85	13	577	38	194	2
20	OFF	99.5	23:35	2:05	209	11	103	9	108	5	–	–	–	–

sediment resuspension and high presence of invertebrates in the area. Fig. 4 shows low turbidity levels in video frames with a clear view of the illuminated grid (e.g., 3.09 $\pm$ 0.28 FTU) whereas a high turbidity level occurred in video frames where the illuminated grid is not visible (e.g., 58.17 $\pm$ 14.39 FTU). Considering turbidity values in every haul, Table 2 shows that, for most hauls, 90% of the towing time the values were above 100 FTU, significantly higher than the value in the dark frame in Fig. 4.

3.2. *Passage probability into lower codend*

Estimation of the passage probability into the lower codend was conducted fitting the combined model to the experimental data. The fit statistics for the model show that, in most cases, *p*-values were $>$0.05, meaning that the applied model describes the experimental data at an acceptable level (Table 3). Only the model for megrim on the treatment design had poor fit statistics (p-value $<$ 0.05, deviance $>>$ DOF), for which the residual deviations between the data and the modelled curves were investigated. No systematic structure was detected, and the low *p*-value was considered a consequence of overdispersion in the data. Therefore, we were confident that the model could also be used for megrim to describe the length-dependent probability to be captured in the lower codend.

The catch comparison curves described well the experimental data, especially for some length classes (Figs. 5 and 6). For the lengths where fewer individuals were caught, the certainty to explain the experimental data decreased, as shown by the increasing size of the confidence intervals. The catch comparison analysis show that the probability for being retained in the lower codend is significantly lower than in the upper codend for all species using both the baseline (Fig. 5) and

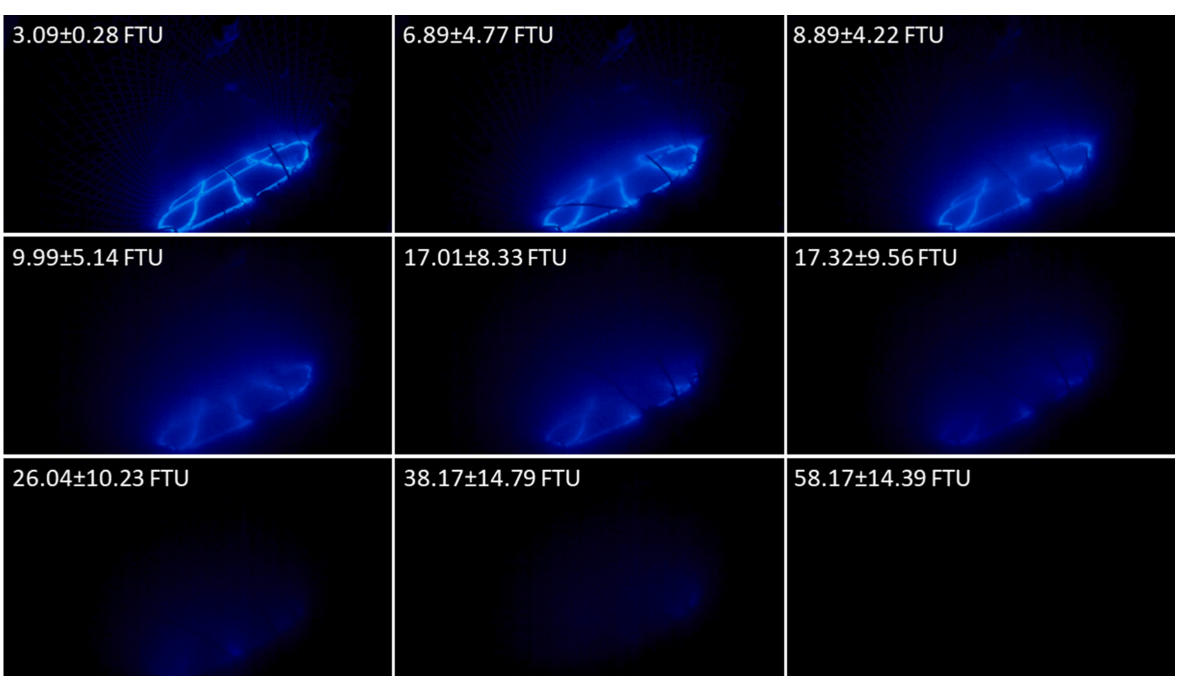

Fig. 4. Underwater video captures during an illuminated haul. Each video frame shows the associated turbidity mean value ($\pm$SD) given by the turbidity meter.

Table 2
Quantiles (10, 25, 50, 75 and 90) of the turbidity data (FTU) registered during each haul. Shadowed rows correspond to hauls with baseline design.

Haul nº	Q10	Q25	Q50	Q75	Q90
1	39.77	85.01	133.31	185.15	236.50
2	105.69	131.28	147.42	170.92	196.10
3	66.63	92.42	119.19	143.84	175.08
4	66.36	92.38	170.86	416.86	527.87
5	312.40	369.40	426.28	482.59	528.60
6	318.89	370.13	441.92	499.86	558.84
7	113.11	141.78	177.43	221.47	276.21
8	94.55	131.21	171.78	213.38	254.09
9	114.27	144.13	187.71	247.06	294.37
10	167.41	194.08	226.92	268.78	326.61
11	169.42	216.24	271.31	341.10	406.17
12	101.79	130.32	157.40	186.68	218.91
13	151.85	242.36	379.68	486.25	547.63
14	193.13	275.15	350.17	495.06	630.67
15	172.67	201.52	248.15	310.54	364.53
16	193.50	241.52	315.02	446.46	528.32
17	120.45	153.53	187.61	231.16	305.21
18	170.31	207.95	254.69	349.53	432.96
19	99.05	137.15	276.49	405.16	470.23
20	158.10	188.74	233.06	284.75	330.87

Table 3
Fit statistics for the modelled grid passage probabilities of the experiments with the light switched on or off. DOF denotes the degrees of freedom and was calculated by subtracting the number of model parameters from the number of length classes in the dataset. *p*-values marked with * show the cases where the residual variation between the models fit and the experimental data required further investigation.

Species	Light	p-Value	Deviance	DOF
Hake	OFF	0.1270	62.65	51
	ON	0.7583	39.92	47
Anglerfish	OFF	0.8995	35.97	48
	ON	0.6814	43.85	49
Megrim	OFF	0.5751	30.84	33
	ON	0.0179*	43.31	26
Horse mackerel	OFF	0.3326	25.35	23
	ON	0.3605	17.40	16
Mackerel	OFF	0.6078	10.09	12
	ON	0.7866	8.82	13

treatment design (Fig. 6). In general, the probability of passing through the grid tends to decrease for larger individuals of all species.

3.3. Effect of artificial light

The difference in retention probability in the lower codend when the lights were on compared to when lights were off for the different species was plotted to show the effect of artificial lights (Fig. 7). Fig. 7 shows that there are not significant differences on grid passage probability between treatment and baseline design except for hake. Hake shows significantly higher retention in the lower codend when the grid is illuminated for individuals between 28 and 36 cm length.

When the average capture probability in the lower codend for each species is analysed, which depend directly on the size structure of the population caught, it is observed that light does not significantly affect fish probability for passing through the grid since any of the indicators calculated were significantly different in between designs (Fig. 8).

4. Discussion

The results obtained in this study show that the catch rate of all species in the lower codend compared to the total catch was low, showing fish were unlikely to pass through the grid. The results suggest that the swimming preferences of the species tested were not strong enough driver to trigger a downwards escape reaction and separate them into upper and lower codend in the fishery under study. The low probability values observed could be a consequence of factors such as low contact ratio between the fish and the grid. Cuende et al., (2022) showed that a square mesh panel located on the bottom panel of the extension piece of the trawl significantly increased the escape of undersized hake, probably due to its tendency to swim towards the bottom. However, Grimaldo et al., (2015) showed that for achieving satisfactory selectivity results for some species, guiding fish to a size selective sorting grid by means of a guiding panel is essential. Therefore, a guiding panel that directs the fish towards the grid, opposite to the current set-up, could increase encounter rates and the likelihood the fish contact the grid and escape through it.

A potential alternative driving out the need for increasing contact probability of target species with the grid can be the use of a horizontally divided codend. This gear design has been often tested in crustaceans and finfish fisheries with different degrees of success (e.g., Karlsen et al., 2019; Krag et al., 2009b), and its optimization is based on additional devices or simple gear modifications. Karlsen et al., (2015) for example, improved fish and Norway lobster (*Nephrops norvegicus*) separation in a horizontally divided codend by encouraging fish to swim upwards with a frame at the entrance of the lower codend. Dividing the codend would eliminate the potential visual effect of the grid, which could make fish more reluctant to pass through than if clearer passage is available (Glass et al., 1995). Additionally, it would provide longer time to fish to swim upwards or downwards and also may constitute a simpler gear design to construct and deploy.

In general, the results suggest a length-dependent capture pattern in the lower codend, since a higher proportion of small individuals pass through the grid regarding the total catch. Previous studies have reported a length-dependent behaviour related to the swimming capacity; with smaller individuals entering the lower compartment more frequently (Melli et al., 2018). In this study, length-dependent effect was identified for all species however, it is believed that the grid bar-spacing may be affecting the passage probability of larger fish. This may be especially relevant for large megrim individuals since longitudinally oriented bars together with narrow bar-spacing may not allow the body shape of flatfish to pass in natural swimming orientation. Santos et al., (2016) were able to reduce up to ~68% of flatfish bycatch by implementing escape grid with horizontal gaps in front of the codend. Therefore, further research on a passage section that minimises physical constrains would be worth to test.

Our results show that the passage probability through the illuminated grid is not significantly different when compared to baseline grid (except for hake, which was only slightly affected by the lights). The estimations showed significantly higher passage probability for hake between 28 and 36 cm length during the illuminated trials. However, these values are far too low to be useful in a commercial fishery. Despite that, the average probability estimations, which are specific for the population structure encountered during the experimental trials, did not show any significant differences between designs for any species.

According to the study carried out by Melli et al., (2018), green LED lights were found to have a significant effect on the vertical separation of some species. Specifically, fish showed a preference for the bottom panel in a horizontally divided codend in the presence of green LED lights. Although they were not able to specify how this effect was given because fish responded differently when the artificial lights were placed in different positions, they suggested that lights could be triggering other behavioural responses such as increased awareness of the surroundings, panic, or species-specific escape behaviours. In our case, considering the poor effect of lights on the passage probability of the species tested, we cannot discard that other factors may be affecting the properties of the artificial light or how the fish perceive the light. According to the turbidity data in our study and the underwater recordings, it is observed that high turbidity levels occurred for extensive periods in different hauls. More specifically, turbidity levels were severe enough to affect

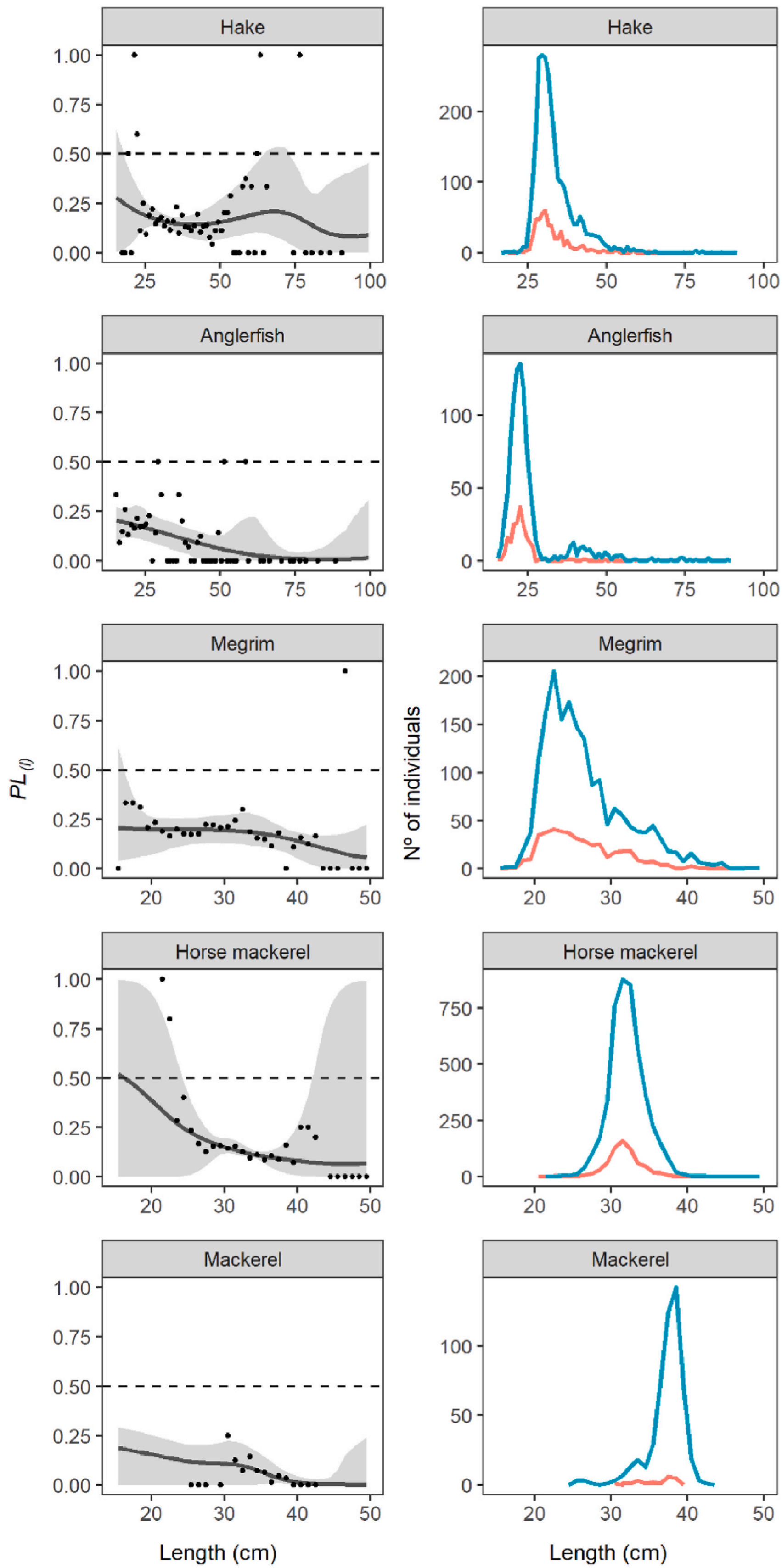

Fig. 5. (Left) Length dependent probability for individuals to be caught in the lower codend conditioned that they are retained when baseline design was used. (Right) Number of individuals retained in upper (blue) and lower (red) codend. Horizontal line represents equal probability to be captured in both codends.

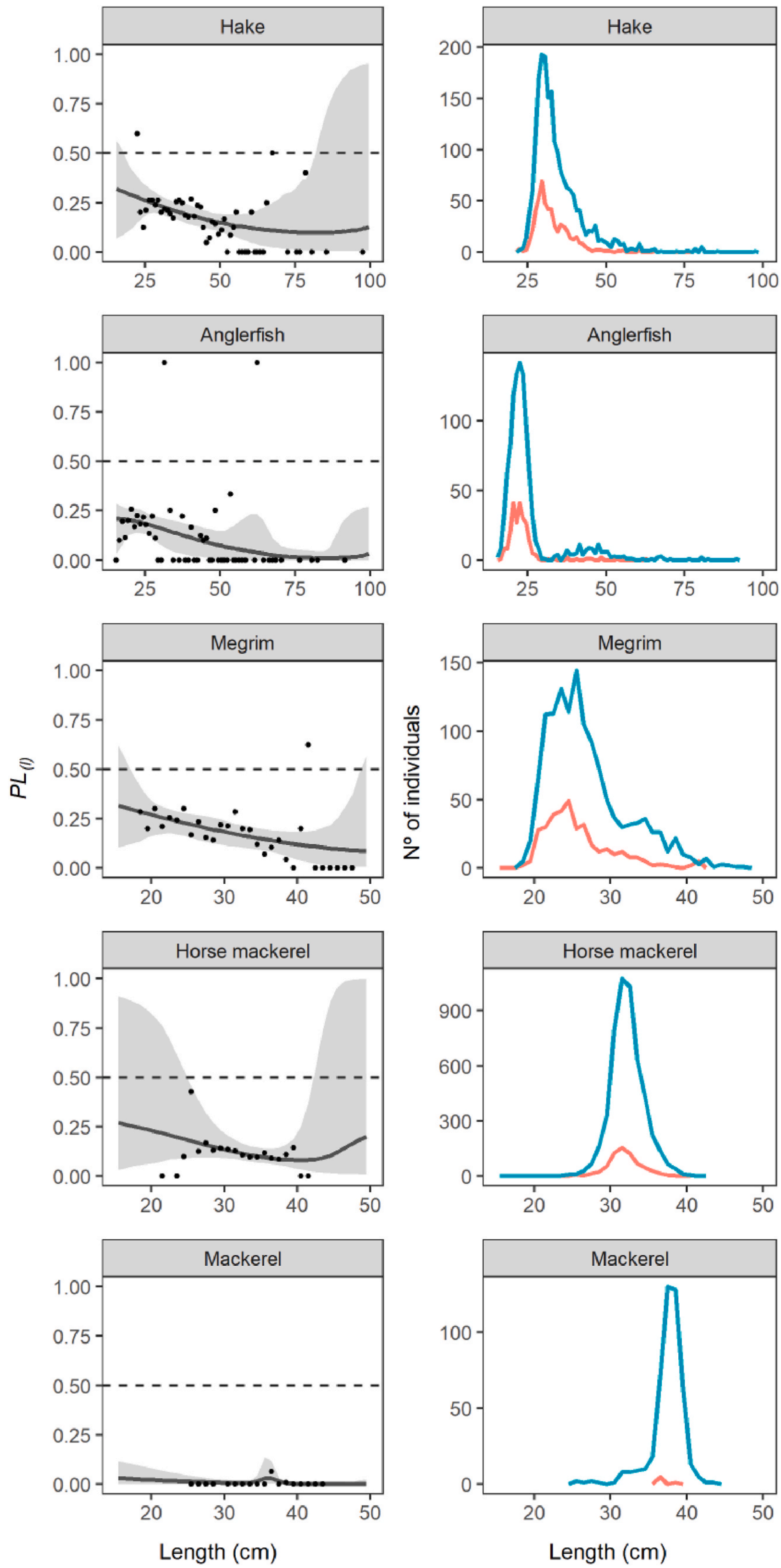

Fig. 6. (Left) Length dependent probability for individuals to be caught in the lower codend conditioned that they are retained when the treatment design was used. (Right) Number of individuals retained in upper (blue) and lower (red) codend. Horizontal line represents equal probability to be captured in both codends.

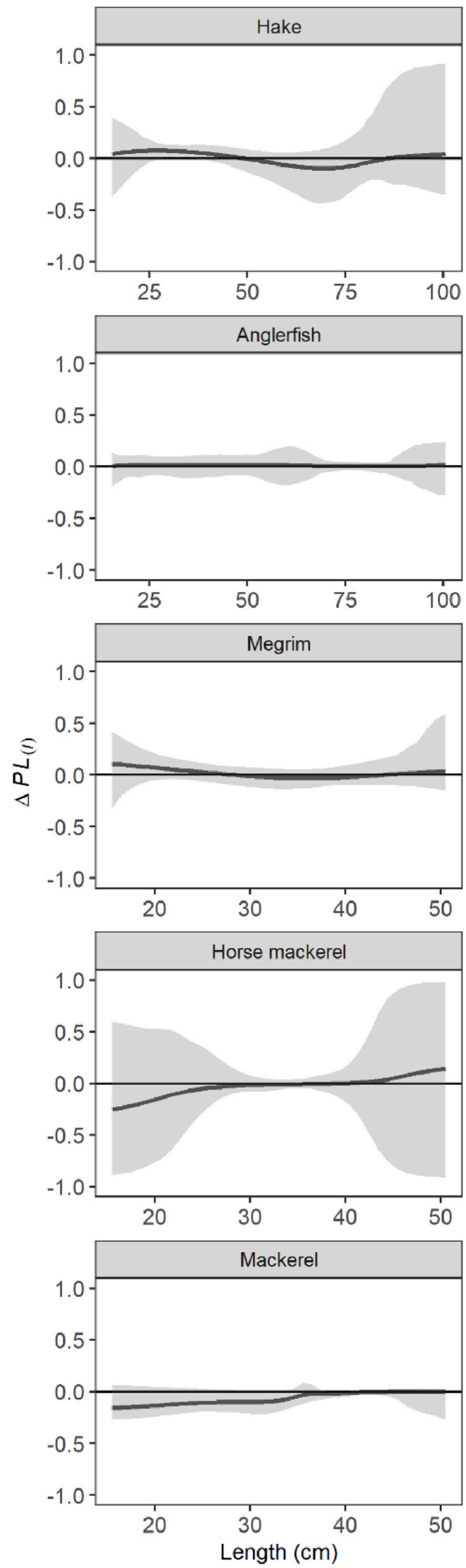

Fig. 7. Probability of fish ending up at the lower codend when treatment design was used with respect to baseline design. Horizontal line represents equal probability for both designs. Mean curve and CIs above or below horizontal line means significantly higher or lower probability to being retained in the lower codend when treatment design is used.

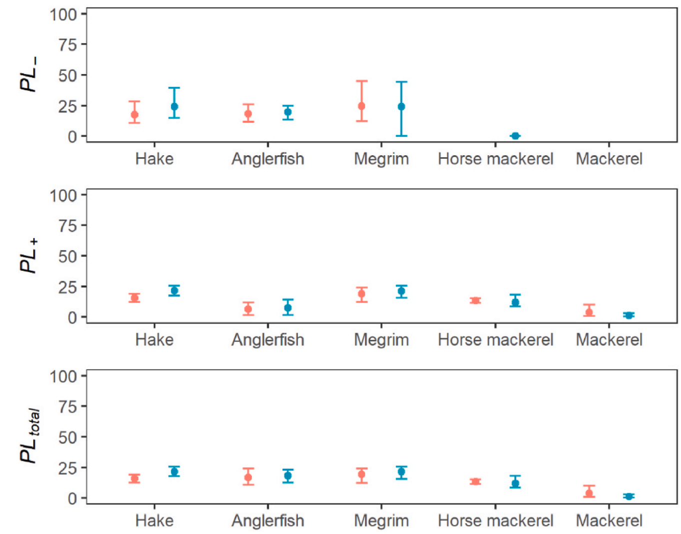

Fig. 8. The average probability (%) for individuals below MCRS (*PL*–), above MCRS (PL_+) and of the total catch (PL_{total}) to be retained in the lower codend when light is on (blue) and off (red), conditioned capture.

viewing capabilities for 75% of the video recordings made. Since our interpretation of the turbidity data is based on our capacity for seeing any light trace from video recordings, we cannot conclude whether the lights used were not visible to fish. Other factors such as the ability of fish to perceive light and physical properties of the light need to be investigated to draw strong conclusions (Nguyen and Winger, 2019). Our turbidity readings show high sediment resuspension, which may compromise fish vision and consequently, affect their reaction towards the grid.

Fishing gears need to be developed so they can perform in the environmental conditions they are intended to be used. The towing speed in the fishery presented here is between 3.9 and 4.2 knots, which can imply that the fish entering the aft of the gear passes by the grid area at ca. 2 m per second. Thus, fish have limited time to react to towards the grid before being drifted back to the codend. In addition to the limited visibility due to the high turbidity values, the drifting speed may limit the ability of the fish to perceive and interact with the grid therefore, potentially impacting the likelihood for fish to enter the lower codend.

The high towing speed and high turbidity values, typical for the fishery under study, may impede the ability of fish to respond to the visual stimulus used. Two conditions need to be fulfilled to ensure fish make contact with the grid based on visual stimulation. First, the fish need to respond to the light stimulus in some way and second, the fish need to have the physical swimming capability to interact with the grid. In this specific fishery, the extreme conditions experienced from the high towing speed and turbidity could significantly affect the ability of the fish to reach the grid or even perceive the artificial light. Therefore, it is not possible to conclude whether the species examined in this study have a positive, negative or no reaction to artificial light based on the grid passage probability obtained.

During the cruise, large quantities of invertebrates (mainly echinoderms and cephalopods) and fish individuals got meshed in the netting section preceding the grid, specifically around the lifting panel. We believe that this meshing was a consequence of halving the transversal area in the section with the lifting panel, and that as it took place in the section prior to the grid we assume it did not affect the results presented in this study.

Finally, the results demonstrated that we were not able to efficiently separate species by means of hake and megrim passage through the grid. However, we cannot rule out a more efficient species separation by using the opposite approach, i.e., guiding the main flow of fish through the lower panel and driving the species separation by means of passage of horse mackerel and mackerel through the grid to the upper codend. Even though a simpler approach could probably be used to take advantage of the behavioural differences between species in this fishery (in the line of those proposed by Karlsen et al., (2019) or Melli et al., (2018)), in more favourable environmental conditions a further developed configuration of the device tested in this study may provide better results. For example, a longer grid or a guiding panel that directs the fish towards the grid, could improve contact probability with the grid and subsequently increase the likelihood for that fish can perceive the artificial light.

The experiments carried out here showed that the probability of fish passing through the grid, under the conditions described, was very low and the additional use of lights did not significantly affect the results. However, it is important to emphasize the relevance of reporting any result, as an experimental outcome, so that future experiments can build upon (Weintraub, 2016). Publishing only selective information, provides a biased view and understanding of the processes, while reporting on all results may help to interpret results obtained in related studies. In addition, reporting all results can help other scientists to adjust their experimental designs and increase chances of success, saving time and resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank to the crew of *FV* Kalamendi for their valuable assistance during the cruise. We also thank SafetyNet Technologies Ltd for lending the light equipment used during the trials and assisting on technical issues regarding the laser diode pods. Finally, we thank the Editor of the journal and the three anonymous reviewers for the constructive comments provided that helped to improve the quality of the manuscript. These trials were conducted under the auspices of the EU-project SMARTFISH H2020 (Grant agreement number: 773521). This paper is contribution n° 1091 from AZTI, Marine Research, Basque Research and Technology Alliance (BRTA).

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Paper VI

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

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

Elsa Cuende[*#1], Manu Sistiaga[#2,3], Bent Herrmann[#3,4,5], Mikel Basterretxea[1], Luis Arregi[1]

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

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

[3]The Arctic University of Norway, UiT, Breivika, N-9037 Tromsø, Norway

[4]SINTEF Ocean, Fishing Gear Technology, Willemoesvej 2, 9850, Hirtshals, Denmark

[5]DTU Aqua, Denmark Technical University, Hirtshals, Denmark

[a]Corresponding author Tel: +34 671 700 519

E-mail address: ecuende@azti.es

[#]Equal authorship

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 on higher escape chances. However, this availability does not imply optimal mesh openness nor guarantees their use. We estimate 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

1. 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 and 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 that most meshes in the codend, except for some rows just ahead of the catch accumulation zone (Herrmann, 2005a, b), get longitudinally stretched (Herrmann *et al*., 2007). Therefore, the probability for 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 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).

During the last 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 escape chances 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 escape chances 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 to 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 fish individuals of commercially relevant species represents a problem (Cuende *et al.*, 2020a; b) that has more serious consequences for the 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 fish escape chances 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, by using morphology data it was investigated whether the differences in size selectivity between these three species can be explained based on fish morphology and behaviour. Finally, we aimed to find out to what extent shortened LR codend meshes offer optimal openness for the different species to pass through. For this purpose, 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 of 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.

2. Materials and methods

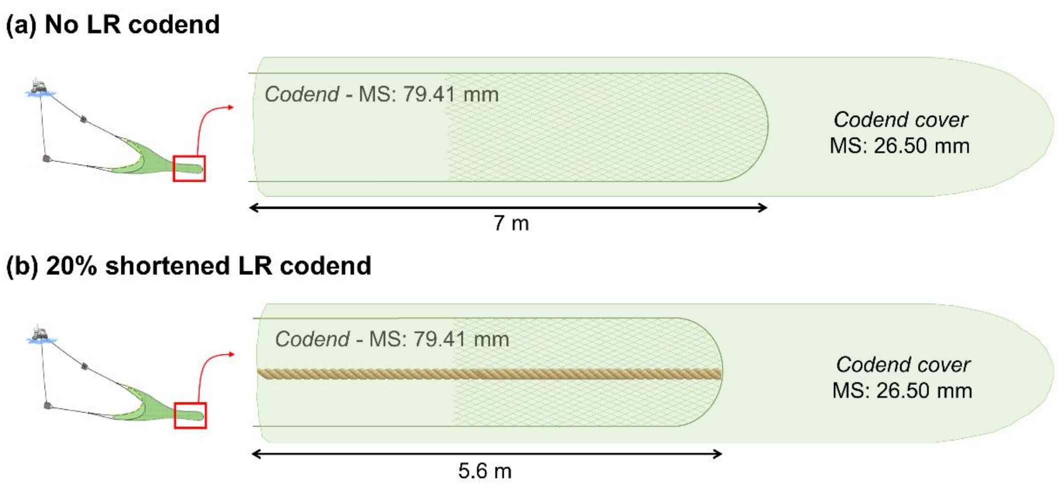
Experimental sea trials

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 LR slightly longer 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 affecting species behavioral responses. The validity of hauls was determined based on the underwater images during shooting and haul-back processes, and on the skippers' expertise.



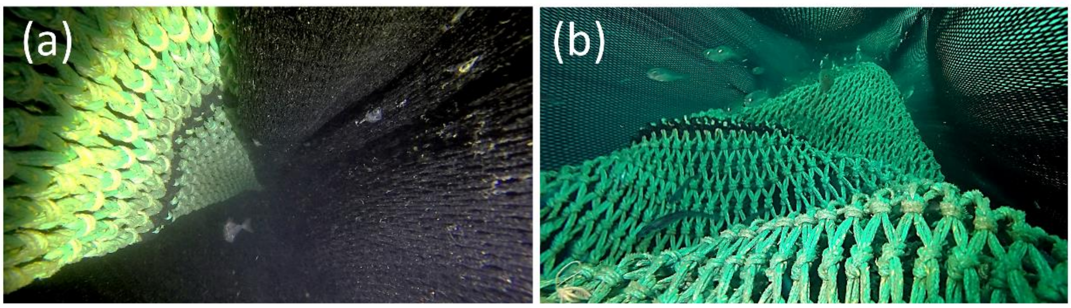


Figure 1.- (a) No LR codend length and mesh size (MS) specifications and underwater image of it; and (b) 20% shortened LR codend specifications and underwater image of it. Both underwater images were taken from a camera positioned between the codend and the codend cover.

Each haul was carried out with one configuration at a time. The species captured in sufficient numbers to be included 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 $r(l)$ (i.e., length-dependent retention probability). For this purpose, 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 size selection combined over all 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 describe $r(l, \boldsymbol{v})$ for each codend and species individually: *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 describe the data sufficiently well 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 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 software tool SELNET (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 $\Delta r(l)$ 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., 2016, 2013b, 2012; Krag et al., 2014, Sistiaga et al., 2020, 2011; Tokaç et al., 2016). Both the FISHSELECT software and specific measuring tools are needed to study the size selectivity of a species using 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 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 degrees 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, of the same mesh size. 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, at least partially, were in 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. The predictions were made for mesh sizes ranging from 50 to 130 mm with 10 mm intervals and only considering the OAs contributing 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).

3. 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).

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 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 right positioned 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 confident bands for the length range 20 – 35 cm, caused by the overdispersion in the data. For these lengths few individuals were captured, both in the codend and the cover (Fig. 2).

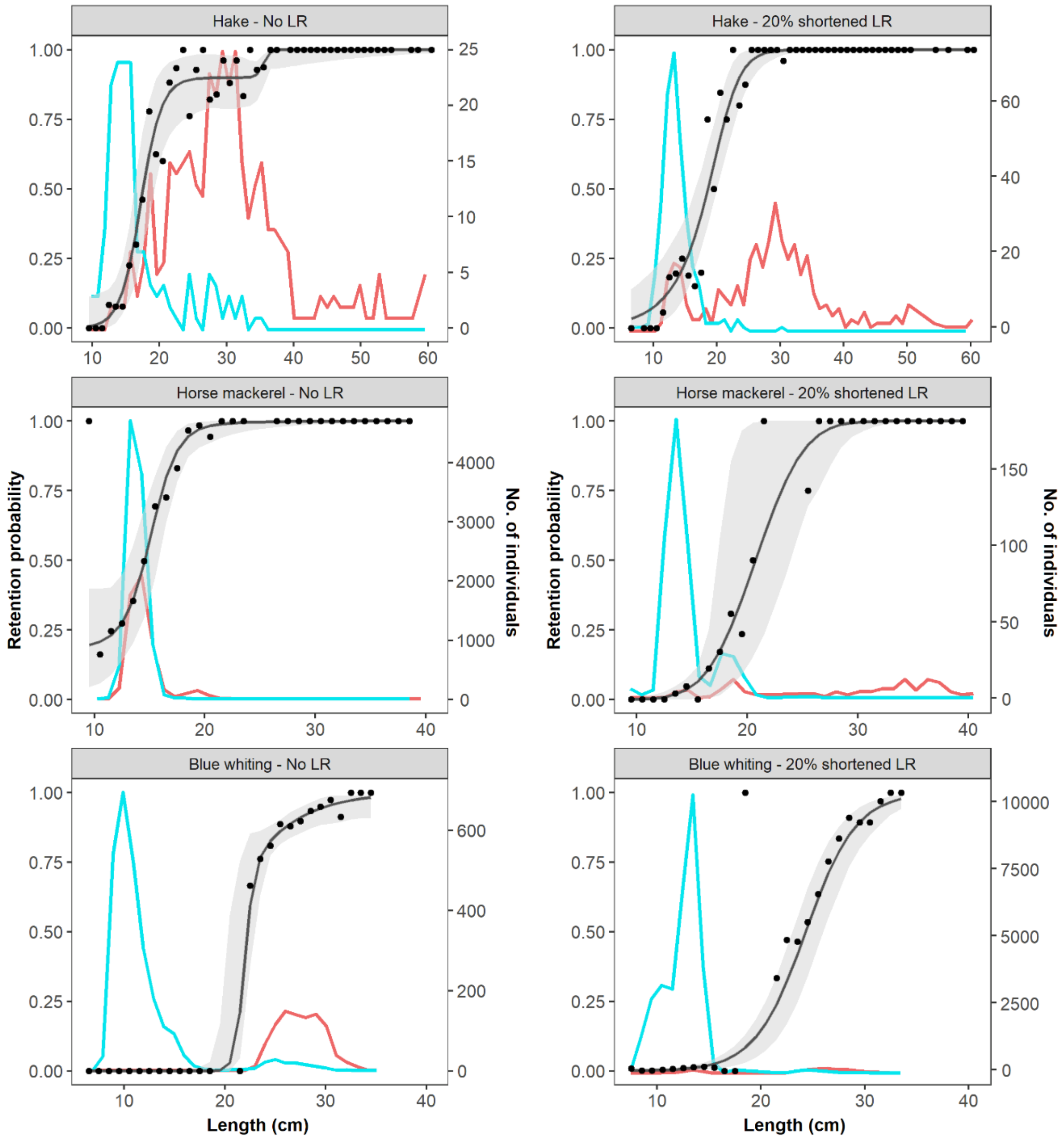


Figure 2.- Experimental size selection curves (black line) for hake, horse mackerel and blue whiting, the corresponding 95% CIs and the experimental retention rates (black dots). Red lines represent the population retained in the codend and blue lines represent the population retained in the codend cover.

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 both for individuals 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).

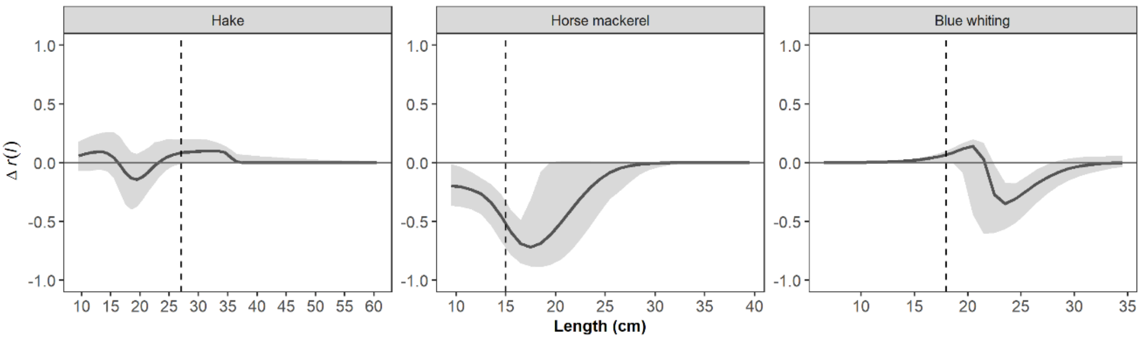


Figure 3.- Changes in retention probability $\Delta r(l)$ between the 20% shortened LR codend configuration and the no LR codend configuration. The horizontal line at 0.0 represents equal retention probability for both designs. Mean curve and CIs above or below horizontal line mean significantly higher 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.

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

Simulation of the experimental size selectivity curves was done based on 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.

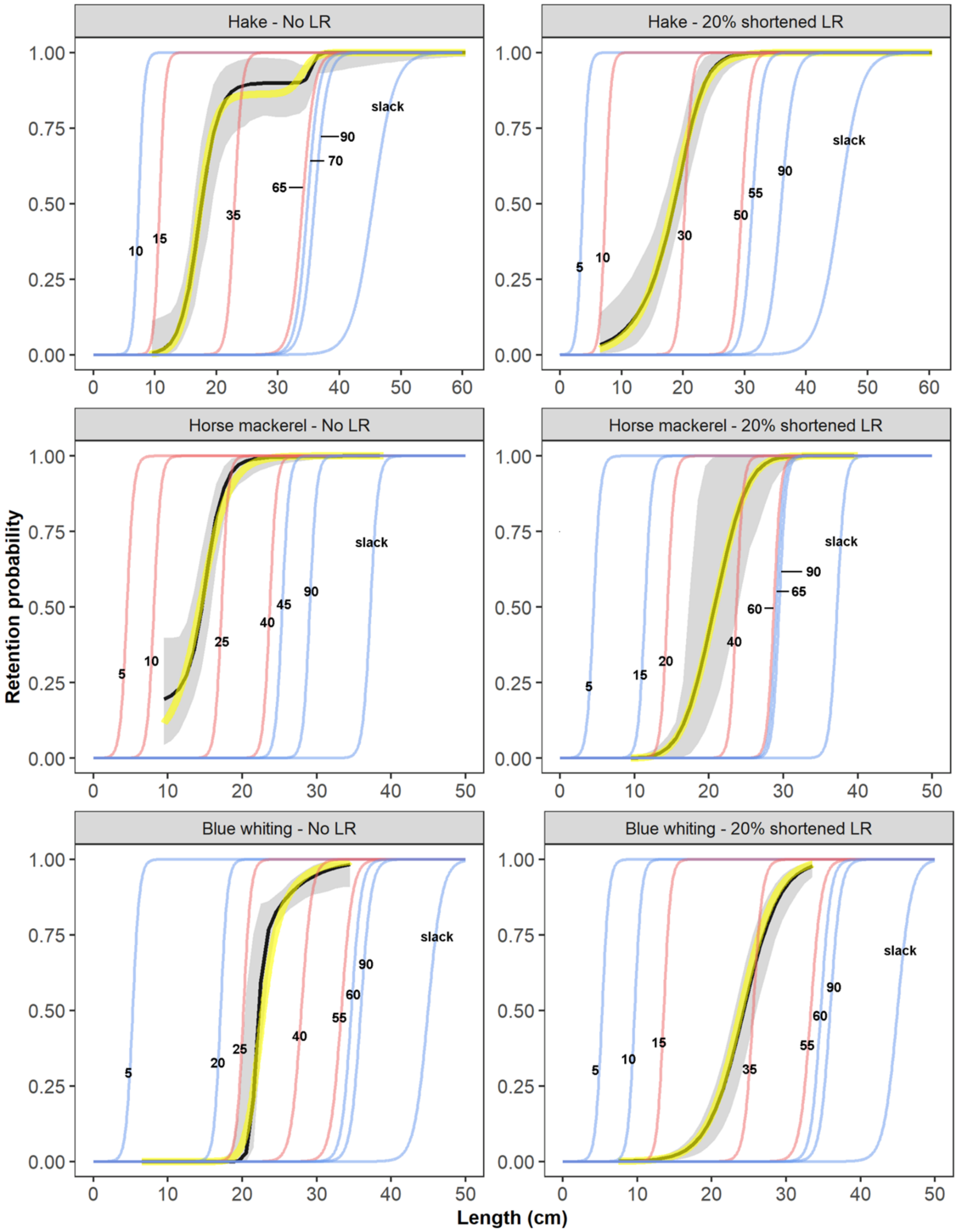


Figure 4.- Black curves show experimental codend size selection curve with corresponding CIs. Blue and red curves show size selection curves simulated for the OAs indicated. The curves with

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.

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 be well 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 obvious 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 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 contribute considerably, which corresponds to the second logistic process of the size selection curve for this configuration (Fig. 2).

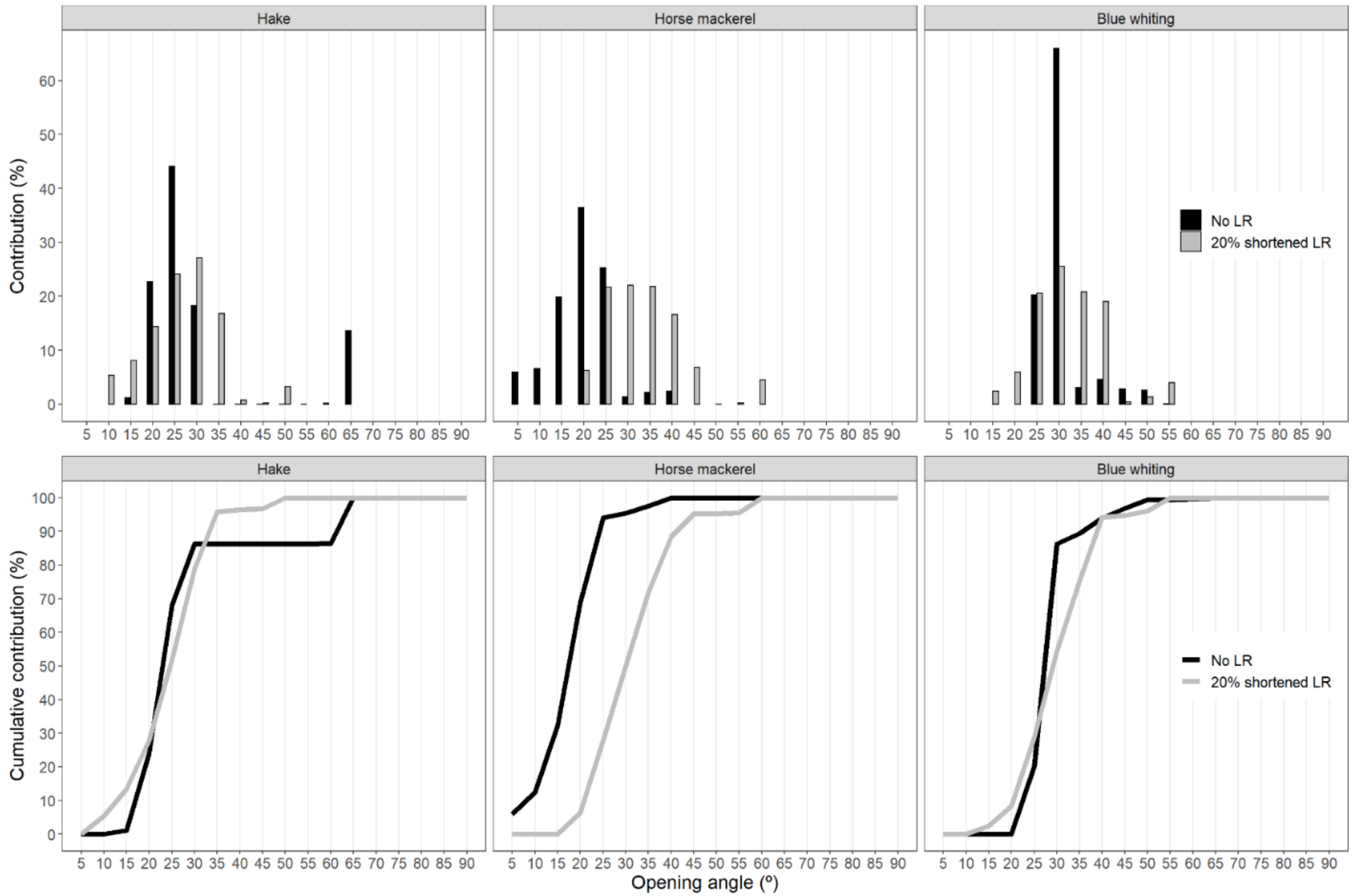


Figure 5.- Percentage of contribution (above) and percentage of cumulative contribution (below) of the different codend mesh OAs explaining the experimental codend size selection curves of hake, horse mackerel and blue whiting. Black bars and lines represent no LR codend and grey bars and lines 20% shortened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

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 (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).

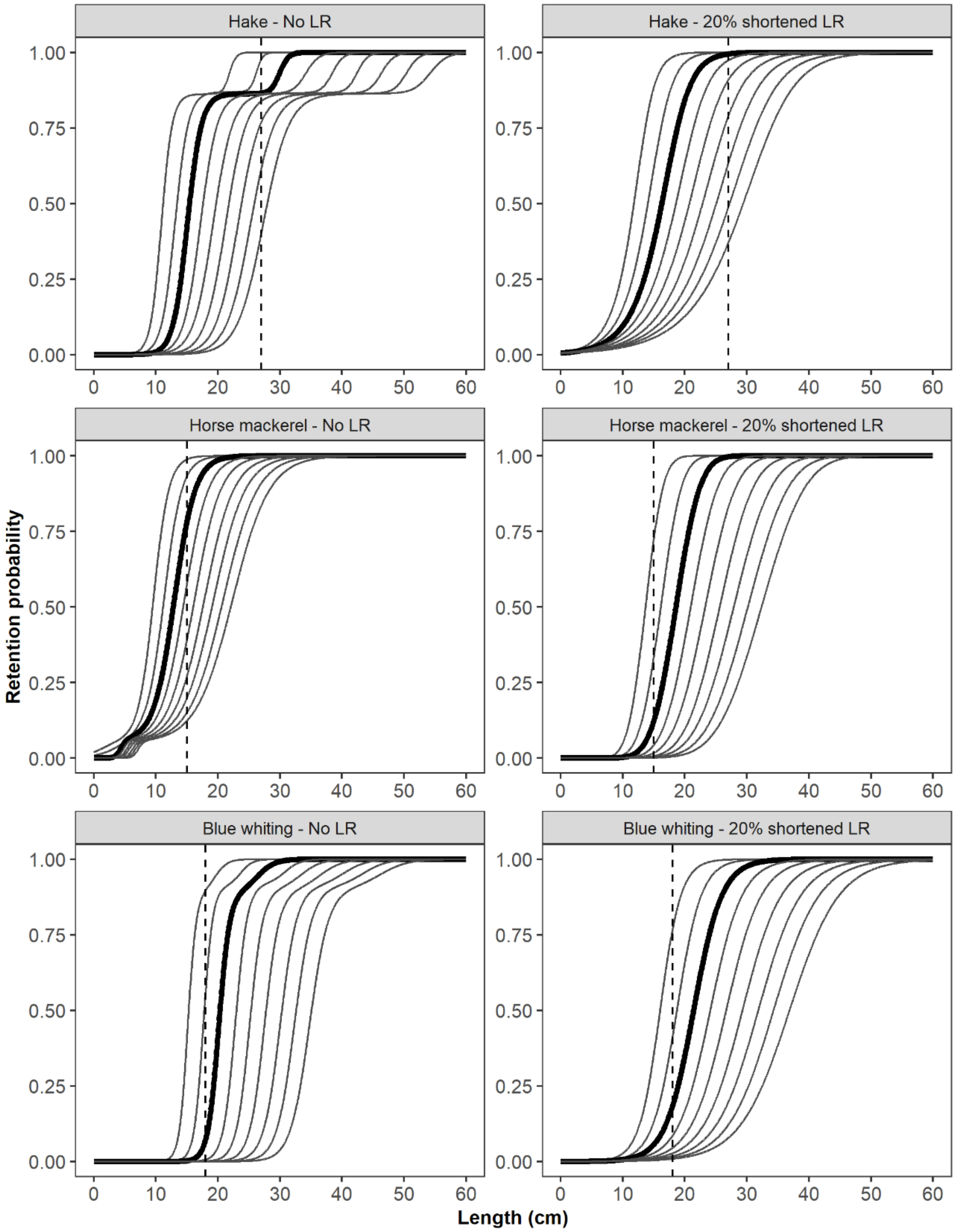


Figure 6.- Predicted size selectivity for hake, horse mackerel and blue whiting and the two codend configurations. The curves in each of the plots show the predictions for the mesh size range of 50 – 130 mm with 10 mm increments from left to right. Thick black curves correspond to the current codend

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.

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).

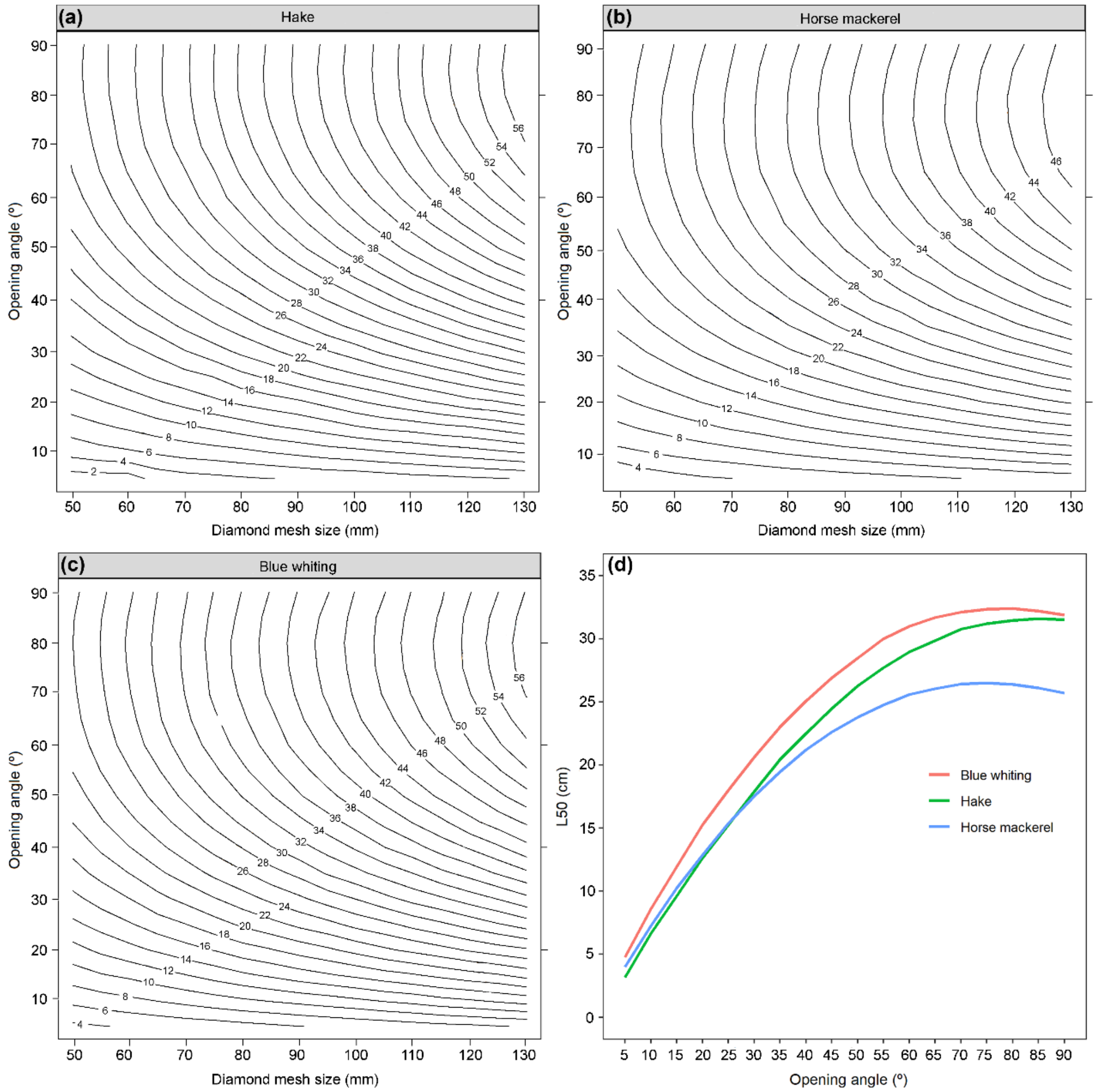


Figure 7.- Design guides for diamond meshes showing L50 isocurves for (a) hake, (b) horse mackerel and (c) blue whiting as a function of mesh size (mm), for sizes between 50 and 130 mm, and mesh OA between 10º and 90º, respectively. (d) Predicted L50 values for a 70 mm diamond mesh codend for mesh OAs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

4. Discussion

One of the main findings in this study was that the codend used by the Basque fleet with 20% shortened LR increases 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 contrary, hake did not show any significant difference on its retention probability between the codend configurations tested and therefore, this configuration does not avoid catching high proportion of undersized hake.

Although several studies have previously demonstrated that, in general terms, shortened LR codends release 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 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 its behaviour (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 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 could be thought 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 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 for an escaping 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 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).

Regarding more active species, which are expected to seek for escape along the entire codend, shortened LR codend can have greater effect on their size selectivity, as it is the case of horse mackerel and blue whiting. The analysis of mesh OA contribution to the explanation of 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 it is when LR are not used, horse mackerel show to be 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 major factor 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 more compressible body than horse mackerel, based on the penetration models developed in this study (Appendix C). Regarding blue whiting, although their more fusiform body shape could favor its passage through meshes better than hake, the reasons why the selection curves for hake have 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 shortened LR codend was well below that 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 75 and 85º for the three species tested. Based on the explanation provided, hake would not have shown relevant changes in its size selectivity even if the mesh OAs would be optimal for its escape because they do not attempt to escape where there would be 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 been 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 (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 to test (e.g., Bak-Jensen *et al*., 2022).

The predictions carried out show that codend with shortened LR can reduce retention probability of all species in the same extent as increasing codend mesh size considerably. 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, regarding our predictions, the mesh size of a codend without LR would need to be increased to 130 mm to get 12% of 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 can be a measure to improve gear selectivity, minimize losses and to be accepted by the fishing sector. In addition, 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 pointed out as major factors affecting fish escape chances since our results indicate that different species have different ability at utilizing open meshes located at different places. For each species and design, we were able to identify those mesh OAs that are potentially used by them to go through, and those 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.

5. Acknowledgements

We thank Xabier Aboitiz, Jose Maria Ferarios and Arkaitz Pedrajas for their help during field work. We also thank the crew of the RV Emma Bardan for their valuable assistance during the cruise. We are grateful for the financial support from the Secretaría General de Pesca (MAPA). We are also grateful to the journal editor and two anonymous reviewers who have helped to improve the quality of this manuscript. This paper is contribution n◦ 1114 from AZTI, Marine Research, Basque Research and Technology Alliance (BRTA).

6. Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

7. Data Availability

The data that support the findings of this study are either published or available from the corresponding author upon reasonable request.

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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 here provided.

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 $r(l, \boldsymbol{v})$, where $\boldsymbol{v}$ is a vector consisting of the parameters in the model. The purpose of the analysis was to estimate the values of the parameters in $\boldsymbol{v}$ 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 qC_j and qCC_j 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 $r(l, \boldsymbol{v})$ six different models were considered: *Logit*, *DLogit* and *DSLogit*, *Probit*, *Gompertz*, and *Richard*. The description is given below:

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

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

To estimate the confidence limits for the average size selection bootstrapping was applied. This bootstrapping approach is identical to the one described in (Millar, 1993) and takes into consideration both within-haul and between-haul variation. The hauls for each codend configuration were treated as a group of hauls. To account for between-haul variation, an outer bootstrap resample with replacement from the group of hauls was included in the procedure. Within each resampled 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, 1000 bootstrap repetitions were conducted. 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 modelling

A short description of the standard FISHSELECT methodology applied for collection of morphology and mesh penetrability data and for compressibility modelling of hake and horse mackerel is here provided. 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 modelling

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 this 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.

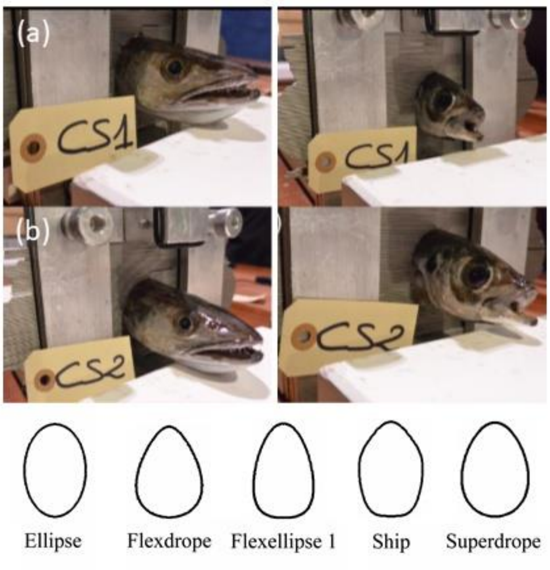


Figure B1-. The two CS measurements collected for each hake (left) and horse mackerel (right) sampled: (a) cross-section 1 (CS1) and (b) cross-section 2 (CS2). The illustrations below show all five geometrical shape models tested for each CS contour.

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 modelled 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 sizes and shapes. Thus, the experimentally obtained fall-through results were compared with 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 modelled relationship between each of the parameters defining CS1 and CS2 and fish length allowed us to create a virtual population of 5000 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.

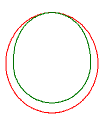
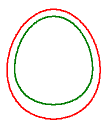
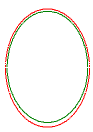
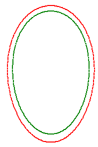
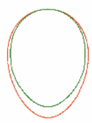
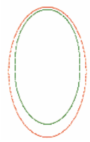
Best CSs shapes models for hake and horse mackerel were the Flexellipse1 for CS1 and CS2 of hake and Flexdrope CS1 and CS2 of horse mackerel, based on R^2 and AIC values (Table C1).

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%