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Reducing discards of demersal species using a 100 mm square mesh cylinder: Size selectivity and catch comparison analysis

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Abstract :

We assessed the impact of an additional 100 mm square mesh cylinder (SMC) on the selective property of the demersal whitefish trawl in the Celtic Sea. Sea trials were conducted on board a French trawler using twin trawl rigging. We tested the effects of the position of the SMC (in front of and behind the mandatory 100 mm square mesh panel) and of the insertion of a dispersive float. Selectivity analysis revealed the 50% retention length () to be greater than the Minimum Conservation Reference Sizes regardless of species (haddock, whiting or megrim) or rigging configuration. Results did not reveal a clear effect of the SMC position. However, the insertion of the float led to a decrease in selection ranges suggesting enhanced contact probabilities with the square meshes. With the largest values, the SMC placed in the front position (and without the float) proved to be the most selective rigging configuration and was then tested under commercial conditions. Catch comparisons revealed that the test gear retained less fish across all size classes than the commercial gear. For haddock, the test gear retained less fish below 50 cm in length. Catch comparisons also indicated significant discards of fish above the MCRS, i.e. “high-grading” practices. Under the requirements of the landing obligation (LO), unwanted catches must be stored on-board and landed regardless of economic value. The SMC is thus a valuable tool to mitigate the impact of the LO on the demersal whitefish fishing fleets operating in the Celtic Sea.

Highlights

► Test of a 100 mm SMC in addition to the mandatory 100 mm SMP. ► No clear effect of SMC position. ► The dispersive float inside the SMC sharpened selection curves, suggesting enhanced escapement trials by fish at any size. ► Escapement of several fish larger than the MCRS, but no commercial losses, due to on-board sorting practices. ► Combination of absolute and relative size selectivity analysis strengthened study conclusions.

1. Introduction

Fish discarding at sea is a major ecological and ethical problem, as it represents substantial food waste and may lead to unsustainable management of fisheries resources [1]. Discard estimates are close to 10% of total marine catches worldwide [2] and are primarily generated (more than 50%) by demersal fisheries [3]. The European Union recently banned this practice by adopting the landing obligation (LO, [4]). The LO requires mandatory landing of all catches from stocks subject to Total Allowable Catch (TAC) or Minimum Conservation Reference Size (MCRS) regulations [4]. Fishermen are urged to reduce unwanted catches and forced to land catches that were previously discarded. New technological solutions to enhance size and species selectivity of fishing gear are therefore necessary to comply with this new regulation and mitigate the impact of the LO on demersal fishing fleet operations.

Many demersal fishing fleets operate in multi-species fisheries. Designing gears to selectively filter out unwanted catches without loss of target species is therefore technically challenging. Unwanted catches lead to increased on-board processing times and competition for storing space [1]. Unwanted catches may also have negative economic impacts on fisherman, because the bycatch of non-target fish are typically of lower economic value (e.g. small size classes, damaged individuals or species with poor commercial value) [1]. In addition, multi-species fisheries are largely constrained by species and area specific TAC restrictions at national and international levels. As previously discarded fish will now count against quotas, there is incentive to avoid species with restrictive quotas and undersized fish in order to maximize the revenue and minimize choke risk.

The Celtic Sea is a major fishing ground in the North-West Atlantic, involving numerous countries and a wide diversity of fleets from small coastal métiers to large pelagic fleets. Haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*) are major target species for demersal fisheries. These stocks are exploited mainly by France, Ireland and the United Kingdom, accounting for 64% (42), 24% (51), and 6% (10) of total landings of haddock (and whiting), respectively, in 2016 in ICES divisions 7.b, 7.c, and 7.e-k [5]. Haddock and whiting discards were high, accounting for 57% and 32% of total catch weights, respectively [5]. This resulted in total catches much higher than the agreed TAC for haddock. Métiers targeting gadoids and benthic species capture large amounts of flatfish, such as megrim (*Lepidorhombus spp*), as target or non-target species (trawlers represent 98% of megrim catches [5]). Common (*Lepidorhombus whiffiagonis)* and four spot megrim (*Lepidorhombus boscii*) are managed under a common TAC in ICES 7.b-k and 8.a,b,d. Megrim are exploited mainly by France, Spain, United Kingdom and Ireland, accounting for 22, 20, 19 and 19% of the catches, respectively in 2016 [6]. Discards accounted for 17% of total megrim catches.

For a given mesh size, square meshes (SM) allow more haddock and whiting of larger length to escape than regular diamond meshes [7,8]. Many studies have demonstrated the benefit of implementing a square mesh panel (SMP) in the North-East Atlantic to reduce fish discards without affecting commercial catches [9–12]. Consequently, in 2012 demersal fleets were required by the European Commission to use 100 mm SMPs [13] to reduce haddock and whiting discards in the Celtic Sea. However, high discard rates were still reported by the ICES Working Group on the Celtic Seas Ecoregion (WGSCE) [5]. The WGSCE thus encouraged better assessment of the selectivity of SM and investigation of additional gear modifications that could increase escapement of small individuals [5]. Selectivity of the SMP can be optimised by adjusting several parameters, such as its position in the net relative to the cod-end, its dimensions, mesh size, twine diameter or colour [10–12]. Krag et al. [14] showed that fish escapement through dedicated escape panels could be enhanced by increasing the probability of contact using a stimulation device made of floats inserted near the panels. In this study, we tested a 100 mm square mesh cylinder (SMC) in addition to the mandatory 100 mm SMP to increase the chance of escapement of both demersal and benthic species. First, we investigated the effects of the SMC position and of an additional dispersive spherical float inside the SMC in a standard selectivity experiment. Second, we performed a catch comparison analysis between the test and commercial gears. We considered catch weights in both discarded and landed fractions as well as the overall length distributions in each gear. Results are shown for three species, i.e. haddock, whiting and megrim, and discussed considering discard reduction and potential commercial losses in a multi-species fishery context. A fisheries management viewpoint was considered to explore the benefit of combining these complementary approaches to better understand the retention process that occurs during trawling.

2. Materials and methods

2.1 Experimental design

All experiments at sea were conducted on board a 22.85 m long and 7.70 m wide commercial fishing vessel, *Le Jusant*, with 497 kW of power and a gauge of 118.77 tx. In this commercial trawl, the extension and cod-end were constructed of 100 regular and 50 double polyethylene meshes (100 mm mesh size and 4 mm twine diameter), respectively (Fig. 1. scheme A). The mandatory SMP was 54 meshes long and 25 meshes wide (i.e. around 3.2 by 1.5 m). The additional SMC was made of two SMPs (Fig. 1) sewn side-by-side to form a cylinder that covered the entire circumference of the cod-end extension. At the junction between the SMC and the diamond mesh cod-end, each square mesh was sewn to two diamond meshes.

Sea trials were performed using twin trawls. In twin trawl experiments, two gears are rigged together and referred to as the “test” and the “control”, respectively. Catch share between both gears are analysed to understand the selective properties of the test gear, with the latter equipped with the device to be tested and the control gear used as the reference. Control and test gears were specific for each experiment, i.e. size selectivity and catch comparison analysis, and described in the following sub-sections.

Catches were weighted (kg) per species and catch fraction, i.e. landings or discards, following current on-board practices. The discards fraction of the catch may have occurred due to TAC constraints, fish length or market related issues. Individual fish were measured to the nearest 1 cm. Common and spotted megrim were sorted on-board as one species, however common megrim were the most abundant. Based on the amount of catch, random subsampling (per species, size class and catch fraction) was often necessary. The subsampling ratio was set based on a trade-off between statistical representativeness and measurement feasibility on-board. The subsampling ratio is defined as $q = \frac{w_{sample}}{w_{\mathrm{total}}}$, where w_{sample} and w_{total} are the weights of the analysed sample and of the total catch, respectively. When appropriate data were pooled among catch fractions. Subsampling ratios were then re-calculated following Cosgrove et al. [15]: $q = \frac{(N_L+N_D)\ q_L*q_D}{N_D*q_L+N_L*q_D}$ where N is the number of fish caught and L and D refer to landings and discards fractions, respectively.

2.1.1. Size selectivity analysis

Assessing the size selectivity of the gear involves comparing the length distribution of individuals in the catch with that of individuals that entered the gear (i.e. those that were either caught or escaped). The former is observed in the cod-end of the tested gear. The latter is observed in the catch of another gear that theoretically prevents escapement of any fish. The "control" gear was designed with the same specifications as the commercial gear, but with the addition of a small mesh (20 mm) inner cover net to capture all fish. This inner cover was stitched inside the entire extension and cod-end (Fig. 1).

Four rigging configurations of the SMC were tested and twinned one at a time with the control. The SMC was either positioned in front of the SMP (configuration P1, around 12.3 m from the cod-end) or behind the SMP (configuration P2, around 4.1 m from the cod-end), with or without a dispersive float (F) in the middle of the SMC. The dispersive float was a 4 L spherical device with a diameter of 250 mm. The float was drilled and filled of seawater when immerged, resulting in a neutral buoyancy.

The four rigging configurations were thus designed to investigate whether the position of the SMC or the addition of the dispersive float influenced fish retention in the test gear. These rigging configurations will be referred as P1, P1F, P2 and P2F (Fig. 1).

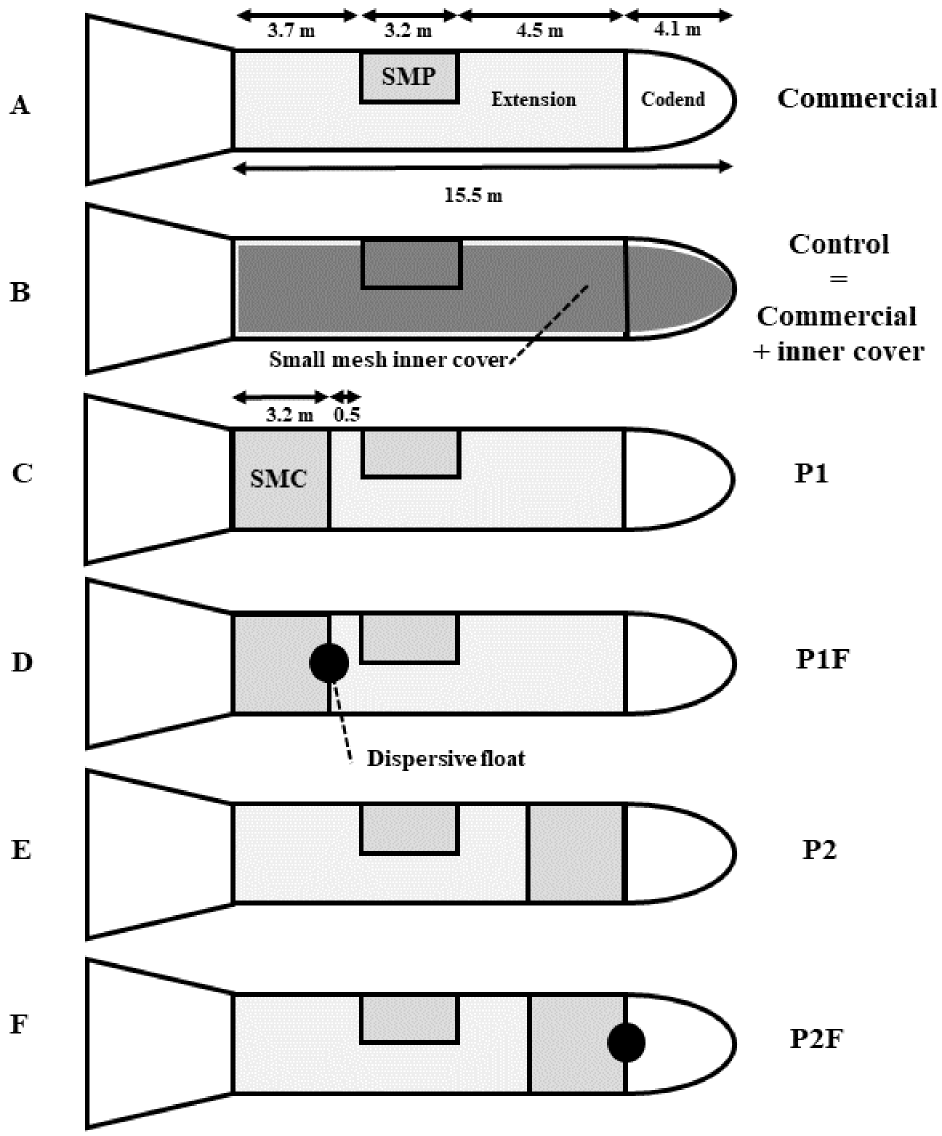

Figure 1. Commercial (A), control (B) and test (C-F) gear configurations. The square mesh cylinder (SMC) is positioned in front of (P1) or behind (P2) the square mesh panel (SMP). F, in P1F and P2F, refers to the addition of a float inside the SMC. The control gear was rigged in the same way as the commercial gear, but with the addition of a small mesh inner cover sewn inside both the cod-end and extension.

Twenty-eight trials were performed in the Celtic Sea in September 2014. Six to eight hauls were conducted per test configuration (Fig. 2, Table 1). Each haul lasted between 1 to 3.7 hours, at depths ranging from 80 to 150 m. Some hauls (particularly for configurations P2 and P2F) were conducted on fishing grounds where large numbers of small size classes of both haddock and whiting were expected. Tow durations were shortened to avoid damaging the small mesh inner cover and to ensure comparable total catch amount with the other hauls.

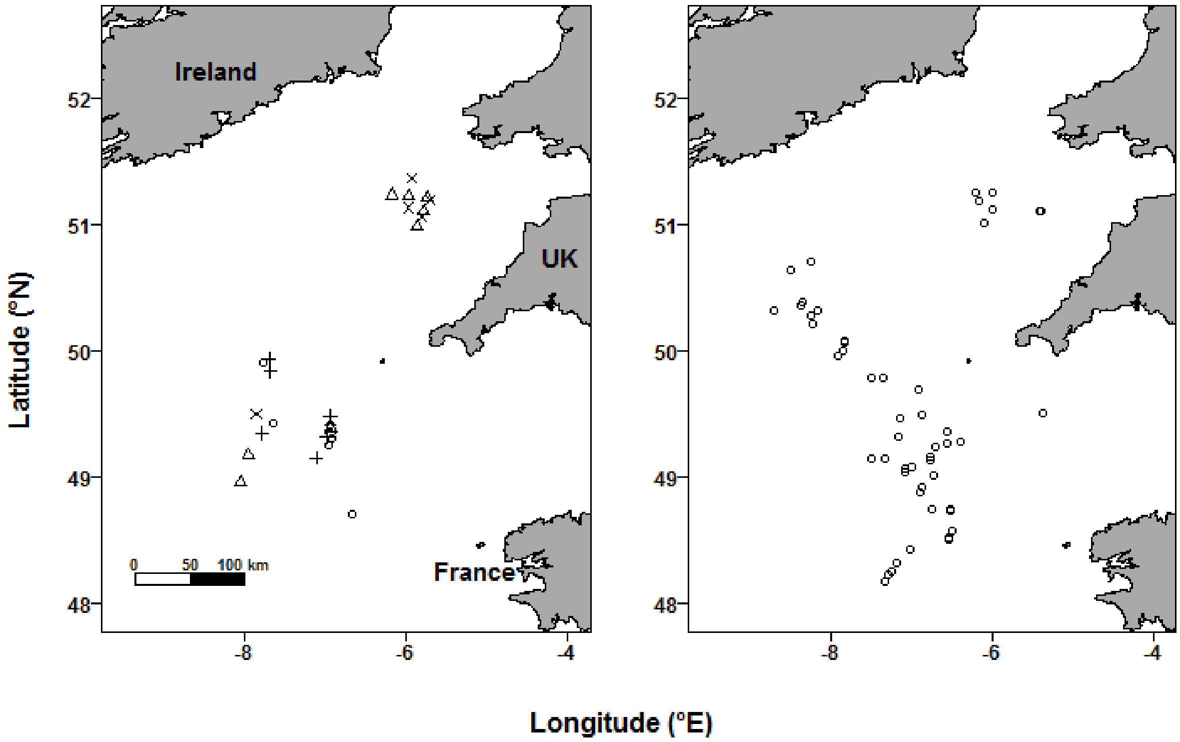

Figure 2. Sampling locations in the Celtic Sea in 2014. Sea trials conducted for size selectivity and catch comparisons are plotted on the left and right panels, respectively. Test gear configurations P1, P1F, P2 and P2F are plotted with circles, vertical crosses, triangles and oblique crosses, respectively.

Table 1. Sampling design: Number, duration, fishing depth, and dates of hauls in each experiment for each test gear configuration

Experiment	Test gear	Number	Mean duration in hours (range)	Mean depth in meters (range)	Dates
Size selectivity	P1	6	2.9 (1.6-3.7)	120 (115-125)	12-17 Sep 2014
	P1F	8	3.3 (3-3.7)	118 (106-130)	14-17 Sep 2014
	P2	6	1.9 (1-3.5)	101 (80-142)	18-23 Sep 2014
	P2F	8	1.9 (1-3.3)	106 (82-150)	18-23 Sep 2014
Catch comparison	P1	54	4.1 (2.5-5)	118 (80-150)	26 Aug-19 Dec 2014

2.1.2. Catch comparisons

Catch volumes (sorted by the crew into landings and discards fractions) and length class distributions were compared between the test and commercial gears under commercial conditions. To ensure enough hauls for the catch comparison analysis, the test gear was only rigged in configuration P1, as it was assumed to be the best trade-off between increased size selectivity for the three species and rigging simplicity. Fifty-four hauls were performed from

August to December 2014, each lasting between 2.5 and 5 hours at depths ranging from 80 to 150 m (Tab. 1 & Fig. 2).

2.2. Statistical analysis

2.2.1. Size selectivity analysis

The selection curve depicts the scaling of the retention probability $r(L)$, i.e. the probability of a fish to be caught at a given length class L. One can also consider the escapement probability which is simply defined as $1 - r(L)$. The selection curve can be summarised by two size selectivity parameters: the 50% retention length (L_{50}) and the selection range (SR), which were used to compare the four test gears. L_{50} is the length at which 50% of the individuals entering the trawl are retained and $SR = L_{75} - L_{25}$ is an indicator of the steepness of the selection curve with size [16].

Selectivity parameters can be derived from coefficient estimates of a binomial model in which the number of experiments is the number of fish that entered the test gear, the response variable is the number of fish retained in the test gear and the probability of success is the retention probability. Assuming that the number of fish that entered the test gear is equal to the number of fish retained in the control gear, the model is defined as follows: $N_{test}(L) \sim B\big(N_{control}(L), r(L)\big)$, where $r(L) = E\big(\, N_{test}(L)/N_{control}(L)\big)$ can be related by a link function of the fish length L. In the case of the twin, paired or trouser trawls N_{test} might exceed $N_{control}$ for a given haul and length class due to numerous factors, such as specific water flow in each gear [17] or fish schooling behaviour, and thus, the model parameterisation is not valid. To overcome this common issue, Millar and Walsh [18] developed an approach commonly referred to as SELECT (Share Each LEngths Catch Total). Millar and Walsh [18] modelled the selectivity process by the probability ϕ that a fish is retained in the test gear given that it entered one of both gears: $N_{test}(L) \sim B\big(N_{test}(L) + N_{control}(L), \phi(L)\big)$, where $\phi(L) = E\left(\frac{N_{test}(L)}{N_{test}(L)+N_{control}(L)}\right) = \frac{r(L)}{1+r(L)}$.

Furthermore, the difference in retention probability can be due to a difference of catchability between the trawls, some avoidance or attraction behaviour of fish due to the darker or turbulent environment or the aggregation of fish within one of the two gears. In these cases, the catch difference is expected to be non null on average. Millar and Walsh [18] suggested to model it by a split parameter p, the probability that a fish entering the whole gear is retained in the test gear: $\phi(L) = \frac{p*r(L)}{(1-p)+p*r(L)}$. Note that the split parameter is assumed to be the same whatever the fish length.

The shape of the retention curve can be reproduced using several functions: *logit*, *probit*, *Gompertz* or *Richards* [16]. For each species and configuration extrapolated data (using subsampling ratios such as $N_e = N/q$) pooled among hauls were used to determine which link function between r and L curves led to the "best model". The best model was selected based on the smallest value of Akaike Information Criterion (AIC), considering improvement between two models to be significant when differences between their AIC values (Δ_{AIC}) exceeded 3. When two models had similarly "good" AIC values (i.e. Δ_{AIC} < 3) the most parsimonious one was selected. Models with relaxed or fixed split parameter $p = 0.5$ were also tested. Subsampling ratios were used as offsets ($offset = \frac{q_{test}}{q_{control}}$) in the log-likelihood: $loglik$

$$= -\sum_L \left[N_{test}(L) * log\left(\frac{offset(L)*\phi(L)}{offset(L)*\phi(L)+(1-\phi(L))}\right) + N_{control}(L) * log\left(\frac{1-\phi(L)}{offset(L)*\phi(L)+(1-\phi(L))}\right)\right].$$

Once the best model was identified, a two-step bootstrap was implemented to account for between haul variability and derive confidence intervals around parameter estimates and model predictions. The first step resampled among hauls and the second resampled among individuals in the selected hauls. This process was re-iterated 10 000 times for each species and configuration.

Millar and Walsh's model [18] as well as bootstrap resampling have been implemented in R [19]. Codes are available at https://github.com/xansantos/selR-select.

2.2.2. Catch comparisons

In this experiment, the test gear P1 and the commercial gear were rigged as twin trawls to perform catch comparison analysis in commercial conditions.

First, weights per catch fraction (i.e. landings and discards) at the haul level were compared using the difference in catch weights $\left(\frac{\mathrm{w_{test}} - \mathrm{w_{commercial}}}{\mathrm{w_{commercial}}} \times 100\right)$ and the Wilcoxon paired test. For haddock, two hauls retained 480 kg and 0 kg, and 0 kg and 63 kg, in the test and control, respectively. Thus, these hauls were considered unreliable and removed from the analysis.

Second, length distributions in the catch of the commercial and test gears were compared. Catch comparison resulted in non monotonous or erratic selection curve with size. Thus, we did not apply the previous methodology but favoured the commonly used approach proposed by Holst and Revill [20] for catch comparison studies. However, this method prevents estimation of a split parameter. Binomial generalized linear mixed models (GLMM) were applied to predict $\phi = \frac{N_{test}}{N_{test}+N_{commercial}}$ as a polynomial function of fish length. GLMMs were fitted using the R package ***lme4*** [21]. Mixed effects enabled consideration of between-haul variability [22–24], which could be attributed to varying conditions such as catch weight, environmental conditions or haul duration. As polynomial regressions can be highly sensitive to extreme values at the edges of the size range, we applied a filter similar to that of Vogel et al. [25] by excluding observations outside the 10% and 90% quantiles of the length distribution. Subsampling ratios per haul (h) and length class (L) were used as offsets in the GLMM following [20,25]: $logit(\phi_h(L)) = log\left(\frac{q_{test}(h,L)}{q_{commercial}(h,L)}\right) + \sum_i a_i * L^i + \varepsilon_h, \quad \varepsilon_h \sim N(0,\sigma^2)$. Polynomial models with degree 0 to 3 were tested and models were selected based on AIC values, following the same method used for size selectivity. All statistical analyses were performed using R software v. 3.4.3 [26].

3. Results

3.1. Selectivity parameters

Table 2. Selected models and associated parameter values for each species and configuration. Split parameter (p), 50% retention length (L_{50}), selection range (SR) and asymmetry in the Richard curve (δ). Parameter confidence intervals derived from boostrap resampling are given in brackets.

	Config.	Model	p	L_{50}	SR	δ
Haddock	P1	*logit*	fixed at 0.5	39.61 [30.8,45.63]	9.34 [4.32,14.01]	-
	P1F	*logit*	fixed at 0.5	35.1 [31.31,49.12]	7.76 [3.49,22.64]	-
	P2	*Richards*	0.57 [0.37,0.75]	34.31 [28.42,48.73]	10.15 [1.91,23.51]	0.06 [0,100]
	P2F	*probit*	0.39 [0.23,0.53]	33.54 [25.99,41.58]	9.49 [6.17,15.67]	-
Whiting	P1	*logit*	fixed at 0.5	42.68 [31.16,45.21]	6.94 [1,9.94]	-
	P1F	*probit*	0.36 [0.2,0.63]	37.48 [33.48,41.75]	4.31 [1.81,6.47]	-
	P2	*probit*	fixed at 0.5	39.71 [33.49,44.96]	8.66 [4.55,11.54]	-
	P2F	*logit*	fixed at 0.5	37.74 [35.56,51.59]	6.85 [5.09,16.03]	-
Megrim	P1	*probit*	fixed at 0.5	34.02 [28.22,39.91]	11.78 [7.25,17.16]	-
	P1F	*Richards*	fixed at 0.5	30.79 [28.99,32.78]	6.69 [3.32,11.79]	2.73 [0,100]
	P2	*probit*	fixed at 0.5	32.65 [24.2,36.54]	8.58 [1,13.3]	-
	P2F	*Richards*	fixed at 0.5	33.77 [30.6,38.4]	7.13 [3.38,15.75]	2.5 [0,100]

The fits of the selected models are illustrated in the supplementary material (Fig. A). Most of the best-fitted models included the simplest link functions, i.e. either *logit* or *probit* (Table 2). For a given parameter set, both functions have very similar shapes. *Probit* only implies a slightly sharper scaling of r with length around the L_{50}. Only haddock in configuration P2 and megrim in configuration P1F and P2F involved the *Richards* curve. The *Richards* curve is a logistic curve that includes a parameter of asymmetry δ. For haddock in configuration P2F, δ was well below 1, which indicated a longer tail on the right of the L_{50}. In other words, fish at length well above the L_{50} may have escaped. For megrim in configuration P1F and P2F, δ values were above 1, indicating that fish at length well below the L_{50} may have been caught. Models were selected with a split parameter value fixed at 0.5, except for haddock in configurations P2 and P2F and whiting in configuration P1F. This means that in most cases, the probability of fish entering either the test or control gear was the same, highlighting the validity of the trials.

Bootstrap confidence intervals showed a high degree of overlap between parameter values (Table 2) and retention probability predictions (Fig. 3), regardless of the species. P1 recorded the largest average L_{50} values, with differences relative to the other configurations ranging from 4.5 to 6.1 cm, 3 to 5.2 cm and 0.3 to 3.4 cm, for haddock, whiting and megrim, respectively. These results indicate that configuration P1 retained less large sized individuals of the three species. Average L_{50} estimates for haddock, whiting and megrim for all configurations were well above the MCRS (30 cm, 27 cm and 20 cm, respectively).

The L_{50} values were higher with configuration P1 than P2. Highlighting that fish were less likely to be retained (or more likely to escape) when using test gear P1. However, the effect of the position between the two gear configurations P1F and P2F was not clear. For haddock, the L_{50} was higher with P1F than P2F. There was no difference in L_{50} values for whiting. For megrim, L_{50} was higher with P2F than P1F. For the two gadidae species, SR values increased consistently from position 1 to 2, but not for megrim (Table 2).

The insertion of the float within the SMC showed a consistent decrease in SR values (regardless of the species or position of the SMC), resulting in lower L_{50} values. For configuration P2 however, the decrease in SR values for haddock was only small (0.8 cm on average) and the L_{50} for megrim was slightly higher (1 cm) with the float.

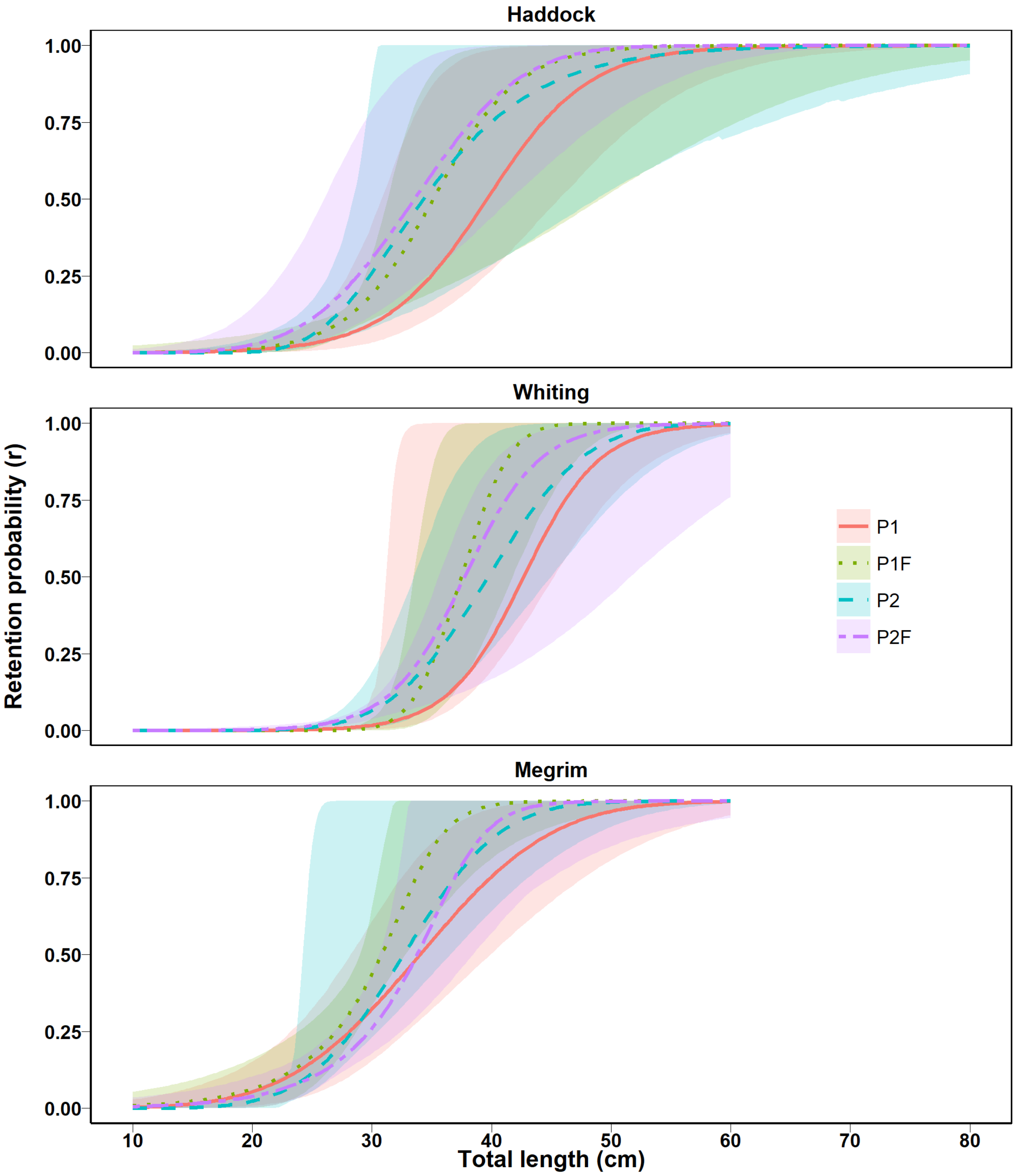

Figure 3. Selection curve: Retention probability (r) against total fish length per species and test configuration. Solid lines and shaded areas represent average model predictions and their 95% confidence intervals, respectively.

3.2. Catch comparisons

As the size selectivity analysis showed that P1 was the most selective device (with the highest L_{50} values), this configuration was selected for the catch comparison analysis.

3.2.1. Catch weight

There was no significant reduction in weight for landings from test gear P1. Distributions of percentage differences in landings weight (Fig. 4) showed median values of 0% for haddock and megrim, and -18% for whiting (Fig. 4). The relative reduction in landings weight was +0.2%, -2.0% and -5.4% for haddock, whiting and megrim, respectively. Landing weights for the test and commercial gears were similar, as indicated by the nearly symmetrical dispersal of points around the 1:1 line (Fig. 4). Wilcoxon tests confirmed no significant differences in landings weights between the test and commercial gears for haddock ($W = 358.5$, $n = 18$, p-value = 0.922), whiting ($W = 118.5$, $n = 28$, p-value = 0.563) or megrim ($W = 48.5$, $n = 53$, p-value = 0.702).

Overall, discards had a negative percentage difference (Fig. 4), with median values close to -30% for haddock and megrim, and -100% for whiting. The relative reduction in discard weights was on average 19.2%, 45.6% and 18.2% for haddock, whiting and megrim, respectively. Wilcoxon tests confirmed significant differences in discard weights between the test and commercial gears for haddock ($W = 40$, $n = 20$, p-value = 0.014) and for whiting ($W = 11$, $n = 11$, p-value = 0.054). No significant difference was detected for megrim ($W = 76$, $n = 18$, p-value = 0.702). For whiting and megrim, the difference in discard weights varied markedly between hauls (Fig. 4).

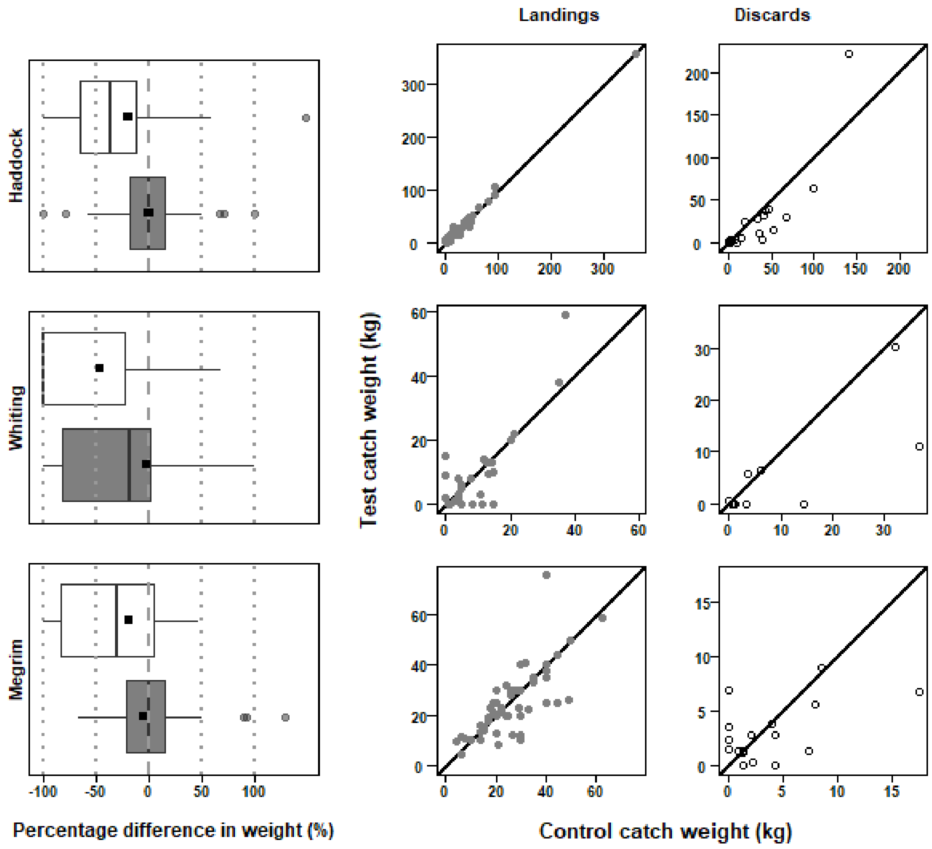

Figure 4. Catch weight comparisons. The first column shows boxplots of the percentage difference in weight from test gear compared to that of commercial gear for landings (grey) and discards (white). Black thick lines and squares represent median and means, respectively. Left and right sides of the box represent the first and third quartiles. The ends of the horizontal lines (i.e. the whiskers) represent 1.5 times the interquartile range. The second and third columns show absolute catch weight for the test gear against the absolute catch weight for the commercial gear for landing (second column) and discard (third column) fractions. Diagonal lines are 1:1 lines.

3.2.2. Length class composition of catches

Coefficients of selected models are provided in the supplementary material (Table A). Marginal fits (per haul) are displayed in Figures B, C and D for haddock, whiting and megrim, respectively. Selected GLMM are polynomials of degree 1, 0 and 0 for haddock, whiting and megrim, respectively. The selected models only account for random effects on the degree 0. For both whiting and megrim, the selected model only account for an intercept, i.e. a constant catch share between the test gear P1 and the commercial gear at any size. Figure 5 displays average model predictions among the hauls (Fig. 5). As long as the curve remains below 0.5, i.e. an even catch share between the test and commercial gears, the test gear retains less fish than the commezrcial gear. Fish smaller than the MCRS were rarely caught during these trials. Despite this, catch rate confidence intervals (< 0.5, Fig. 5) indicated that the test gear retained fewer small sized individuals of haddock and whiting than the commercial gear. For megrim, average predictions remained below 0.5, suggesting increased escapement of smaller sized individuals as well. But that may not be significant as there was little overlap between confidence intervals and the $\phi = 0.5$ line. For haddock, average catch share reached 50% at a length of 55 cm. Here, we assume that above the length at which ϕ reaches 0.5 the retention process is the same in both gears.

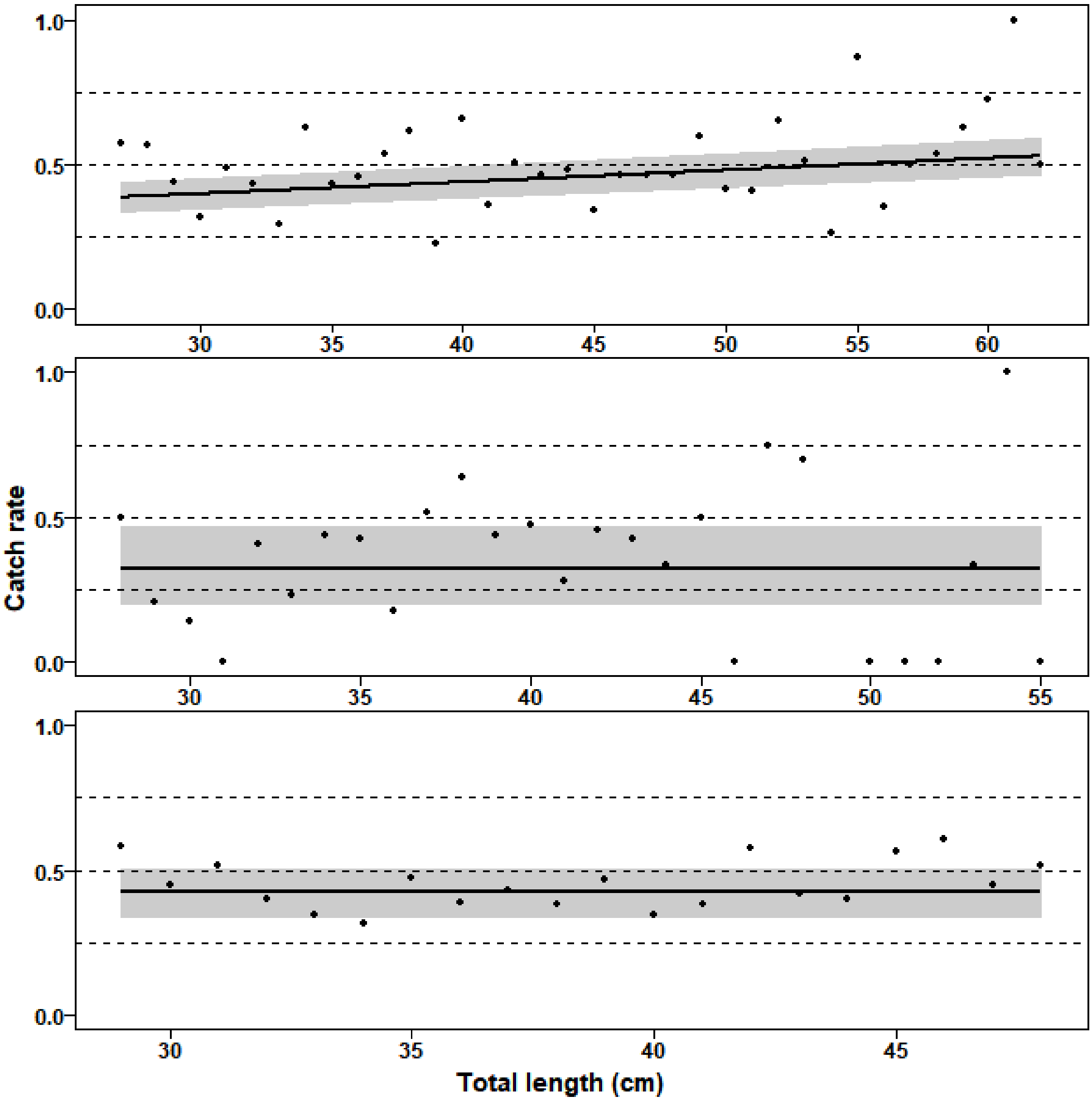

Figure 5. Catch share $\left(\phi = \frac{N_{test}}{N_{test}+N_{commercial}}\right)$ *among the test and commercial gears against total length (cm) for haddock, whiting and megrim (upper, middle and lower panels, respectively). Black dots and black lines represent extrapolated and pooled data and average*

model predictions, respectively. Grey shaded areas represent 95% confidence intervals of model predictions.

4. Discussion

We investigated the change in selectivity by insertion of a 100 mm SMC, in addition to the mandatory 100 mm SMP, on two target roundfish species and a flatfish species considered as by-catch on board a demersal twin-trawler in the Celtic Sea. We analysed the respective effects of SMC position and of the insertion of a dispersive float. The insertion of the float had a similar effect on haddock, whiting and megrim by decreasing SR values, i.e. sharpening the selection curve. In most cases, the float also resulted in a slight decrease in L_{50} values, indicating an increase in escapement of smaller sized fish with the float inserted in the SMC. The effect of the SMC position did not show a clear pattern for either round fish (haddock and whiting) or flatfish (megrim). The test gear P1 (i.e. the SMC inserted ahead of the SMC without the dispersive float) resulted in the largest L_{50} values for all three species and was thus considered as the most selective configuration. Configuration P1 was subsequently used in the catch comparison analyses as it was assumed to be the best trade-off between increased size selectivity for the three species and rigging simplicity. Analyses revealed increased escapement for all size classes of whiting and megrim, but only for haddock below 55 cm, and a reduction in discard weights, equal to 19.2%, 45.6% and 18.2% for haddock, whiting and megrim, respectively.

4.1. Size selectivity analysis

Confidence intervals derived from bootstrap for both selectivity parameters and model predictions were relatively large and overlapped between test configurations. Given the between haul variability, 6-8 hauls per configuration resulted in a lack of statistical power. When the float was inserted within the SMC a decrease in the selection range, and thus sharpening of the selection curve, was recorded for all three species. Fish escapes were mainly due to chance contact with the net and not active attempts [27,28]. Glass and Wardle [29] found that inserting a black tunnel into the extension changed the behaviour of fish, which tended to avoid this device and make more attempts to escape through the mesh. Krag et al. [14] also showed that implementing a stimulation device increased the probability of contact with the mesh and thus enhanced selectivity. The reduction in SR observed in the present study (for the three species with the float) may reflect a less random retention process with size, likely induced by a disruption of swimming direction and thus increased contact probability regardless of size. The float also led to decreased L_{50} except for megrim in position P2, indicating that its insertion decreased the probability of escapement of smaller individuals.

The effect of SMC position was less clear, but also tended to reduce L_{50}, except for whiting and megrim when the float was present, which might suggest an interaction of both effects. Many studies have demonstrated the contrasting effect of SMP position [11,12,30]. Catchpole and Revill [11] reported that "generally the closer to the cod-end the SMP is inserted, the higher the rate of escape of whiting and haddock". However, Drewery et al. [31] found that SMP position had no significant effect on whiting and haddock retention.

For each rigging configuration, absolute L_{50} estimates were 2.5 to 5.4 cm larger for whiting than for haddock. A larger L_{50} for whiting than for haddock agrees with results from previous studies [8,32,33] and is related to their respective shapes, which is more elongated for whiting. Previous studies showed that SMPs [34–36] and SMC [37] do not enhance escapement of undersized hake, a gadiform with an elongated shape similar to that of whiting. Alzorriz et al. [36] also demonstrated that undersized hake (*Merluccius merluccius*), red mullet (*Mullus surmuletus)* and pouting barely (*Trisopterus luscus*) unsuccessfully escaped through a SMP, despite "fall through" experiments demonstrating that the square mesh does enable escapement. This suggests that not only shape, but also behaviour, affects the efficiency of selective processes through SMP and SMC. Haddock and whiting are known to swim relatively high in the trawl when caught [11]. The SMP is usually placed at the top of the trawl net to exploit this behaviour. The SMC covers the entire circumference of the gear and could theoretically enable escapement of species that behave differently inside the gear, e.g. flatfish, which tend to remain at the bottom [38]. Nevertheless, dorsal and ventral insertion of square meshes were found ineffective in altering escapes of undersized hake [34], with the majority of fish escapes expected to occur in the codend [16].

4.2. Catch comparisons

The primary objective of this study was to identify a rigging configuration for the additional SMC to decrease discards by reducing the catch of undersized fish. The test gear P1 caught less haddock than the commercial gear up to 55 cm in length, which is well above the MCRS set at 30 cm. The test gear P1 also caught less whiting and megrim than the commercial gear across the entire sample size range. For whiting, the lack of a size effect may be due to the low number of hauls (n=5). However, this is unlikely to be the case for megrim, which occurred in 21 hauls. The SMP is designed specifically for roundfish species and may therefore be less suitable for flatfish. Also, very few fish below the MCRS were captured in the catch comparison trials. Further analysis designed to assess the size selectivity of the control gear is therefore required to better understand whether undersized fish were not present in the environment or if they escaped through both the test and the control gear.

Lower discards occurred with the P1 configuration, despite a limited effect of size on the catch share between P1 and the commercial gear. The addition of the SMC in the commercial gear led to discard reduction of 19.2%, 45.6% and 18.2% for haddock, whiting and megrim, respectively, without significant commercial loss given the sorting practice of the crew. Few undersized individuals were caught during the catch comparison trials. This suggests that large amounts of discard were composed of fish larger than the MCRS.

4.3. Fisheries implication with regards to the landing obligation

We tested four rigging configurations for the SMC and performed absolute size selectivity experiments on three species. In the context of a multi-species fishery, determining which device performed the best is challenging and involves finding the best trade-off among species. Optimal choice depends on the *métier* and on-board sorting practices. When considering one species at a time, the best gear configuration is the one with the most abrupt selection curve, i.e. the lowest SR, and a L_{50} as close as possible to the target length, usually the MCRS. Accordingly, P1F, i.e. insertion of the SMC with the float in front of the SMP, appeared to be the best option for the three species. However, catch comparison analyses revealed significantly high levels of discards above the MCRS. This is documented for the entire fleet. For example, in 2016 undersized fish comprised 44%, 18% and 5% of discards (by number) for haddock, whiting and megrim, respectively, for French demersal trawlers (larger than 18 m) fishing in the Celtic Sea, the Western English Channel and West of Ireland [39]. International stock assessment data also indicated that large proportions of discards were composed of oversized individuals [5], most likely due to TAC restrictions at the national or vessel level and avoidance of lower-priced individuals (i.e. “high-grading” practices [40,41]). In this instance, the best configuration for fishermen may be the one with the L_{50} closest to the size that distinguishes landings from discards and the smallest SR. P1 may provide the best configuration for fleets primarily targeting haddock and whiting, as larger L_{50} estimates were recorded with this device for the three species and was associated with a reasonably small SR for haddock and whiting.

Gear P1 is a relatively simple configuration that can be easily implemented in the demersal trawling fleet operating in the Celtic Sea. Despite a limited size effect on the selection curve (relative to the commercial gear), test gear P1 significantly reduces discards. Moreover, the limited size effect may be advantageous when TAC is highly constraining, as oversized fish will still be discarded. The latter is especially true for megrim, which is considered as a by-catch species. Thus, inserting a SMC could be an efficient way to save on-board storage capacity by decreasing the volume of unwanted catches that are required under the LO.

At the time of the experiments in 2014, the mandatory SMP was constructed from 100 mm mesh [13]. However, this regulation was amended in 2015 [42] and 2018 [43], and the SMP is now (since July 2019) constructed from 160 mm mesh. Thus, one can expect higher rates of escapement than those observed in the present study. Vogel et al. [25] showed that SMP and SMC with meshes of 100 mm or larger were not appropriate to target whiting. This is because it does not increase undersized fish escapement (relative to the 80 mm mesh), only for commercial size classes. Since high-grading practices are observed in the Celtic Sea demersal fishery, the resulting escapement of small commercial sizes should not decrease landings drastically.

4.4. Benefits from a combined analysis

Performing size selectivity and catch comparison analyses based on the same experimental gear provides complementary insights into the selection process. The two approaches benefit both scientists and fishermen. Scientists require accurate data on size selectivity for stock assessment and management scenarios, while fishermen are especially sensitive to the balance between reducing discards and maintaining landings.

Absolute size selectivity experiments are costly and time consuming, but essential for estimating selectivity parameters and escapement of small individuals. Approaches which combine size selectivity and catch comparison analyses are therefore particularly valuable for management-planning and decision-making processes. Implementation of the LO in a demersal multi-species fisheries context, which includes most European fleets, requires analysing similar experiments for both target and non-target species under TAC or MCRS regulations, which seldom occurs.

Conducting sea trials on board commercial vessels has two advantages. First, the fishermen taking part in the experiment can adopt the tested gear based on the relative effectiveness and ease of use. Second, it ensures the representativeness and validity of the results for the fishery.

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Supplementary material

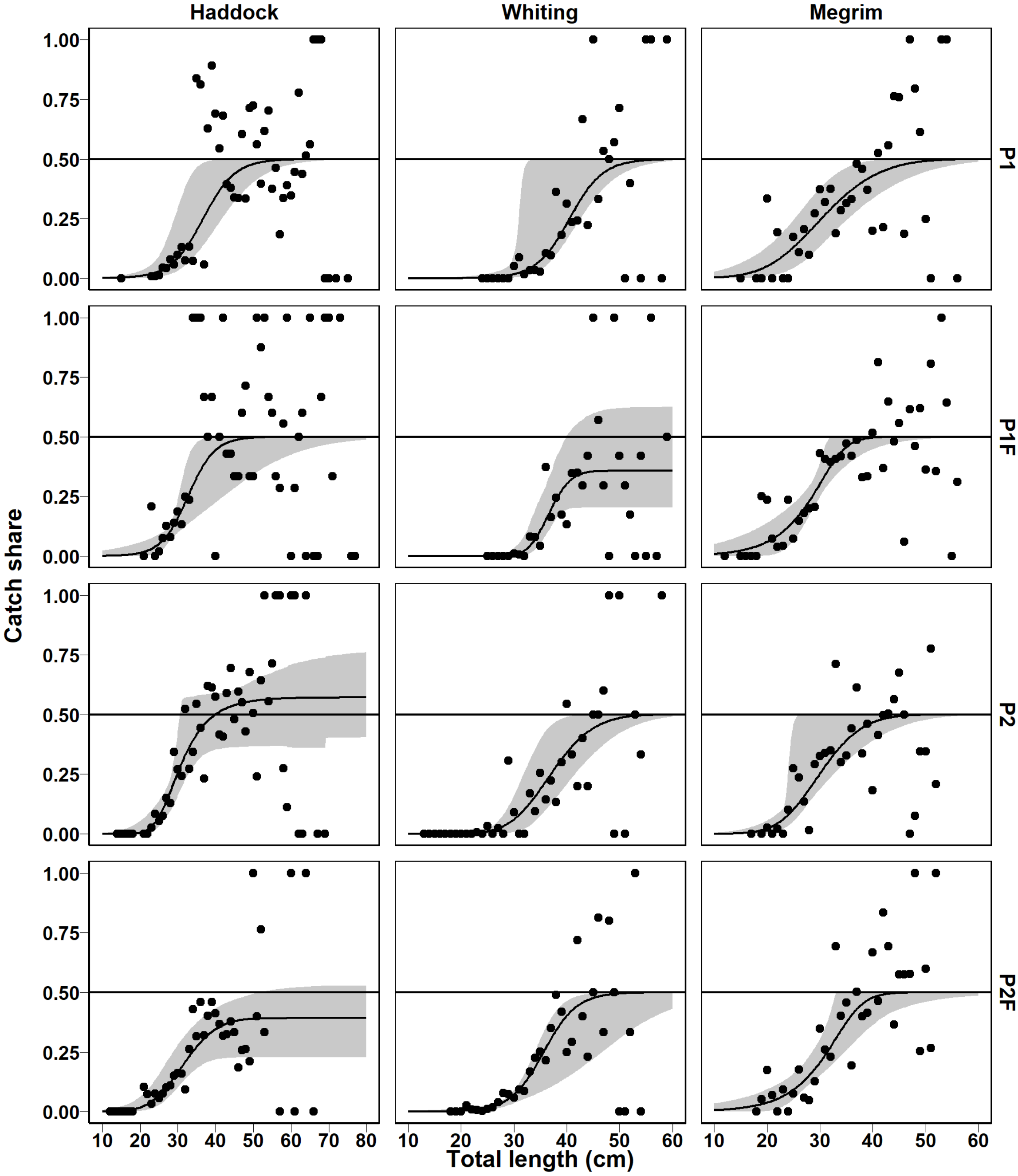

Figure A. Catch share $\left(\phi = \frac{N_{test}}{N_{test}+N_{control}}\right)$ *against total fish length per species and test configuration. Points represents extrapolated and pooled data. Solid lines and shaded areas represent average model predictions and their 95% confidence intervals, respectively.*

Table A. Summary of generalized linear mixed models: Number of hauls, fixed-effect estimates (with standard errors (SE)) and random-effect standard deviations.

	Haddock	**Whiting**	**Megrim**
Number of Hauls	13	5	21
AIC	588.25	149.91	875.7
Fixed effects (SE)			

Intercept	-0.211 (0.114)***	-0.754 (0.324)***	-0.315 (0.173)***
Slope	2.68 (1.22)***	-	-
Random effects			
Intercept	0.288	0.559	0.735

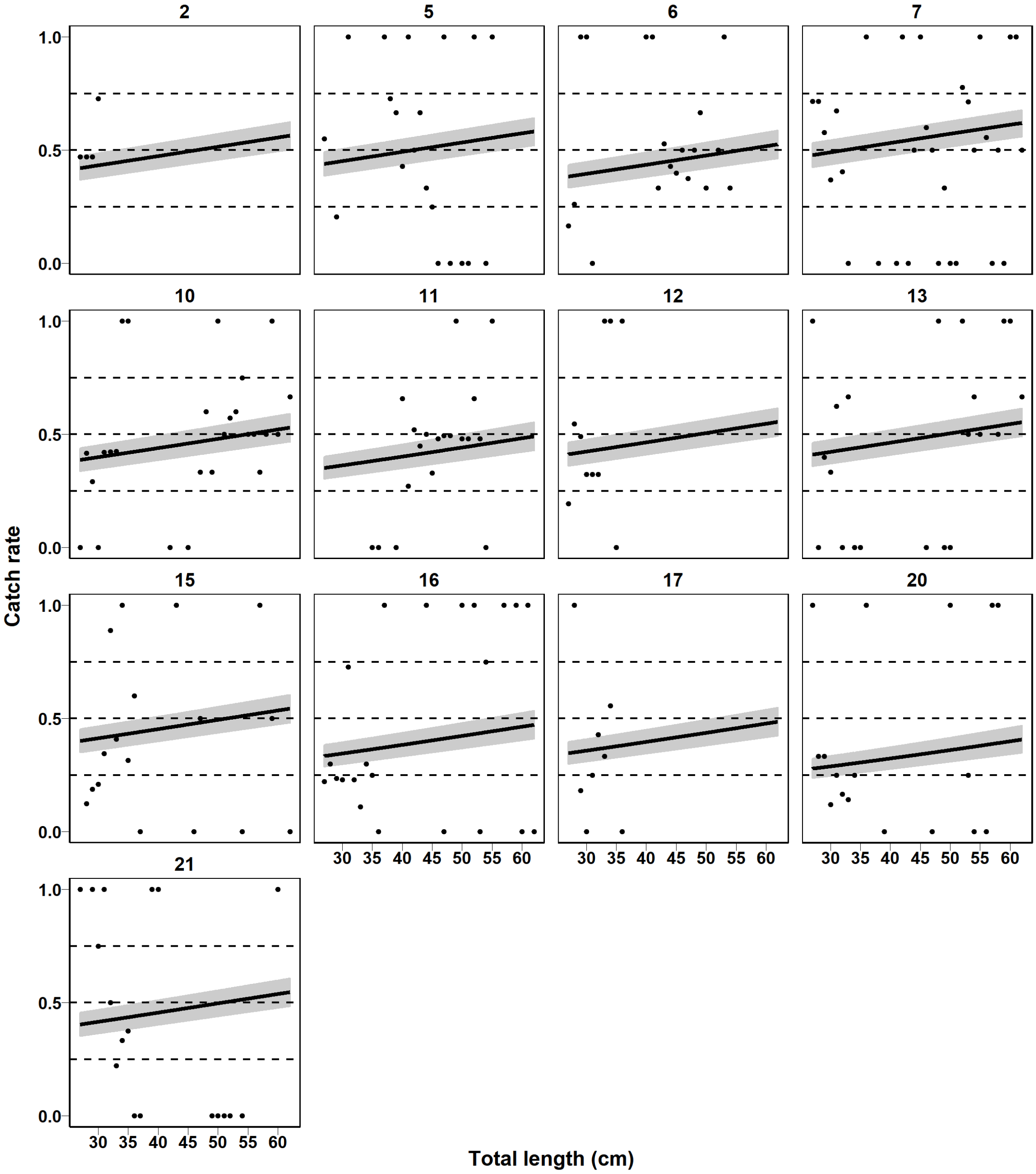

Figure B. By haul catch share of haddock among the test and commercial gears against total length (cm). Black dots and black lines represent extrapolated data and average model predictions, respectively. Grey shaded areas represent 95% confidence intervals of model predictions.

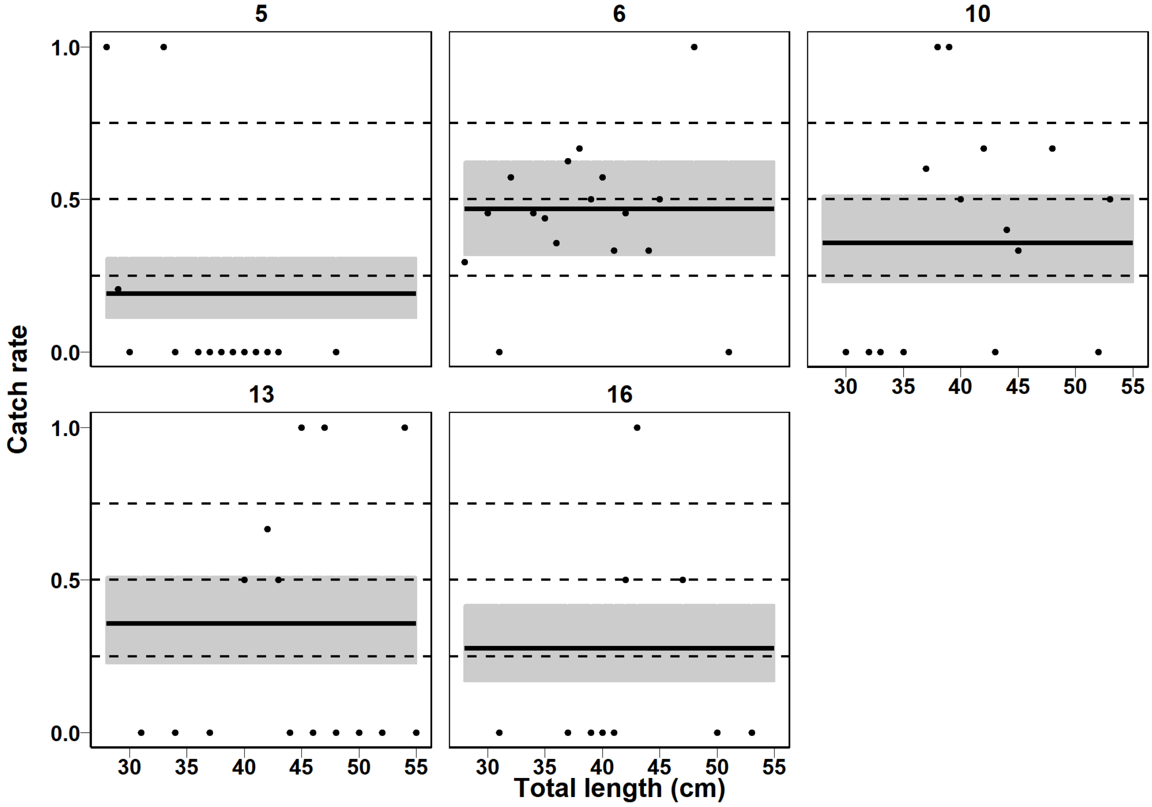

Figure C. By haul catch share of whiting among the test and commercial gears against total length (cm). Black dots and black lines represent extrapolated data and average model predictions, respectively. Grey shaded areas represent 95% confidence intervals of model predictions.

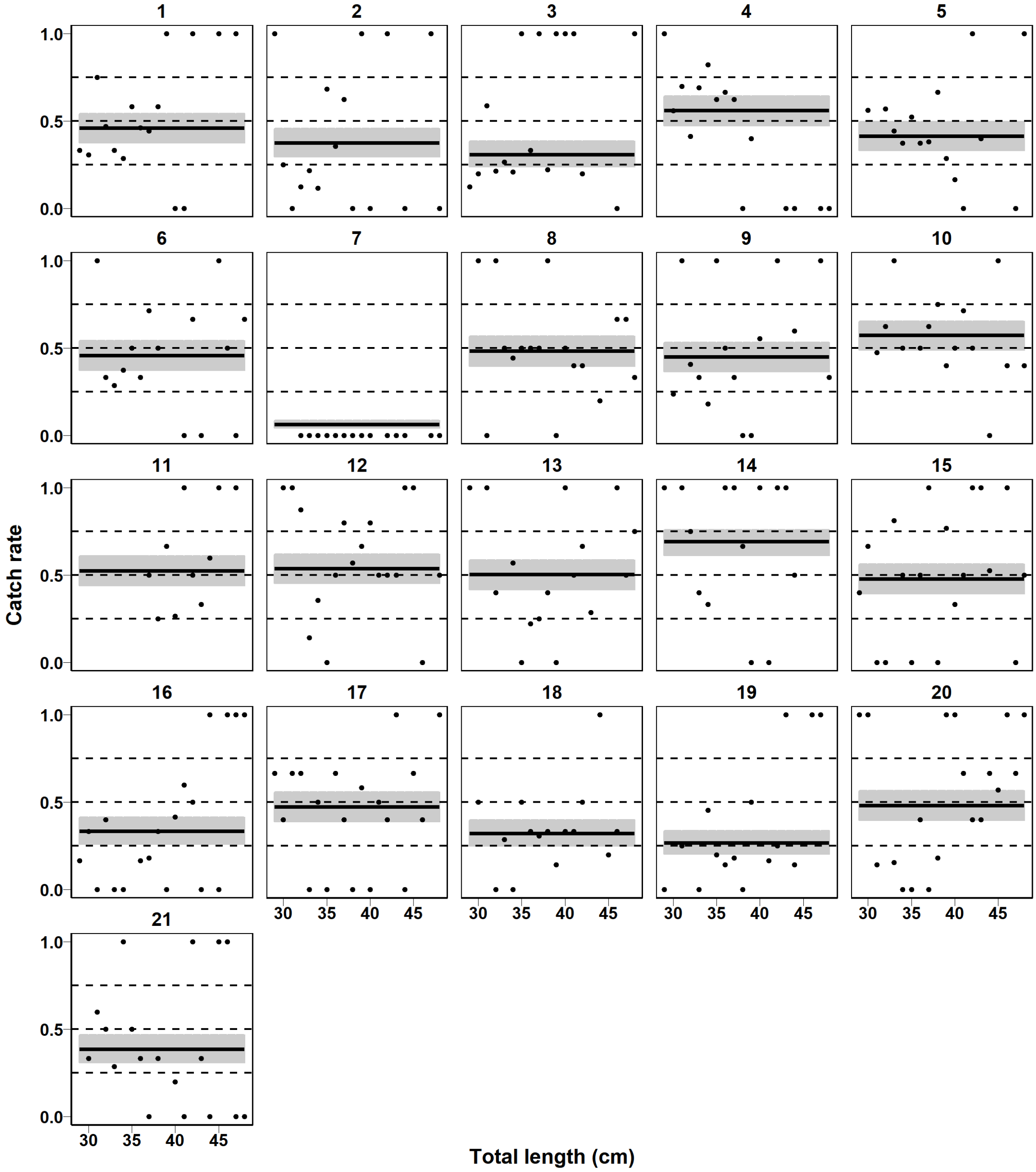

Figure D. By haul catch share of megrim among the test and commercial gears against total length (cm). Black dots and black lines represent extrapolated data and average model predictions, respectively. Grey shaded areas represent 95% confidence intervals of model predictions.

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