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Experimental and theoretical study of red mullet *(Mullus barbatus)* selectivity in codends of Mediterranean bottom trawls

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Abstract – The objective of this study was to investigate the effect on *Mullus barbatus* (red mullet) codend selectivity by increasing the codend mesh size or reducing the number of meshes in the codend circumference. This was performed through experimental sea trials and computer simulations. The sea trials were carried out in the Adriatic Sea using a polyamide codend in order to assess its selectivity, to record morphological (height, width and length) and population size structure parameters of red mullet (*Mullus barbatus*). The selectivity process in the codend was also simulated with an individual-based model (PRESEMO) and a finite element model (FEMNET) to calculate the codend shapes. By adjusting the behavioural description of red mullet in the simulation, the model results reached an agreement with the experimental results. Next these, behavioural parameters were used in the simulation model to predict the effect of changing mesh size and number of meshes around in new codend designs. The predicted effect and the benefit of enforcing these designs on catch efficiency below and above minimum landing size (MLS) were investigated. The results confirm that the reduction of number of meshes in the codend circumference will be more beneficial than increasing the mesh size.

Key words: Codend selectivity / Trawl / Codend shape simulation model / Red mullet / *Mullus barbatus* / Mediterranean Sea

Résumé – Étude expérimentale et théorique de la sélectivité du rouget barbet *(Mullus barbatus)* dans les culs de chaluts de la pêcherie de chalut de fond en Adriatique. Cette étude repose sur des essais en mer et des simulations numériques. Les essais ont été réalisés en Adriatique, pour mesurer la sélectivité de culs de chalut polyamide, pour collecter les données de morphologie du poisson (hauteur, largeur et longueur) et les paramètres de la structure de la population de rouget barbet *(Mullus barbatus)*. Les simulations numériques ont été réalisées, d'une part, à l'aide d'un modèle individu-centré pour le processus de sélectivité dans le cul de chalut (PRESEMO), et d'autre part, avec un modèle éléments-finis pour le calcul des formes du cul de chalut (FEMNET). Les paramètres de description du comportement du rouget barbet utilisés dans le modèle de comportement ont été ajustés pour obtenir un bon accord avec les résultats d'essais en mer. Ensuite ces paramètres de comportement ont été utilisés dans les modèles pour prédire l'effet d'une modification de la taille de la maille et du nombre de mailles autour, dans des nouveaux plans de cul de chalut. La prédiction de l'effet et le bénéfice de l'utilisation de ces nouveaux plans en terme d'efficacité de capture des poissons, de taille inférieure ou supérieure à la taille minimale de débarquement, ont été étudiés.

1 Introduction

In October 2004, the European Commission submitted a proposal to the Council for amending the rules currently governing Mediterranean fisheries. One of the main aims of the new regulation was to improve the selectivity Mediterranean fisheries. At present, the management of fish stocks is mainly based on defining closed areas and seasons, Minimum Landing Sizes (MLS) and Minimum Mesh Sizes (MMS). However, in multispecies fisheries, where several species are caught simultaneously, it is difficult to define the effect of a minimum codend mesh size for towed nets. In Italy, the MMS of trawl codends has been fixed at 40 mm (opening of stretched mesh) by Regulation EC-1626/94. Nevertheless, the capture of undersized fish and discards are still significant. Peak effort in the Adriatic bottom trawl fishery (Mediterranean Sea) coincides with large concentrations of juvenile of red mullet *(Mullus barbatus)* on the fishing grounds. Red mullet is

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subjected to a MLS of 11 cm (Regulation EC-1626/94). Even with the regulation on the MMS, it can be observed that large numbers of these fish are discarded being undersized. Improvement of trawl net selectivity is therefore of prime importance.

To avoid heavy discards rates of red mullet it is important that there be a good balance between the selective properties of the codends used, the legal MLS and the population structure of the harvested fish population. For example if the 50% retention lengths ($L50$) for the legal codends are small compared to MLS and the harvested population contains many fish smaller than MLS, then large discards rates will be the consequence. On the other hand if $L50$ is too large many of the fish sized above MLS will escape leading to loss of fish which could have been landed.

The selectivity of bottom trawl codends can vary in two ways. Firstly, there is haul to haul variation even though the net has not been altered. This variation is generally attributed to a number of "uncontrolled" variables such as sea state, catch size or water temperature. Secondly, there is the variation due to "controlled" changes in the net such as changes in mesh size, mesh twine thickness and number of meshes around. Currently, in many fisheries and based on various studies, the number of meshes around the codend is limited to a maximum value, whilst this effect still needs to be scientifically assessed in the Mediterranean.

Experimental work by Reeves et al. (1992) and by Galbraith et al. (1994) on the North Sea trawl fishery has documented that, besides mesh size, the number of meshes around the codend circumference is an important factor for the selective properties of a codend. Previous studies on codend selectivity carried out in the Adriatic Sea (Ferretti and Froglia 1975; Jukic and Piccinetti 1988; Dremière et al. 1999; Sala et al. 2005) demonstrated that current mesh sizes do not permit the escape of undersized fish. Some of these studies concerned the comparison of the selectivity of different mesh sizes, while others were devoted to compare the selectivity of different trawl gears. To date no papers have been published that demonstrate the effect of number of meshes around on codend selectivity with respect to some commercially important fish species in the Mediterranean.

Based on the above, the objective of the present study was to investigate size selection of red mullet in the Adriatic Sea trawl fishery and predict how this depends on codend mesh size and number of meshes around and thus predict the consequences of enforcing different regulations in terms of discards and possible loss of marketable fish.

This objective could have been fulfilled through extensive sea trials to cover all the different codend designs of interest. Due to the high cost of such trials we choose to perform sea trials with one reference codend design and then applied the computer-based codend selection simulation program PRESEMO (Herrmann 2005a) associated with the codend shape simulation model FEMNET (Priour 1999, 2001) to make predictions on what would be the effect of changing the design.

A first series of simulations were run for the reference codend for which the experimental results had been collected. The model's behavioural parameters were then adjusted, so that the simulated results reflected the experimental ones. Finally, the calibrated parameter values were used to run new sets of simulations, for other codend designs, so as to predict the expected effects of changing codend mesh size and number of meshes around the codend circumference. This also allowed for an estimation of the impact on discards, and of possible loss of marketable fish by enforcing these design changes. PRESEMO requires information on the shape of the codend and how this depends on the catch build-up during fishing.

FEMNET, which is a numerical tool based on the finite element method to estimate the shape of netting structures like trawls, was used to estimate the codend shapes.

2 Materials and methods

2.1 Codend shapes assessment

The shape of flexible structures such as fish cages, trawls and codends can be assessed by underwater observations and flume tank tests. However, numerical models are more and more used as they are well adapted and easy to use to study structures made of netting, cables and bars.

Two categories of numerical models to study net structures exist.

- Bessonneau and Marichal (1998), Niedzwiedz and Hopp (1998), Tsukrov et al. (2003), Lee et al. (2005) have developed 3D numerical methods which describe netting twines by numerical bars. These methods take into account a large number of twines in each numerical bar. The forces considered are the drag due to the water flow, but also the weight and the buoyancy of the net. The drawback of these models is that the numerical bars must be parallel to the actual twines of the netting, which means that the user of the modelling is not free to create the numerical bars.
- O'Neill (1997) has developed a model for axi-symmetrical structures adapted to conventional trawl codends. It is a 2D model taking into account the twine tension, as previously, but also the mesh opening stiffness and the pressure of the fish catch on the net. The drawback of this model is that it is devoted to axi-symmetrical structures only.

To avoid the problem of constrained numerical elements and axi-symmetry hypothesis, and to take into account further mechanical behaviours, a 3D Finite Element Method model of the net (FEMNET) based on a triangular element has been developed (Priour 1999, 2001). The triangle was chosen for being the simplest shape to describe a surface element.

FEMNET takes into account the inner twine tension, the drag force on the net due to the current as does the first category of models, but also, like O'Neill's model the pressure created by the fish in the codend, the twine contact when the meshes are closed, the mesh opening stiffness and the bending stiffness of the net.

FEMNET is able to describe nets, cables and bars, which means that for a codend, the netting, the selvedges and, if needed, the grids and the square mesh window are taken into account. The net is modelled by triangular elements whereas cables, warps, bridles and bars are modelled by linear elements (i.e. bars).

2.2 Calibration of PRESEMO

As explained in detail in Herrmann (2005a), PRESEMO is an individual-based structural model of the selection process in the codend of a trawl fishing gear. It models different populations of fish entering the codend during a haul. Each fish is assigned a weight and a maximum width and height dependent on its length, and is assumed to be of elliptical cross-section. Each is also allocated a travel time down to the codend, a time it can swim in the codend without being exhausted, a time between escape attempts and a packing density for swimming in front of the catch. An escape attempt is deemed successful if the fish can pass through the mesh opening at the point of the codend where the attempt takes place. Fish become part of the catch when their exhaustion time is reached. The codend shape is continuously updated as the catch builds up during the haul. At the end of a simulation, a logistic function is automatically fitted to the simulated selection data to obtain estimates of the 50% retention length (*L*50) and selection range *(SR)*.

PRESEMO requires information on codend design, fish behaviour, escape process, fish population structure, and fish morphology (Herrmann 2005a). Herrmann and O'Neill (2005) developed a protocol for using PRESEMO to simulate size selection of haddock in the North Sea trawl fishery. Their protocol ensured, for the specific fishery, that the resulting predictions were an accurate reflection of experimentally obtained estimates of codend selectivity parameters, their variances and the dependency on total catch weight. The parameter settings/descriptions, used in the simulations carried out here, are based on the same procedures. Because a different species was studied here, the behavioural description of the fish, entering the codend during the fishing process, needed to be adjusted accordingly. Also, the codends used were quite different: the twine material was softer, the mesh size was smaller and the number of meshes around was greater. Therefore, the ability of fish to partly distort the meshes during escape attempts, as modelled in PRESEMO, needs to be set up differently for the trawl fishery in the Adriatic Sea. In order to obtain usable values for the parameters, describing fish behaviour and mesh distortion, in the model to simulate size selection of red mullet in the Adriatic Sea trawl fishery, a set of experimental results was needed against which the values of such parameters could be calibrated. We simply adjusted the values of these parameters. Thus, the results of the simulated fishing process using PRESEMO reflected the experimentally obtained results for similar codend designs.

2.3 Selectivity trials at sea

The selectivity trials were carried out onboard RV *"G. Dallaporta"*, an Italian research vessel of 810 kW at 1650 rpm, Length Over All of 35.30 m and Gross Tonnage of 285 GT. The gear used during the selectivity tests was a conventional Italian commercial trawl employed in the Central Adriatic Sea. It is entirely made up of knotless polyamide netting, approximately 58 m long from the wing tips to the codend, with 600 meshes of 60 mm in the top panel at the footrope level. It was equipped with a 60.3 m length footrope made up of 38 mm combined rope, weighted with 80 kg of leads along its whole extension (Fig. 1). Trawl rigging included 150 m sweeps and Italian otter boards of 280 kg each. All the rigging components of the gear coincided with the common commercial practice in the Central Adriatic bottom trawl fishery.

During the sea trials, the codend mesh opening was measured while the netting was wet with an ICES mesh gauge with 4 kg tension, according to the Italian Regulation UNI 8738. The mean mesh opening, which conventionally for knotless netting, is the inside distance between two opposite joints in the same mesh when fully extended in the N-direction (EN ISO 1107, 2003), was 45 mm (Table 1).

During all the hauls done, a SCANBAS SGM-15 system (SCANMAR, Norway) was used to measure the gear performance: door spread, horizontal net opening and vertical net opening. The main aim of these measurements has been to check, and obtain in real time, detailed knowledge of the gear performance, by measuring the principal parameters that describe the mechanical and hydrodynamic behaviour of the gear.

A set of sea trials was conducted on fishing grounds in the Central Adriatic Sea normally exploited by local fishermen and took place in September 1-10, 2004, in an area situated approximately 5 nautical miles north of Ancona, at a depth of about 20 m. This period coincided with the end of the seasonal fishing closure and the abundance of some species was high. A total of 12 valid hauls was carried out following commercial practices with respect to trawling speed, towing duration and hauling time. Towing duration was considered as the time between the achievement of optimal gear opening and the moment when speed was reduced to heave in the warps.

Selectivity was measured using the covered codend technique. The cover of a nominal mesh opening of 20 mm was supported by circular hoops to hold it clear of the codend to minimize masking effect (Main and Sangster 1991). The cover was made of polyamide netting and was mounted 1 m ahead of the codend and was approximately 1.5 times larger and longer than the codend as recommended by Stewart and Robertson (1985).

For each haul a random sample of the catch was measured and the length frequency distributions were then determined by multiplying up the sub-sampled frequencies with the total weight divided by the sub-sample weight.

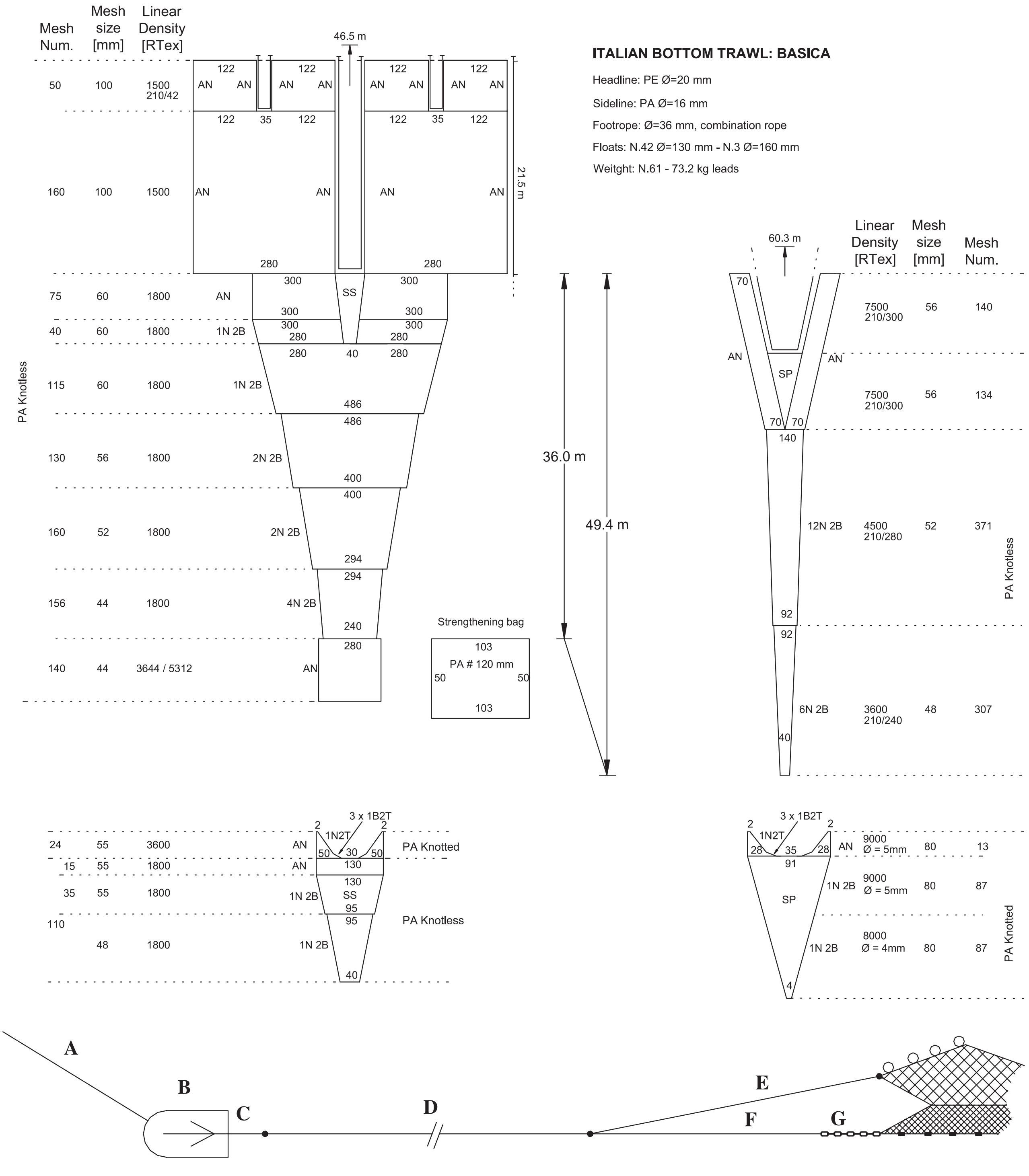
2.4 Selectivity data analysis

For each haul, the retention probability $r(l)$ in the codend was modelled by means of the logistic selectivity curve:

$$r(l) = \frac{e^{\upsilon_1+\upsilon_2 l}}{1+e^{\upsilon_1+\upsilon_2 l}},$$

where $r(l)$is the probability that a fish of length l is retained, given that it entered the codend (Wileman et al. 1996) and $\hat{\upsilon} = (\upsilon_1, \upsilon_2)^T$ is the vector of the selectivity parameters.

Correction for the effects of sub-sampling in individual hauls have been respected according to Millar (1994). The model of between-haul variation of Fryer (1991) was then used to investigate the between-haul variation of the selectivity parameters υ_1 and υ_2, allowing the estimation of a mean logistic selectivity curve.



A	Wire Ø 16 mm	150 m
B	Doors (1800 mm x 1150 mm) - 280 kg	-
C	Combination rope Ø 22 mm	6 m
D	Combination rope Ø 22 mm	100 m
E	Wire Ø 14 mm	52.5 m
F	Combination rope Ø 36 mm	50 m
G	Chain	3.30 m

Fig. 1. Design of the trawl and gear rigging adopted for the study during the selectivity tests.

Table 1. Characteristics of the reference codend (M44C280: nominal mesh opening 44 mm; number of meshes around 280), the cover and the hoops tested in the selectivity fishing cruises (Sept. 1–10, 2004). Mean values in bold and standard deviations enclosed in parenthesis.

	Codend	Cover	Hoops	
			Forward	Rearward
Nominal mesh opening [mm]	44	20	-	-
Twine linear density [tex]	3644 (*96*)	-	-	-
Twine diameter [mm]	2.38 (*0.03*)	-	-	-
Twine bending stiffness [N·mm^2]	47.42 (*2.23*)	-	-	-
Netting material	PA	PA	-	-
Mean mesh opening (ICES gauge) [mm]	45 (*0.8*)	-	-	-
Mean full mesh size [mm]	47 (*0.9*)	-	-	-
Circumference mesh number	280	1050	-	-
Nominal circumference [m]	6.3	10.5	3.5	5.0
Length [m]	6.3	10	-	-
Diameter of the plastic tube section [mm]	-	-	20	20

Table 2. Design of the codends used in the PRESEMO and FEMNET simulations. The acronyms of codend name provide the nominal mesh opening (Mxx) and the number of meshes around (Cxxx).

Codend name	**M44C280**	**M44C210**	**M44C140**	**M50C280**	**M50C210**	**M55C280**
Mean mesh opening (mm)	45	45	45	50	50	55
Full mesh size (mm)	47	47	47	52	52	57
Number of meshes around	280	210	140	280	210	280

The curve is commonly described in terms of the selectivity parameters $L50$ and SR. $L50$, the length at 50% retention, can be obtained by solving $r(l) = 0.5$, giving $L50 = -\upsilon_1/\upsilon_2$. Analogously, SR, the selection range, can be expressed by $SR = 2\ln(3)/\upsilon_2$.

The haul-by-haul maximum likelihood estimation of the selectivity parameters for individual hauls was carried out using the software CC2000 (Constat 1995). Models, incorporating between-haul variation, were estimated using the software ECModeller (Constat 1995) which implements the methodology proposed by Fryer (1991). In the latter models, the REML *(REsidual Maximum Likelihood)* approach has been used as estimation mode in the analysis.

2.5 Morphology measurement

In order to be able to set up PRESEMO simulations and predict whether a fish can escape through a mesh, morphology data for red mullet were collected. Each day during the selectivity cruise, total length (TL), height (H) and width (W) were measured on samples of red mullet taken from some hauls. TL was measured to the nearest 0.5 cm below, whilst H and W were measured to the nearest millimetre. Regression analyses were carried out to describe the relationships between the measured dimensions of the fish: H and W with TL. All the statistical procedures were performed using the *SPSS for Windows (Rel. 13.0)* software package.

2.6 Codend designs and shape estimations

The main data for the reference codend named used in the sea trials and in the simulations aimed at calibrating fish behaviour and mesh distortion parameters in PRESEMO are listed in Table 1.

In order to predict the effect of increasing mesh size or reducing the number of meshes around on codend selectivity, 5 other codend designs differing from the reference, by either increased mesh size or/and reduced number of meshes around the codend circumference, were defined. Table 2 summarizes the main data for these codend designs and their acronym names used in the rest of the paper. The acronyms provide for each codend the nominal mesh opening (Mxx) and the number of meshes around (Cxxx).

For each design the codend shapes, as required for the PRESEMO simulations, are calculated by FEMNET for 20 catch weights: 5, 6, 8, 10, 12, 15, 19, 24, 30, 37, 47, 59, 73, 91, 114, 143, 179, 224, 280, 350 kg. This progression was chosen in order to have a large number of calculations for small catches where the shape varies quickly.

As estimations of codend shape for very small catch weights are uncertain, the shape for catches below 5 kg was assumed to be the same as for 5 kg. The limit of 350 kg was chosen, because it is just above the maximal catch weight obtained during the sea trials. A towing speed of 3.5 knots was used for shape calculations.

2.7 Simulation of the fishing process

Based on the morphological data, population size structure information, by-catch, towing time and speed, obtained from the experimental trials, many of the parameters required to simulate a realistic fishing process using PRESEMO could be set up. Then, using shape estimations for the reference codend, similar to the shape of the codend used in the sea trials, different parameter values describing fish behaviour and mesh distortion during escape attempts were simulated.

The results of the simulated fishing processes were then compared with the results of experimental fishing. The set of parameter values yielding the best agreement between both was selected to describe fish behaviour and mesh distortion for the other codend simulations.

For each codend design, 100 repeated simulations were carried out applying the haul entry pattern of fish described in Herrmann and O'Neill (2005) to simulate between-haul variation, yielding 100 estimates for *L*50 and *SR* and total catch weight. By defining MLS, PRESEMO can also, for each haul, predicts the catch efficiency in kg of fish with respect to fish below and above MLS. This routine, together with information on the number of fish involved, enables an evaluation of the consequences of enforcing different technical regulations (e.g. mesh size or maximum number of meshes around the codend circumference) on discards and loss of marketable fish.

2.8 Quantifying discards and catch efficiency

This section formulates two parameters *(dfw, efw)* to estimate discards of undersized fish and catch efficiency when using different codend designs in the same trawl fishery. PRESEMO simulations for repeated hauls provides four parameter values that can be used to quantify these aspects:

- wt_- is the average between hauls of the total weight of fish with a length below MLS entering the codend;
- wr_- is the part of wt_- retained by the codend; thus $wr_- \leq wt_-$; in fact wr_- is the discards weight;
- wt_+ is the same as wt_- but for fish lengths above MLS;
- wr_+ is the part of wt_+ which is retained; thus $wr_+ \leq wt_+$, in fact, it is the weight of landed fish.

Based on the above, discards are described by the discards factor (*dfw*), as follows:

$$dfw = \frac{wr_-}{wr_+}. \tag{1}$$

In which wr_- is the weight of discards of small fish which are lost for the latter years, while wr_+ is the weight of landed fish, and *dfw* expresses the amount in kg of undersized fish caught to land one kg. When *dfw* is small, the codend contributes to sustainable fisheries and obviously when *dfw* is large, this is not the case.

The catch efficiency is described by the efficiency factor, which is defined by:

$$efw = \frac{wr_+}{wt_+} \tag{2}$$

wr_+ quantifies the weight of commercial fish which were caught when wt_+ fish have entered the codend. If *efw* is small, the codend is inefficient for the specific fishery. If *efw* is close to 1, the codend is most efficient for the specific fishery.

Another way to quantify the catch efficiency of a new design relative to a reference one is the needed fishing effort to land the same quantity. We quantify this by the effort factor, which is defined by:

$$eff = \frac{efw_{\text{reference}}}{efw}. \tag{3}$$

If *eff* > 1, then the new design is not as efficient as the reference design for that specific fishery. If *eff* < 1, it is more efficient than the reference design.

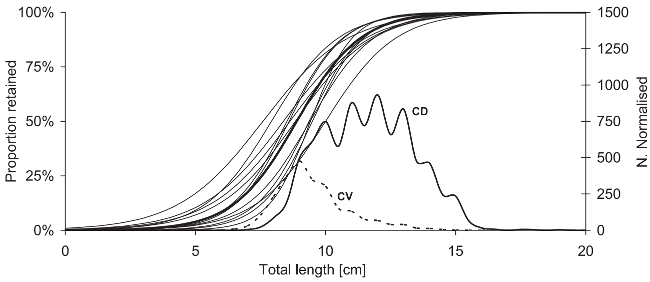


Fig. 2. Selectivity curves of *Mullus barbatus* (red mullet) for individual hauls (thin lines) and mean curve (thick lines) according to Fryer (1991). *X*-axis: total length (cm). *Y*-axis (left): proportion retained (%). Size structure in the codend (CD) and in the cover (CV). *Y*-axis (right): normalised numbers of individuals caught per haul.

dfw, *efw* and *eff* are used to quantify the benefit of using a different codend design in the specific fishery.

3 Results

3.1 Experimental selectivity results

Selection data for red mullet were obtained from sea trials using codend M44C280 (Tables 1 and 2). In all hauls, the overall catch of red mullet was between 63% to 85% of the total catch weight. Total catch weights were in the range of 125 kg to 344 kg, while the catches of red mullet varied between 90 kg and 237 kg.

The first step of the selectivity analysis was to calculate the selectivity of each single haul. The results of the individual haul selectivity parameter estimates are given in Table 3. The small values of R_i estimated in many of the hauls indicate low within-haul variability and reflect the high numbers of individuals in all hauls both in the codend and in the cover.

The parameters $\hat{\upsilon}_i = (\upsilon_{i1}, \upsilon_{i2})^T$, describing the selectivity of haul *i* and estimated by maximum likelihood from the numbers of fish at length retained and released in the codend, were approximately normally distributed with mean υ_i and variance R_i. All the hauls met these normality criteria and all were used in the subsequent experimental data analyses, which yielded the mean selectivity estimates together with the respective within-haul variation and between-haul variation of these parameters.

The normalised length frequency distributions, individual haul and mean fitted logistic curves are shown in Figure 2, while the parameters of the selectivity analysis are shown in Table 3. Following Fryer's method, the mean *L50* was 8.9 cm with a standard deviation of 0.2 cm; the mean *SR* was 2.7 cm with a standard deviation of 0.2 cm.

Red mullet ranged in size between 3.5 cm and 21 cm showing a unimodal distribution, which can be well modelled by a single normal distribution with a mean length of 11.2 cm and a standard deviation of 2.1 cm (Fig. 3).

3.2 Fish morphology

The relationships of fish height (H) and width (W) with total length (TL) are summarised in Table 4, which also reports

Table 3. Individual haul and mean curve (Fryer 1991) selectivity estimates of *Mullus barbatus* (red mullet) in the reference codend (M44C280). TS: towing speed; CC: Codend catch size; L50: Retention length at 50%; *SR*: Selection Range; υ_1 and υ_2: maximum likelihood estimators of the selectivity parameters; *{R_i}*: variance matrixes measuring the within-haul variation; D: Deviance; dof: Degree of freedom; *p*-value of the Goodness of fit; *{D}*: variance matrix measuring the between-haul variation.

ID HAUL	TS	CC	L50	*SR*	υ_1	υ_2	*{Ri}*			*D*	dof	*p*-value
	[kn]	[kg]	[cm]	[cm]			R_{i11}	R_{i12}	R_{i22}			
1400	3.3	344	9.49	2.16	–9.64	1.02	0.013	–0.011	0.020	30.83	20	0.057
1401	3.6	327	7.92	2.80	–6.21	0.78	0.057	–0.050	0.058	7.37	14	0.919
1410	3.2	339	8.52	2.35	–7.97	0.94	0.018	–0.016	0.027	25.83	18	0.104
1411	3.2	186	10.00	2.95	–7.44	0.74	0.012	–0.008	0.034	13.35	19	0.820
1412	3.2	192	8.84	3.27	–5.94	0.67	0.027	–0.027	0.052	13.52	21	0.889
1413	3.4	194	7.59	3.58	–4.66	0.61	0.099	–0.094	0.116	29.76	18	0.040
1418	3.2	200	9.42	1.75	–11.83	1.26	0.010	–0.006	0.013	21.51	20	0.368
1419	3.1	125	9.40	2.68	–7.70	0.82	0.018	–0.016	0.045	17.88	17	0.396
1404	4.1	309	9.37	2.24	–9.20	0.98	0.010	–0.008	0.021	20.17	19	0.385
1405	4.2	263	8.38	3.46	–5.33	0.64	0.045	–0.048	0.079	17.00	18	0.523
1406	4.2	240	8.64	3.38	–5.61	0.65	0.094	–0.100	0.178	51.25	19	0.000
1407	4.2	265	8.60	2.29	–8.24	0.96	0.024	–0.022	0.034	17.64	19	0.546
Mean curve (Fryer, 1991)			8.90 (6.85–10.94)	2.68 (2.06–3.29)	–7.30	0.82	0.433	–0.156	0.280	-	19	0.000
{D}			-	-	-	-	0.039	–0.016	0.028	-	-	-

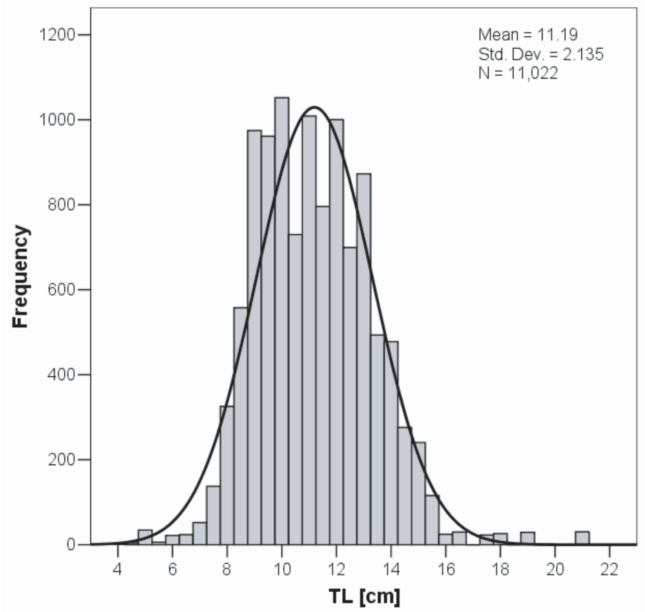


Fig. 3. Size structure of *Mullus barbatus* (red mullet) population entered the codend. *Y*-axis: normalised numbers of individuals caught per haul. TL (cm): total length. Mean = 11.2 cm, Std. Dev. = 2.1 cm, *N* = 11 022 fishes.

Table 4. Length-width and length-height regression analyses in *Mullus barbatus* (red mullet). H: Height (cm); W: Width (cm); TL: Total length (cm). **: highly significant, $p < 0.01$.

MODEL SUMMARY		LINEAR REGRESSION				
Model	Adjusted R^2	β	Std. Err.	Beta	*t*	
$H = \beta \cdot TL$	0.996	**0.209**	0.001	0.998	325.3	**
$W = \beta \cdot TL$	0.993	**0.117**	<0.001	0.997	239.2	**

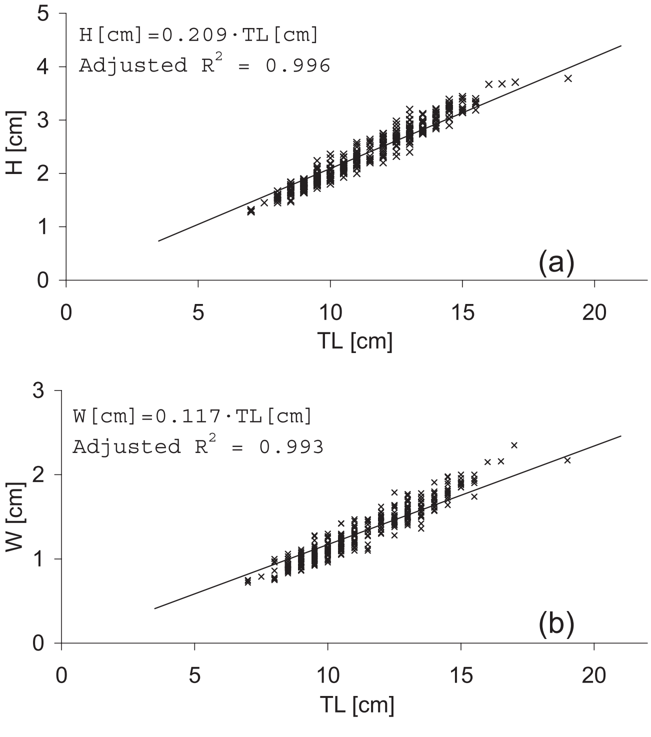


Fig. 4. Length-Height (a) and Length-Width (b) relationships in *Mullus barbatus* (red mullet). H: height, cm, W: width, cm; TL: total length, cm.

some descriptive statistics information of total length, height and width. The value of R^2 reported is interpreted as the proportion of the total variation in height or width accounted for by total length. In our analysis, the slopes of the regressions were all significantly different from 0 and R^2 values were all higher than 0.990. Figure 4 plots these regressions. Although

Table 5. Parameter settings in PRESEMO for the fishing process. *Towing time*: duration of the time the gear fish on the bottom of the sea; *Hauling time*: the time to haul the gear from the sea bottom onto the deck of the fishing vessel; *Escapement model:* describes whether or not potential mesh distortion is taken into account when simulating the fish escapement processes (Herrmann 2005b). (*a*) 0: the level of potential maximum mesh distortion starts decreasing from catch weight 0 kg; (*b*) when the catch weight reaches 70 kg, the fish is assumed not to be able to distort the mesh shape during escape attempts; (*c*) 1: fish keeping position just ahead of the catch in the codend try to make escape attempts within the total range of the codend occupied by the fish just ahead of the catch (Herrmann 2005a); (*d*) 0.8: fish not being exhausted can continue to make escape attempt for the first 80% of the period when the gear is hauled from the bottom of the sea; (*e*) fish attempting to escape during the initial phases of the fishing process can distort the mesh opening ratio as much as 20%; (*f*) the number of fish populations used to model the target species and by catch fish that enter the gear during a simulated fishing process; (*g*) the number of populations used to simulate the target population; (*h*) the number of populations used to model all other fish entering the gear.

Towing time (min)		60
Hauling time (min)		20
Escapement model		Soft distortion
Catch weight break value (kg)	*a*	0
Catch weight zero distortion (kg)	*b*	70
Infront of factor	*c*	1
Escapement during haul factor	*d*	0.8
Max distortion mesh opening	*e*	0.2
Populations in simulation	*f*	1,2,3,4,5,6
Populations as target	*g*	1,2,3
Red mullet populations		1,2,3
By catch populations	*h*	4,5,6
Target species		Red mullet
Minimum Landing Size MLS (cm)		11

by default the regression model includes a constant term, here the regression models have been forced through the origin and only the β coefficients (slope) have been provided. The estimates of the model slope coefficients are 0.209 and 0.117 for height and width respectively.

3.3 Calibration of PRESEMO

Based on the data from the sea trials, the same parameter values for towing time, population size, size structure and head cross-section morphology were used as input of PRESEMO. Different values for the parameters describing mesh distortion, during escape attempts and behaviour in the codend, were then tested against the experimental selectivity results. In general, an escape attempt is deemed successful if the fish can pass through the mesh opening at the location of the codend where the attempt takes place, without having to deform the mesh. At the beginning of a haul, however, when the catch is small this approach is not adequate. In this situation, when the hydrodynamic forces and consequently the tensions in the mesh bars at the aft end of the codend are small, we can assume that escaping fish can, to a certain extent, deform the meshes. As the catch builds up, the hydrodynamic forces acting on the codend netting and the tensile forces acting in the mesh bars increase, making it more difficult for the fish to deform the meshes when trying to escape (Herrmann and O'Neill 2005).

Table 6. Fish population data used in the PRESEMO simulations. These data concern fish morphology, fish time of entry to the gear as well as time to exhaustion, to travel in the codend and frequency escape attempting. These settings are described in detail in Herrmann (2005a); (*) Travel time = *par A* × Fish length, time it takes the fish to fall back to the aft end of the codend just ahead of the catch; *par A*: constant of proportionality.

	Population 1–3	Population 4–6
Species	Red Mullet	By-catch
Number	550⟨−⟩4500	450⟨−⟩4000
Size of fish distribution	Normal	Normal
Mean length (cm)	11.2	11.2
Var length (cm^2)	4.6	4.6
Height factor (dimensionless)	0.209	0.209
Height var (dimensionless)	0.000147	0.000147
Width factor (dimensionless)	0.117	0.117
Width var (dimensionless)	0.00008	0.00008
Condition factor (g cm^{-3})	0.0121	0.0121
Condition var ($g^2 cm^{-6}$)	0	0
Entry interval distribution	Random	Random
Entry interval (% of entry period)	50–100	50–100
Entry period (minute)	70	70
Time travel down distribution	Linear on Length	Linear on Length
Time travel down par A (min mm^{-1})(*)	0.025	0.025
Time trawl down par A var (min^2)	0.0013	0.0013
Exhaustion time distribution	Random	Random
Exhaustion time min. (min)	4	4
Exhaustion time max. (min)	10	10
Time between distribution	Random	Random
Time between min. (min)	4	4
Time between max. (min)	7	7
Catch packing density	1	1
In front of packing density	0.5	0.5

For red mullet, the best agreement with the experimental results was found by assuming that escaping fish can deform the mesh opening ratio (defined as the circumferential opening of the mesh divided by the mesh size) by as much as 20% during the initial stage of the haul, then decreasing linearly with increasing catch size until the catch size reaches 70 kg, after which escaping fish are not able to deform the meshes anymore. For the behaviour description, the best results were achieved assuming that there is a linear dependency of fish length with the time need to travel down to the codend towards a position just ahead of the accumulated catch, that there is a random interval between escape attempts and that there is a random time for the period a fish is able to swim in the codend before being exhausted.

Tables 5 and 6 summarize the parameter values used in PRESEMO to achieve these simulations. For simplicity purpose similar parameter values were used to model the by-catch fish. It can be seen (Table 6) that 3 identical populations (1-3) were used to model the red mullet population entering the fishing gear during the simulated fishing process. The reason for splitting the population up in 3 identical sub-populations each not necessarily having the same entry times in the individual hauls was to enable modelling of clustered entry in groups, thus reflecting the uneven distribution of fish in the sea. For the same reason 3 sub-populations (4-6) were also used to

Table 7. Comparison of experimental and simulated selectivity results of Mullus barbatus (red mullet) in the reference codend (M44C280). Mean (in bold) and respective standard deviation (SD) of the retention length at 50% (L50) and the Selection Range (SR) reported based on methods described in Fryer (1991).

		Experimental results		**Simulation results**	
		Mean	SD	Mean	SD
Total catch weight	(kg)	**249**	71	**250**	76
L50	(cm)	**8.9**	0.7	**8.8**	0.2
SR	(cm)	**2.7**	0.5	**2.8**	0.4

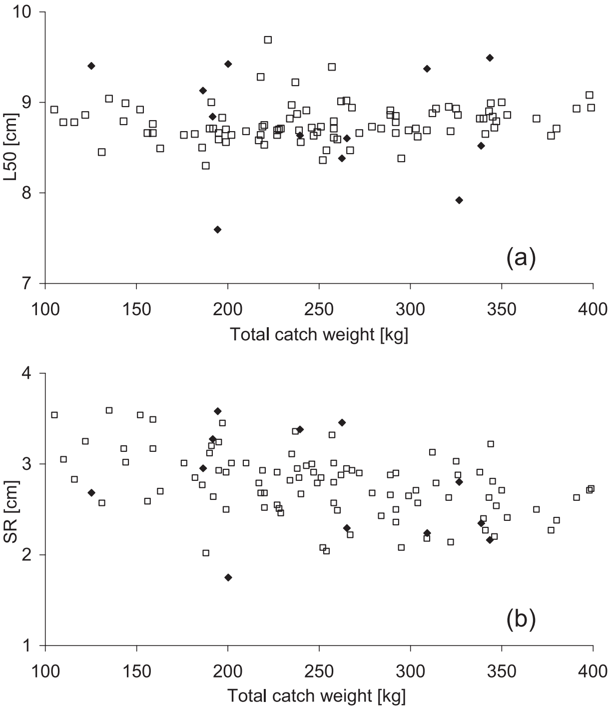


Fig. 5. *L*50 versus total catch weight (a) and *SR* versus total catch weight (b) in *Mullus barbatus* (red mullet) for the individual hauls. Experimental results (◇); simulated results (☐) using FEMNET and PRESEMO.

model the by-catch fish. Figure 5 plots the experimental results for *L*50 and *SR* against total catch weight at the end of the fishing process for single hauls and the results obtained from PRESEMO using the parameter values of Tables 5 and 6. Table 7 compares the mean results of experimental fishing and those obtained from PRESEMO, both based on Fryer's method.

By choosing appropriate values for fish behaviour in the codend, and for maximum mesh distortion during escape attempts, it is possible to obtain values for mean *L50*, mean *SR* and mean catch weight that are in reasonable agreement with the experimental results obtained for the same codend, even though the between-haul variation in *L50* was underestimated (Fig. 5 and Table 7).

Figure 6 shows a set of screen dumps from PRESEMO for a simulated fishing process using the reference codend and the parameter values described above.

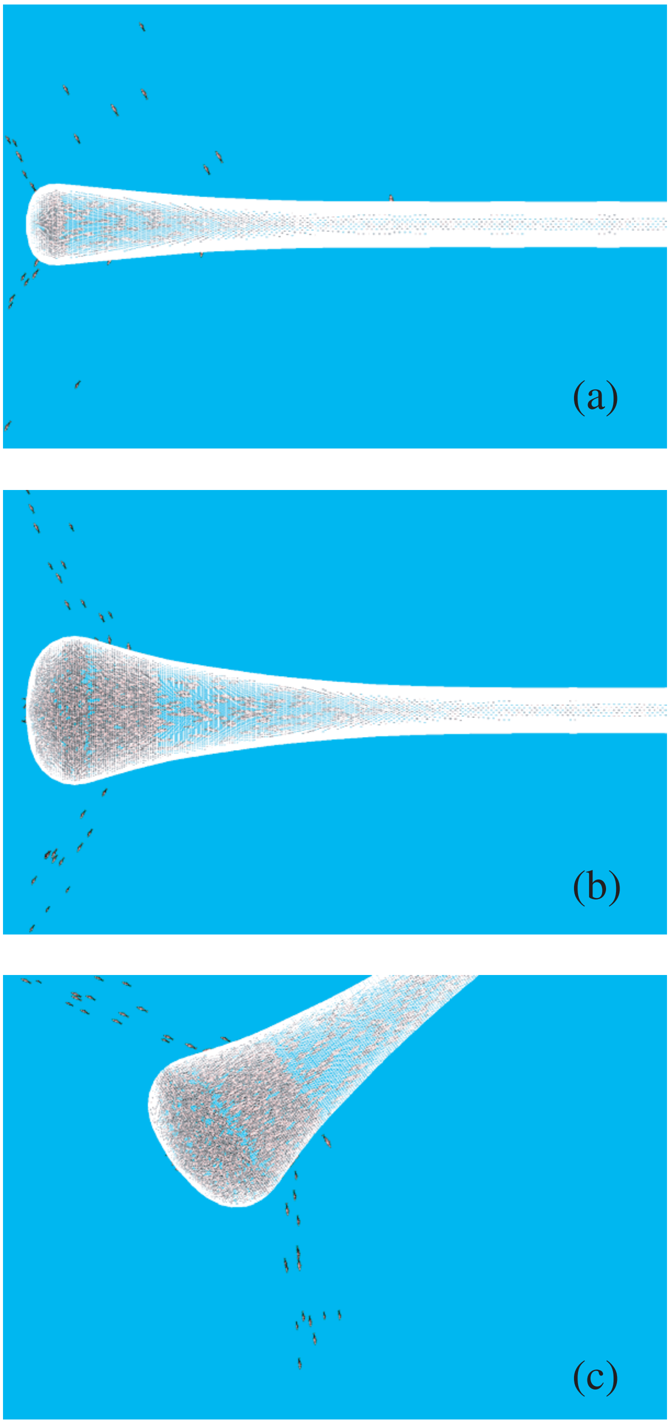


Fig. 6. Set of screen dumps from PRESEMO for a simulated fishing process using the reference codend (M44C280). The codend shaped were estimated using FEMNET. (a) Early in a tow. Fish are seen moving down the codend. Some fish are making successful escape attempts through the nearly closed meshes whilst others are exhausted and have fallen back to the aft end of the codend and the catch begins to build up. (b) Late in a tow. Since the start of the tow, the geometry of the codend has now changed considerably. At this moment not only the smallest fish are able to pass through the open meshes just ahead of the catch. (c) Hauling to the surface. The towing have now ended and the gear is hauled to the surface. Some fish are still able to escape.

Table 8. Simulated selectivity results of *Mullus barbatus* (red mullet) in each codend using PRESEMO. Mean (in bold) and respective standard deviation (SD) have been reported for each parameter based on methods described in Fryer (1991).

		M44C210		**M44C140**		**M50C280**		**M50C210**		**M55C280**	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Total catch weight	(kg)	**204**	69	**178**	74	**221**	78	**197**	72	**163**	63
L50	(cm)	**9.8**	0.3	**10.9**	0.7	**9.3**	0.4	**10.4**	0.3	**11.4**	0.8
SR	(cm)	**3.0**	0.2	**4.7**	0.5	**3.4**	0.6	**3.6**	0.3	**5.8**	1.4

Table 9. Prediction of fish weight proportion of *Mullus barbatus* (red mullet) entering the codend that will be caught below and above MLS (see Sect. 2.8 for details and definitions of terms).

	M44C280	M44C210	M44C140	M50C280	M50C210	M55C280
wt_-(kg)	40	34	38	37	37	36
wr_-(kg)	27	16	14	21	15	12
wt_+ (kg)	115	98	108	105	107	103
wr_+ (kg)	111	90	82	97	90	71
dfw	0.24	0.18	0.17	0.22	0.16	0.17
efw	0.96	0.92	0.76	0.92	0.84	0.69
eff	1.00	1.05	1.27	1.05	1.14	1.39

3.4 Prediction of selectivity, discards and catch efficiency

Using the parameter values for simulating size selection of red mullet in the Adriatic Sea trawl fishery described in the previous section, it was possible to predict the selectivity for the other codend designs listed in Table 2. The results for the simulations for the various designs, based on 100 repeated hauls for each design, are summarised in Table 8. The results show that the predicted effect of increasing the mesh size from 44 mm (design M44C280) to 50 mm (design M50C280) was an increase in *L*50 by +5 mm, whilst that of reducing the number of meshes around the codend from 280 to 140 (design M44C140) resulted in a predicted effect of more than +21 mm, thus being much more effective than increasing mesh size (Tables 7 and 8).

The parameter values (wr_-, wt_-, wr_+, wt_+) used to predict the effect of different codend designs on discards and catch efficiency are listed in Table 9. Using these values in formula (1), (2) and (3) it was possible to estimate this effect. The results are given in Table 9.

With regard to the discards *(dfw),* all the new codend designs yielded better discards factors (0.16-0.22) than the reference (0.24). The best design was M50C210 (0.16) leading to a decrease of 80 kg discards per ton of landed fish. All the new designs were similar in terms of discards factors (0.16–0.18) with the exception of design M50C280 (0.22).

All new designs had a worse efficiency (*efw*: 0.69–0.92) than the reference codend (0.96). This means that they would all require an increase in fishing effort (*eff*: 1.05–1.39) to counteract this effect. The most efficient new design was M44C210 with a catch efficiency of 0.92.

Changing from the reference design to design M44C210, would reduce the discards factor from 0.24 to 0.18 (i.e. by 60 kg discards per ton of landed fish). However, the catch efficiency factor would be reduced from 0.96 to 0.92 requiring an increase in effort *(eff)* by 5% in order to catch the same amount of landed fish. Further reduction of the number of meshes around, by using the M44C140 design, would only yield a slight improvement of the discards factor (0.17), but the catch efficiency would decrease dramatically to 0.76 requiring a 27% increase in effort compared to the reference codend and a 21% increase compared to design M44C210. A decrease in the number of meshes around to the extent of design M44C140 is thus not a good option.

The most sustainable design would be M44C210. A reduction in the discards factor similar to that obtained with design M44C210 can be achieved by increasing the mesh size as in design M55C280 (Table 9; discards factor 0.17). However, the catch efficiency of this design is very small compared to both the reference design and M44C210. Design M55C280 has a catch efficiency factor of 0.69 which would require an increase in effort by 39% and by 33% compared to the reference codend and design M44C210 respectively.

4 Discussion

Using the simulation tools FEMNET and PRESEMO we theoretically investigated the expected effect of increasing mesh size and/or reducing the number of meshes around the codend on codend selection of *Mullus barbatus* (red mullet). Red mullet was used in this study, but it would expect similar tendencies for other round fish species in the Adriatic Sea. There is an obvious advantage in using the described simulation method compared to experimental fishing: each codend design is exposed to the same set of a large number of hauls with varying fishing conditions, so that the results obtained are explicitly comparable. This methodology allows to compare the consequences of enforcing different codend designs on fisheries, with much less costs than carrying out experimental fishing trips.

This study indicates that when using PRESEMO to predict the selectivity of a given codend in a given fishery, one should first carry out a parameter validation. This should include a comparison of the simulated results with a reference set of experimental selectivity data from that fishery. Then, predictions can be made on the selectivity of other codends with different technical characteristics. PRESEMO and FEMNET are "structural models", based on the understanding of the underlying physical and biological processes, thus, these can be used to make predictions outside the range of conditions against which they were verified. This is their main advantage over the empirical models that have been generally used in selectivity studies and which should not be extrapolated. Nevertheless, one must be cautious when using PRESEMO. Some of the parameter values used, particularly when modelling behaviour, are no more than best guesses, and may not be accurate if the conditions differ considerably from the reference cases used in the verification process.

This study demonstrates how PRESEMO and FEMNET together with a limited set of sea trial results can be used as a fishery management tool to predict the effect of enforcing different technical regulations in a specific fishery.

Discards, catch efficiency and increase in effort when applying new codend designs can be quantified. The study could be completed with an economic study and studies of fishery management scenarios in order to verify the impact on the fishery. Also the potential best codend designs found should be tested at sea in order to validate or precise the results.

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