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Estimating selectivity of experimental diamond (T0) and turned mesh (T90) codends in multi-species Mediterranean bottom trawl

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Abstract

This paper evaluates the effect of changing from a diamond mesh codend (T0) to a 90° turned mesh codend (T90) on the size selectivity of seven commercially important species in the Mediterranean bottom trawl fishery. In sea trials conducted in the north-western Adriatic, two experimental codends made of 54 mm nominal mesh size netting and differing only in mesh configuration were alternately mounted on the same trawl. Overall, the T90 mesh significantly improved codend size selection for all the species analysed. The difference in the predicted average L50 values between the T90 and T0 codend was particularly marked in European hake (*Merluccius merluccius*, 21.26 vs 11.26 cm total length), common squid (*Loligo vulgaris*, 12.06 vs 7.88 cm mantle length) and mantis shrimp (*Squilla mantis*, 20.78 vs 13.35 mm carapace length). Both codends showed an excessive size selectivity, which involves a commercial loss, especially for red mullet (*Mullus barbatus*), Mediterranean horse mackerel (*Trachurus mediterraneus*) and whiting (*Merlangius merlangus*). These findings demonstrate the efficiency of the T90 configuration in excluding undersized specimens, especially of hake, whose average L50 was above the minimum conservation reference size of 20 cm. The adoption of this practical and inexpensive solution can contribute to improve the management of the demersal resources targeted by the Mediterranean bottom trawl fishery.

Keywords: Selectivity; bottom trawling; mesh configuration; T90 turned mesh; experimental codends; Mediterranean demersal fishery.

Introduction

Bottom trawling in the Mediterranean Sea is conducted by numerous fishing vessels (FAO, 2018), which target a wide range of commercially important species (Lucchetti, 2008). However, this fishery involves high discard rates (20-65% of the total catch, according to Tsagarakis *et al.* (2014)) of organisms with low or no commercial value (benthic invertebrates) but also of individuals of commercial species under the minimum conservation reference size (MCRS; Tsagarakis *et al.,* 2017). The bycatch of undersized specimens induces significant effects on the population dynamics of the main demersal species and contributes to the unsustainable exploitation of more than 80% of the demersal stocks assessed in the region (GFCM, 2018).

In the past few decades, the scientific community has been working to reduce bycatch and juvenile mortality by increasing trawl net selectivity. Most of the selectivity experiments have focused on changing the mesh size and configuration in the codend (STECF, 2015) , rarely in the extension piece (Sola & Maynou, 2018; Bonanomi *et al.,* 2020). All other net parameters being equal, a larger mesh clearly improves size selectivity (Ragonese *et al.,* 2001; Sala & Lucchetti, 2011; Dereli & Aydin, 2016). With regard to mesh configuration, it has conclusively been demonstrated that compared with a diamond mesh (DM) codend, a square mesh (SM) codend reduces the catch of juveniles, hence discards (Özbilgin *et al.,* 2005; Bahamon *et al.,* 2006; Guijarro & Massutí, 2006; Ordines *et al.,* 2006; Sardà *et al.,* 2006; Lucchetti, 2008; Sala *et al.,* 2008; Deval *et al.,* 2009; Sala & Lucchetti, 2010). The legal codend mesh size of Mediterranean bottom trawls is currently 40 mm (SM), or 50 mm (DM) at the duly justified request from the shipowner (EU, 2019). In contrast, relatively little research has been conducted to assess the selectivity of the T90 turned mesh codend in the Mediterranean Sea. This configuration is obtained by turning a typical diamond netting by 90°; as a result, its meshes remain more open under the weight of the catch, enabling smaller specimens to escape (Madsen *et al.,* 2012). Most of the work on the T90 mesh has been conducted by comparing it to a standard DM codend in Turkish waters (Tokaç *et al.,* 2014; Dereli & Aydin, 2016; Dereli *et al.,* 2016; Deval *et al.,* 2016; Ilkyaz *et al.,* 2017; Genç *et al.,* 2018; Kaykac *et al.,* 2018).

The T90 codend, like the SM codend, generally provides greater selectivity than the DM codend (Tokaç *et al.,* 2014; Deval *et al.,* 2016) even though its size selection properties vary according to the cross-sectional morphology of target species (Herrmann *et al.,* 2013; Tokaç *et al.,* 2014; Bayse *et al.,* 2016). In recent years, other practical advantages of this configuration have attracted the attention of the scientific community, particularly the fact that no netting is lost when constructing T90 panels, whereas SM panels involve cutting the corners of a standard panel (Herrmann, 2009, 2010, 2011). The T90 codend is mentioned in no regulation regarding Mediterranean fisheries, whereas it is included in Regulation EC 2187/2005 (EU, 2005) for the Baltic Sea cod (*Gadus morhua*) trawl fishery as an alternative to the BACOMA codend (Wienbeck *et al.,* 2011).

Given these premises, a study was devised to investigate the selectivity of a T90 codend towards some commercially important species targeted by the Mediterranean bottom trawl fishery. We tested two experimental codends obtained from the same netting panel: a DM (T0) and a T90 codend. Since the selectivity data of legal codends were inadequate for European hake (STECF, 2015; Mytilineou *et al.,* 2020), which is the main target species for this *mètier* in the Mediterranean Sea (Angelini *et al.,* 2016; Sion *et al.,* 2019), we tested a slightly larger mesh size. A nominal 54 mm mesh size was selected to avoid an excessive divergence from commercial trawling conditions.

Materials and Methods

Sea trials and data collection

The study was carried out in FAO Geographical Sub-Area 17 (North-western Adriatic Sea). This area, which is characterized by a wide and shallow continental shelf mainly consisting of sandy-muddy sediments, is intensively exploited by bottom trawlers (Colloca *et al.,* 2017; Bargione *et al.,* 2019). The trials were conducted 7-10 nm off the coast of Senigallia (central Italy; Fig. 1) at a depth of about 30 m in the course of a 6-day survey that was conducted from 28th October to 9th November 2019 on board R/V "G. Dallaporta" (810 kW at 1650 rpm, Length Over All 35.30 m, Gross Tonnage 285 GT).

The gear used in the experiments was a typical commercial trawl employed in the area. It was entirely made of knotless polyamide (PA) netting (see Sala *et al.* (2008) and Sala & Lucchetti (2011) for trawl design). The length from the wing tips to the codend was approximately 60 m, with 600 meshes in the top panel at the footrope level. The T0 and T90 codends were made of the same netting material (knotless PA, nominal mesh size 54 mm) and had the same dimensions (i.e. length and circumference, Table 1). The codend mesh size was measured with an OMEGA gauge (Fonteyne *et al.*, 2007) at 50 N while the netting was wet (Table 1). The two codends were alternately mounted on the same trawl (alternate paired haul design).

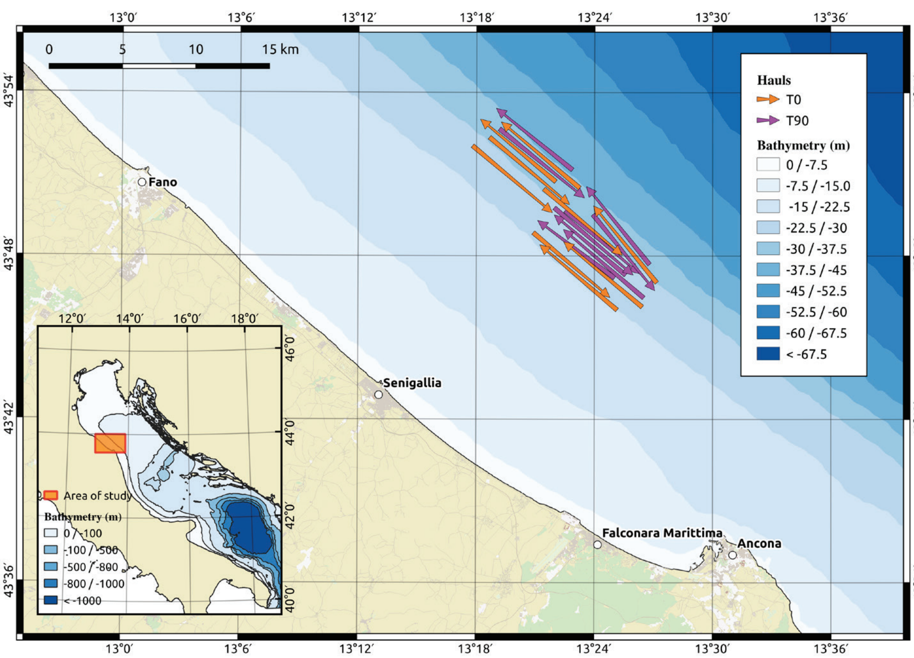

Fig. 1: Map of the area where the sea trials were conducted in the Adriatic Sea in October and November 2019. All 18 hauls are represented (orange arrows, T0 codend; purple arrows, T90 codend).

Table 1. Main characteristics of the two codends and of the cover used in the sea trials. (s.e. = standard error).

	T0 Codend	T90 Codend	Cover
Nominal mesh opening [mm]	54	54	20
Mean mesh opening (ICES gauge) [mm]	55.2 ± 0.2	55.3 ± 0.2	-
Netting material	PA	PA	PA
Circumference mesh number	222	222	1050
Stretched length [m]	5	5	10

All hauls were performed in daylight with a standard towing duration of 1 hour at an average towing speed of 3.7 knots (range 3.5-3.8 knots). Gear performance (horizontal and vertical net opening) was monitored using acoustic sensors (SIMRAD, Norway). A codend cover, made from the same PA netting but having a 20 mm nominal mesh opening, was used to collect the fish escaping from the codend (covered codend technique) (Wileman *et al.,* 1996). The cover was supported by circular hoops, to keep it clear of the codend and minimize masking effects, and was about 1.5 times larger and longer than the codend, as recommended by Stewart & Robertson (1985). The catches of the codend and the cover of each haul were kept separate. All taxa were identified to the lowest possible level and the respective weight was recorded. For the most abundant species found in the catch, reflecting the main target species in the area, total length (TL, cm) for fish, mantle length (ML, cm) for cephalopods and carapace length (CL, mm) for crustaceans were measured, to obtain data for the size selectivity analysis. In case of large catches (mostly of horse mackerel *Trachurus mediterraneus,* which often exceeded 150 - 200 individuals per haul), measurements were conducted on a randomly selected subsample.

Data analysis

Catch data

The gear performance (horizontal and vertical opening) and the difference in the total catch of each codend were analysed by the Kruskal-Wallis H test ($\chi 2$). The catch per unit effort ($CPUE_w$) was computed for the most abundant species and standardized as mean weight per hour of tow. The number of specimens of each 0.5 cm length class (fish and cephalopods) and of each 0.5 mm length class (crustaceans) found in the cover and the codend in each haul and their subsampling ratios were obtained for the species of which at least 200 individuals had been measured for length.

Size selectivity

The catch data, i.e. the number of individuals in the codend and the cover for each length class caught in each haul and the relevant subsampling ratios, were used for the size selectivity analysis, which was implemented in the software tool SELNET (Herrmann *et al.,* 2012).

The experimental design (covered codend technique) enabled analysing the catch data as binominal data: the individuals retained either by the cover or by the codend were used to estimate the length-dependent retention probability in the codend, i.e. its size selection properties. The probability of finding an individual of length l in a codend in haul j was expressed by the function $r_j(l)$. The values of this function for all relevant sizes were estimated separately for each species as described below.

Within the same codend (T0 or T90), the value of $r_j(l)$ was expected to vary (Fryer, 1991) between hauls. In this study, we determined the length-dependent values of $r(l)$ averaged over hauls, assuming that the information provided would describe the average consequences for the size selection process when applying the two different codend configurations in a commercial fishery (Millar, 1993).

Estimation of the average size selection over hauls $r_{av}(l)$ involved pooling data from the different hauls (Herrmann *et al.*, 2012). Since different parametric models for $r_{av}(l)$ were tested, we wrote $r_{av}(l,_v)$, which included the vector $\boldsymbol{v}$ consisting of the parameters of the model. The aim of the analysis was to estimate the values of the parameter $\boldsymbol{v}$ that made the experimental data (averaged over hauls) most likely to be observed, assuming that the model was able to describe the data sufficiently well. Therefore, the average size selectivity of the codend was estimated by minimizing the following expression with respect to parameters $\boldsymbol{v}$:

$$-\sum_{j=1}^{m}\sum_{l}\left\{\frac{nR_{jl}}{qR_j}\times ln\big(r_{av}(l,\boldsymbol{v})\big)+\frac{nE_{jl}}{qE_j}\times ln\big(1.0-r_{av}(l,\boldsymbol{v})\big)\right\} \quad (1)$$

The outer summation is over m hauls conducted and the inner summation is over length classes l. $nRjl$ and $nEjl$ are respectively the length-dependent numbers of length measured specimens retained in the codend and escaping to the cover. qRj and qEj are the sampling factors for the fraction of the specimen length measured in the codend and the cover, respectively. Minimizing expression (1) is equivalent to maximizing the likelihood for the observed data in the form of $nRjl$ versus $nEjl$.

We considered five models to describe for each codend and species: Logit, Probit, Gompertz, Richards and Poly4. The first three models are fully described by the two selection parameters L50 (length of an individual that has a 50% probability of being retained) and SR (difference in length between individuals that have 75% and 25% probability of being retained, respectively). The Richards model requires an additional parameter (1/δ) that describes the asymmetry of the curve. The formulas for the first four classic selection models are reported below (2), according to Wileman *et al.* (1996). We also considered a group of flexible models (Poly4) to model the codend size selection:

$$
r_{av}(l,\boldsymbol{v}) = \begin{cases} Logit(l, L50, SR) = \dfrac{exp\left(\frac{ln(9)}{SR}\times(l-L50)\right)}{1.0+exp\left(\frac{ln(9)}{SR}\times(l-L50)\right)} \\ Probit(l, L50, SR) \approx \left(\dfrac{exp\left(\frac{1.349}{SR}(l-L50)\right)}{1+exp\left(\frac{1.349}{SR}(l-L50)\right)}\right) \\ Gompertz(l, L50, SR) \approx \exp\left(-\exp\left(-\left(0.3665+\frac{1.573}{SR}(l-L_{50})\right)\right)\right) \\ Richards\left(l, L50, SR, \frac{1}{\delta}\right) = \left(\dfrac{\exp\left(logit(0.5^{\delta})+\left(\frac{logit(0.75^{\delta})-logit(0.25^{\delta})}{SR}\right)*(l-L_{50})\right)}{1+\exp\left(logit(0.5^{\delta})+\left(\frac{logit(0.75^{\delta})-logit(0.25^{\delta})}{SR}\right)*(l-L_{50})\right)}\right)^{\frac{1}{\delta}} \\ Poly4(l,\boldsymbol{v}) = \dfrac{exp\left(v_0+v_1\times\frac{l}{100}+v_2\times\frac{l^2}{100^2}+v_3\times\frac{l^3}{100^3}+v_4\times\frac{l^4}{100^4}\right)}{1.0+exp\left(v_0+v_1\times\frac{l}{100}+v_2\times\frac{l^2}{100^2}+v_3\times\frac{l^3}{100^3}+v_4\times\frac{l^4}{100^4}\right)} \end{cases} \quad (2)
$$

As regards the Poly4 model, leaving out one or more of parameters $v_0 \ldots v_4$ in equation (2) provided 31 additional models that were also considered as potential models to describe .

The ability of the size selection models to describe the experimental data was evaluated by calculating the corresponding p-value, which expresses the likelihood of obtaining at least as large a discrepancy between the fitted model and the experimental data by coincidence. The lower limit for the selection model for an adequate description of the experimental data is 0.05 (Wileman *et al.,* 1996). In case of poor-fit statistics (p-value < 0.05), the residuals were inspected to determine whether it was due to structural problems when modelling the experimental data or to overdispersion in the data (Wileman *et al.,* 1996). The best of the five models considered in (1) was selected based on the Akaike information criterion (AIC; Akaike, 1974) by choosing the one with the lowest AIC value.

Once a size selection model was identified for a particular species and codend, a double bootstrap method was used to estimate the confidence limits for the size selection curve and the associated parameters. This bootstrapping approach is identical to the one described by Millar (1993) and accounts for both within-haul and between-haul variation. The hauls of each codend were used to define a group of hauls. An outer bootstrap resample with replacement from the group of hauls was included in the procedure, to account for between-haul variation. Within each resampled haul, an inner bootstrap was used on data for each length class, to account for within-haul variation. The dataset obtained from each bootstrap repetition was then analyzed using the identified selection model, resulting in an average selection curve. For each species analysed, 1000 bootstrap repetitions were performed to estimate the Efron percentile 95% confidence intervals (CIs; Efron, 1982) for the selection curve and the selection parameters.

Finally, a method based on bootstrap files separately obtained (described by Larsen *et al.* (2018)) was used to examine the length-dependent differences between the selection curves of the two codends (T90 and T0), which were quantified as differences (delta) in retention probability.

Results

Catch data

A total number of 18 valid hauls (9 with each codend) were carried out (Table 2). No significant differences were found between the horizontal (H = 1.193; p = 0.273) and vertical (H = 1.648; p = 0.193) opening of the net tested with the two codends.

The total catch retained in the codend was comparable for both gears (H = 0.329; p = 0.566). The mean weight ($CPUE_w$) of the catch of the most abundant species is reported in Table 3. With both codend configurations, Atlantic mackerel (*Scomber scombrus*), grey mullet (*Mugil cephalus*), mantis shrimp (*Squilla mantis*), European hake (*Merluccius merluccius)*, tub gurnard (*Chelidonichthys lucernus*) and common squid (*Loligo vulgaris*) accounted for the largest catches found in the codend (> 500 g/h of tow). The most abundant species caught in the cover (> 1000 g/h of tow) were European anchovy (*Engraulis encrasicolus*), European pilchard (*Sardina pilchardus*), Mediterranean horse mackerel (*T. mediterraneus*), red mullet (*Mullus barbatus*) and Atlantic mackerel (*S. scombrus*).

Size selectivity

The data thus collected allowed analysing the size selection properties of the two codends for seven target species for this fishery: Atlantic mackerel (*S. scombrus*), European hake (*M. merluccius*), red mullet (*M. barbatus*), Mediterranean horse mackerel (*T. mediterraneus*), mantis shrimp *(S. mantis*)*,* common squid (*L. vulgaris*) and whiting (*Merlangius merlangus*)*.* The summary of the individuals of each species measured in the codend and the cover in each haul is reported in Table 4 together with the subsampling ratios of the total catch.

The AIC values obtained from the five models considered (2) for each species and codend are compared in Table 5. Model selection was based on the lowest AIC values: the Richards model was the one selected most commonly (5 cases), followed by the Probit (3 cases) and the Gompertz, Logit and Poly4 models (2 cases).

The size selection parameters and fit statistics were calculated using the model selected for each species and codend type (Table 6). The resulting selectivity curves and their CIs are represented in Figures 2 and 3. Inspection of the p-values revealed that the experimental data were adequately described by the selected models with the only exception of *S. scombrus* – T0 configuration (p-value = 0.02); nevertheless, the inspection of the modelled curve against the experimental rates did not indicate any length-dependent pattern in the deviation observed (Fig. 2A). Therefore, the low p-value was assumed to be due to overdispersion in the experimental rates rather

Table 2. Hauls performed during the cruise. (HNO = Horizontal Net Opening; VNO = Vertical Net Opening; s.e. = standard error).

ID haul	Codend type	Latitude		Longitude		Mean depth [m]	Mean HNO [m]	Mean VNO [m]	Mean speed [knots]	Codend catch [kg]	Cover catch [kg]
		Start	End	Start	End						
1	T90	43°47.19’	43°49.30’	13°25.02’	13°21.11’	27.3 ± 0.1	17.27 ± 0.29	1.84 ± 0.03	3.52 ± 0.04	16.10	54.80
2	T90	43°49.66’	43°47.35’	13°22.51’	13°26.29’	31.5 ± 0.4			3.59 ± 0.04	13.94	46.14
3	T90	43°47.30’	43°49.50’	13°25.58’	13°21.95’	29.4 ± 0.3			3.57 ± 0.02	13.50	42.14
4	T90	43°47.69’	43°50.55’	13°26.80’	13°23.59’	37.2 ± 3.2	16.15 ± 0.18	2.12 ± 0.03	3.63 ± 0.02	22.62	21.68
5	T90	43°51.16’	43°53.32’	13°22.88’	13°19.01’	39.7 ± 0.5			3.79 ± 0.05	43.08	93.10
6	T90	43°52.66’	43°50.13’	13°19.16’	13°23.49’	36.6 ± 0.4			3.92 ± 0.02	28.00	44.58
7	T90	43°49.52’	43°46.72’	13°23.91’	13°27.07’	32.8 ± 3.3			3.64 ± 0.10	21.90	80.12
8	T90	43°46.47’	43°48.97’	13°26.50’	13°22.42’	28.7 ± 0.5	17.25 ± 0.20	1.28 ± 0.03	3.77 ± 0.02	20.72	28.54
9	T90	43°49.77’	43°47.30’	13°21.96’	13°25.97’	30.9 ± 0.4			3.70 ± 0.04	16.78	28.99
10	T0	43°47.02’	43°49.85’	13°27.17’	13°23.95’	35.1 ± 3.3	16.33 ± 0.21	1.78 ± 0.04	3.70 ± 0.02	24.32	29.90
11	T0	43°50.49’	43°52.92’	13°23.25’	13°19.26’	38.2 ± 0.2			3.72 ± 0.05	30.12	12.10
12	T0	43°46.13’	43°48.53’	13°26.43’	13°22.44’	27.3 ± 0.4	16.67 ± 0.38	1.86 ± 0.06	3.76 ± 0.03	39.52	54.90
13	T0	43°50.73’	43°53.02’	13°22.03’	13°18.20’	35.8 ± 0.4			3.70 ± 0.03	22.50	17.00
14	T0	43°52.36’	43°49.89’	13°18.66’	13°22.74’	33.9 ± 0.1			3.76 ± 0.03	25.08	18.26
15	T0	43°52.04’	43°49.59’	13°17.79’	13°21.87’	30.2 ± 0.1			3.74 ± 0.02	21.02	14.30
16	T0	43°48.86’	43°46.48’	13°20.89’	13°24.79’	25.2 ± 0.4			3.72 ± 0.05	14.42	11.96
17	T0	43°46.02’	43°48.41’	13°25.15’	13°21.22’	24.5 ± 0.5			3.78 ± 0.03	8.66	49.48
18	T0	43°50.46’	43°48.03’	13°21.42’	13°25.42’	32.8 ± 0.3			3.83 ± 0.02	19.54	25.96

than to a poor ability to model the size selection.

The change from the T0 to the T90 codend resulted in an increase in the predicted average L50 value for most of the species analysed (*S. scombrus, M. merluccius, S. mantis, L. vulgaris*) and in a general reduction in the average SR (Table 6), which reflected a higher slope of the selection curves (Figure 2 A-B, D-E; Figure 3 A-B, D-E). With the change from the T0 to the T90 mesh, *T. mediterraneus* and *M. merlangius* displayed a slight reduction in the average L50 value but a marked reduction in the average SR (Table 6; Fig. 2 L-M; Fig. 3 G-H). In contrast, *M. barbatus* exhibited increased average L50 as well as SR values (Table 6; Fig. 2 G-H).

The delta plots (Fig.s 2 and 3, right column) show the difference in length-dependent retention probability of the two codends. In all the species analysed, the CIs for the curve in the delta plot did not contain 0.0 for some length classes, thus demonstrating a significant difference between the two selectivity curves. In most cases the CIs were < 0.0, meaning that the T90 codend had a lower retention rate, hence better size selection properties, than the T0 codend.

For *S. scombrus,* the length range where the CIs were < 0.0. was 16 - 20 cm and included the MCRS of 18 cm (Fig. 2C). As regards *M. merluccius*, the T90 mesh was significantly more selective for a wider size range (0 - 23 cm), which included the MCRS of 20 cm (Fig. 2F). The results were different for *M. barbatus*, since the lower retention probability of the T90 codend was significantly above 16 cm, while the MCRS of the species is 11 cm

Table 3. Mean catch weight (grams) ± standard error per towing hour of the most abundant species caught in the T90 and T0 codends and covers during the cruise. The species in bold are the ones chosen for the selectivity analysis.

	T0 Codend	T0 Cover	T90 Codend	T90 Cover
Alloteuthis media	266.9 ± 23.8	933.7 ± 89.1	180.3 ± 32.7	785.0 ± 116.6
Arnoglossus laterna	96.5 ± 21.4	87.3 ± 20.6	110.9 ± 43.1	79.9 ± 15.2
Boops boops	49.6 ± 11.0	867.0 ± 398.3	32.0 ± 8.0	838.9 ± 116.6
Chelidonichthys lucernus	708.9 ± 130.3	0.0	976.9 ± 149.2	143.0 ± 0.0
Citharus linguatula	37.5 ± 10.3	354.7 ± 86.0	100.9 ± 34.2	222.7 ± 88.7
Eledone spp.	460.0 ± 0.0	0.0	162.7 ± 0.0	0.0
Engraulis encrasicolus	160 ± 45.6	9059.7 ± 4190.0	585.2 ± 238.5	25554.8 ± 7126.0
Gobius niger	74.1 ± 15.8	293.6 ± 41.9	64.5 ± 44.5	469.6 ± 130.0
Illex coindetii	135 ± 49.2	116.3 ± 57.1	24.8 ± 7.3	76.1 ± 13.5
Loligo vulgaris	**726.7 ± 252.0**	**327.1 ± 142.0**	**639.4 ± 121.6**	**825.0 ± 291.5**
Melicertus kerathurus	285.9 ± 64.3	48.3 ± 20.0	311.8 ± 105.2	74.3 ± 28.7
Merlangius merlangus	**402.2 ± 88.7**	**567.3 ± 101.6**	**404.4 ± 126.1**	**1022.6 ± 264.3**
Merluccius merluccius	**1191.1 ± 352.7**	**258.0 ± 79.6**	**569.9 ± 107.6**	**220.4 ± 62.3**
Mugil cephalus	1080.0 ± 0.0	0.0	3000.0 ± 1500.0	0.0
Mullus barbatus	**795.6 ± 94.8**	**3581.3 ± 435.3**	**452.0 ± 106.0**	**3042.9 ± 348.9**
Octopus vulgaris	1060.0 ± 0.0	0.0	426.0 ± 0.0	0.0
Pagellus erythrinus	148.9 ± 48.4	461.5 ± 126.6	180.8 ± 65.2	692.0 ± 193.1
Sardina pilchardus	151.2 ± 47.9	3278.7 ± 1023.0	408.1 ± 191.8	3188.2 ± 899.1
Scomber colias	0.0	0.0	200.0 ± 0.0	139.8 ± 44.2
Scomber scombrus	**2828.9 ± 560.5**	**2383.9 ± 1403.7**	**2623.3 ± 1170.9**	**1034.0 ± 278.2**
Sepia officinalis	409.1 ± 116.4	29.3 ± 5.2	492.8 ± 120.7	31.1 ± 8.2
Solea solea	130.0 ± 30.0	0.0	246.8 ± 50.0	0.0
Sparus aurata	120.0 ± 0.0	0.0	303.3 ± 183.7	0.0
Spicara flexuosa	16.3 ± 2.3	131.8 ± 28.3	62.5 ± 17.5	86.4 ± 24.8
Squilla mantis	**1908.0 ± 244.5**	**52.8 ± 11.7**	**729.5 ± 166.6**	**98.2 ± 20.8**
Trachurus mediterraneus	**300.0 ± 80.1**	**2979.8 ± 532.0**	**763.6 ± 176.3**	**10035.9 ± 2068.3**

(Fig. 2I). *T. mediterraneus* displayed an unusual trend: the T90 codend was significantly more selective than the T0 configuration from 13 to 20 cm of length, which includes the MCRS (15 cm), whereas it was significantly less selective above 23 cm (Fig. 2N). The latter result may be explained by the absence of measured individuals of lengths > 23 cm in the T0 codend, which may have prevented the effective model prediction of the selection curve for that size range. With regard to the other three species, which do not have an MCRS (Fig. 3), the T90 codend exhibited a significantly greater selectivity for some length classes (*S. mantis,* 0 - 26 mm, Fig. 3C; *L. vulgaris*, 9 - 13 cm, Fig. 3F; *M. merlangius*, 0 - 21 cm, Fig. 3I).

Discussion

The T90 mesh configuration has attracted the interest of the researchers who, after the introduction of the Landing Obligation (EU, 2013), are working to identify technical solutions to reduce discards. In fact, the T90 mesh provides selectivity advantages that can be obtained in a simple way (Herrmann, 2009). Its improved size selection compared with the DM, documented in northern European fisheries (Wienbeck *et al.,* 2011), and its ease of application and repair compared with the SM (Moderhak, 1995) have the potential to help its diffusion in the Mediterranean fishing industry. Its larger cross-section and more limited flow and turbulence may also reduce the risk of damaging the more delicate fish species (e.g. haddock), thus improving their quality (Hansen, 2004; Digre *et al.*, 2010). This is the first study comparing the selectivity of an experimental 54 mm DM codend (T0) and a 54 mm 90° turned mesh codend (T90) for seven commercially important species in the Adriatic bottom trawl fishery.

There are no size selectivity studies for Atlantic mackerel in the Mediterranean bottom trawl fishery. We found predicted L50 values above the MCRS (18 cm) (EU, 2006) with both configurations. The significantly better selection properties of the T90 codend, at least for some length classes, may be explained by the round body shape of Atlantic mackerel, which is more likely to go through the T90 than the DM (Tokaç *et al.,* 2014).

Selectivity data for European hake are important for stock management. For the first time, we report an aver-

Table 4. Number of individuals from the codend and cover of the species chosen for the selectivity analysis, measured for each haul. Values in parentheses represent the subsampling coefficients.

Haul	Codend	*S. scombrus*		*M. merluccius*		*M. barbatus*		*T. mediterraneus*		*S. mantis*		*L. vulgaris*		*M. merlangus*	
		Codend	*Cover*	*Codend*	*Cover*	*Codend*	*Cover*	*Codend*	*Cover*	*Codend*	*Cover*	*Codend*	*Cover*	*Codend*	*Cover*
1	T90	9 (1)	16 (1)	1 (1)	1 (1)	22 (1)	170 (1)	7 (1)	190 (0.3)	-	-	10 (1)	9 (1)	6 (1)	17 (1)
2	T90	5 (1)	1 (1)	3 (1)	2 (0.4)	5 (1)	150 (1)	14 (1)	269 (0.4)	-	-	10 (1)	85 (1)	6 (1)	5 (0.4)
3	T90	30 (1)	11 (1)	2 (1)	4 (1)	15 (1)	221 (1)	24 (1)	165 (0.3)	-	-	20 (1)	34 (1)	4 (1)	17 (1)
4	T90	32 (1)	5 (1)	4 (1)	5 (1)	8 (1)	43 (1)	18 (1)	178 (0.6)	-	-	10 (1)	7 (1)	3 (1)	14 (1)
5	T90	32 (0.3)	44 (1)	16 (1)	17 (1)	-	-	3 (1)	98 (0.2)	53 (1)	10 (1)	9 (1)	5 (1)	17 (1)	52 (1)
6	T90	14 (1)	18 (1)	7 (1)	4 (1)	50 (1)	278 (1)	0 (1)	150 (0.3)	33 (1)	6 (1)	6 (1)	3 (1)	3 (1)	10 (1)
7	T90	10 (1)	7 (1)	2 (1)	4 (1)	22 (1)	139 (1)	7 (1)	115 (0.2)	15 (1)	2 (1)	25 (1)	35 (1)	2 (1)	12 (1)
8	T90	14 (1)	9 (1)	0 (1)	1 (1)	9 (1)	260 (1)	5 (1)	200 (1)	17 (1)	3 (1)	16 (1)	12 (1)	3 (1)	8 (1)
9	T90	11 (1)	6 (1)	2 (1)	3 (1)	1 (1)	221 (1)	5 (1)	155 (1)	29 (1)	5 (1)	1 (1)	14 (1)	2 (1)	12 (1)
10	T0	58 (1)	148 (0.6)	8 (1)	0 (1)	24 (1)	243 (1)	4 (1)	98 (1)	110 (1)	0 (1)	11 (1)	2 (1)	5 (1)	2 (0.6)
11	T0	9 (1)	0 (1)	46 (1)	17 (1)	17 (1)	151 (1)	3 (1)	115 (1)	64 (1)	2 (1)	19 (1)	7 (1)	6 (1)	10 (1)
12	T0	47 (1)	13 (1)	7 (1)	1 (1)	21 (1)	304 (1)	8 (1)	203 (1)	37 (1)	3 (1)	50 (1)	11 (1)	2 (1)	10 (1)
13	T0	45 (1)	11 (1)	11 (1)	7 (1)	22 (1)	139 (1)	5 (1)	138 (1)	57 (1)	2 (1)	5 (1)	1 (1)	11 (1)	16 (1)
14	T0	39 (1)	5 (1)	23 (1)	5 (1)	29 (1)	193 (1)	5 (1)	188 (1)	48 (1)	5 (1)	1 (1)	0 (1)	11 (1)	19 (1)
15	T0	22 (1)	5 (1)	8 (1)	2 (1)	22 (1)	205 (1)	3 (1)	271 (1)	59 (1)	2 (1)	4 (1)	0 (1)	2 (1)	8 (1)
16	T0	14 (1)	5 (1)	1 (1)	1 (1)	13 (1)	123 (1)	7 (1)	160 (1)	52 (1)	4 (1)	17 (1)	9 (1)	4 (1)	1 (1)
17	T0	10 (1)	43 (1)	5 (1)	3 (1)	6 (1)	140 (1)	12 (1)	483 (1)	28 (1)	2 (1)	20 (1)	29 (1)	2 (1)	10 (1)
18	T0	24 (1)	24 (1)	18 (1)	13 (1)	22 (1)	213 (1)	23 (1)	356 (0.6)	25 (1)	1 (0.6)	3 (1)	2 (1)	7 (1)	19 (1)

Table 5. Summary of the AIC values (Akaike, 1974) derived from the selectivity models. The values in bold represent the lowest values for each species, indicating the model subsequently selected for the analyses.

		Logit	Probit	Gompertz	Richards	Poly4
S. scombrus	*T0*	572.33	575.56	593.23	570.02	**565.17**
	T90	304.16	302.72	**305.90**	306.12	-
M. merluccius	*T0*	186.27	185.61	186.97	**185.35**	-
	T90	93.32	93.43	95.07	**91.72**	-
M. barbatus	*T0*	892.60	898.13	908.76	**891.14**	-
	T90	874.57	**874.49**	874.51	876.50	-
T. mediterraneus	*T0*	**534.83**	537.03	539.39	535.48	-
	T90	678.87	701.00	717.74	671.48	**638.83**
S. mantis	*T0*	142.05	**140.76**	143.22	142.07	-
	T90	107.95	108.59	**106.68**	108.82	-
L. vulgaris	*T0*	231.57	**231.27**	232.46	231.31	-
	T90	378.26	378.30	380.67	**374.95**	-
M. merlangus	*T0*	**186.99**	187.12	187.64	187.21	-
	T90	200.84	201.55	202.98	**200.48**	-

Table 6. Selectivity parameters and fit statistics for the seven species, sampled in the T0 and T90 codends, analysed based on the selected model. SR: selection range; DOF: degrees of freedom. Values in parentheses are the Efron 95% confidence intervals.

		L50	SR	p-value	Deviance	DOF
S. scombrus	*T0*	21.37 (18.31 - 22.67)	3.57 (0.01 - 5.76)	0.0167	47.46	29
	T90	22.08 (21.41 - 23.23)	2.72 (1.73 - 3.71)	0.9380	15.14	25
M. merluccius	*T0*	11.26 (1.3 - 14.82)	21.33 (13.72 - 44.36)	0.7802	28.33	35
	T90	21.26 (19.67 - 25.11)	7.02 (3.91 - 10.61)	0.2768	29.78	26
M. barbatus	*T0*	16.70 (16.31 - 17.31)	2.78 (2.27 - 4.77)	0.8287	16.59	23
	T90	23.10 (18.74 - 31.80)	11.48 (7.63 - 19.03)	0.4937	24.45	25
T. mediterraneus	*T0*	24.99 (22.72 - 28.25)	8.03 (5.76 - 10.55)	0.0513	48.47	34
	T90	22.32 (21.65 - 23.07)	1.66 (1.14 - 2.93)	0.0715	49.10	36
S. mantis	*T0*	13.35 (7.53 - 17.62)	8.86 (5.40 - 13.28)	0.9162	32.59	45
	T90	20.78 (18.79 - 22.27)	4.36 (2.38 - 7.42)	0.9447	21.96	34
L. vulgaris	*T0*	7.88 (0.33 - 10.00)	5.67 (2.41 - 14.77)	0.5600	15.49	17
	T90	12.06 (10.05 - 13.36)	4.94 (3.08 - 7.82)	0.6288	16.42	19
M. merlangus	*T0*	23.02 (20.29 - 59.07)	12.86 (6.16 - 100.00)	0.1704	27.01	21
	T90	22.88 (22.18 - 24.83)	3.92 (2.45 - 7.55)	0.2799	22.09	19

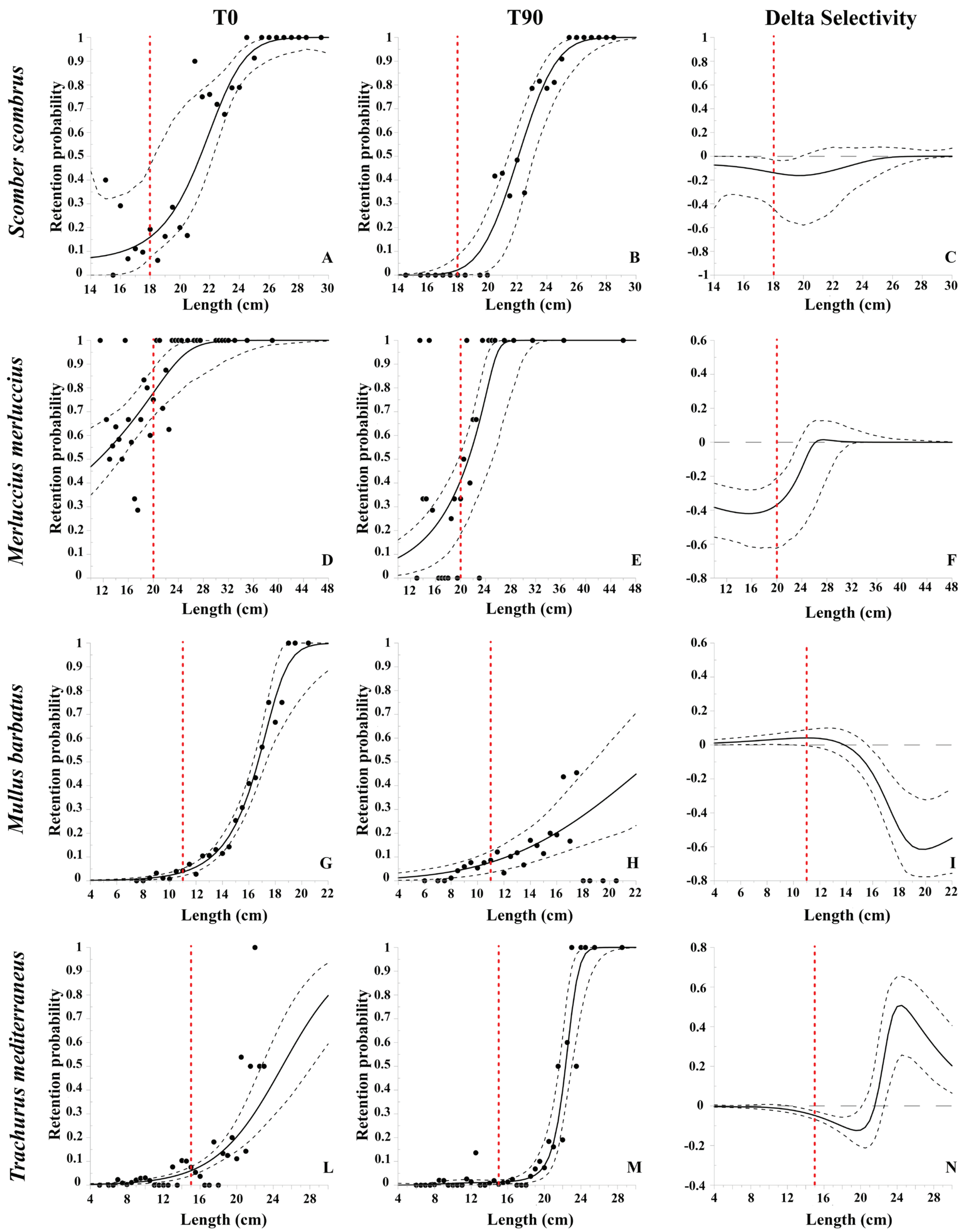

Fig. 2: Selectivity diagrams for *Scomber scombrus* (A, B, C), *Merluccius merluccius* (D, E, F), *Mullus barbatus* (G, H, I) and *Trachurus mediterraneus* (L, M, N). The first two columns show the size selectivity curves (full lines) with the confidence intervals (dashed lines) together with the experimental retention data (black dots) obtained with the T0 (A, D, G, L) and the T90 (B, E, H, M) codends. The right column shows the delta selectivity curve (full line) with confidence intervals (dashed lines), representing the differences between the curves of the two codends for each species.

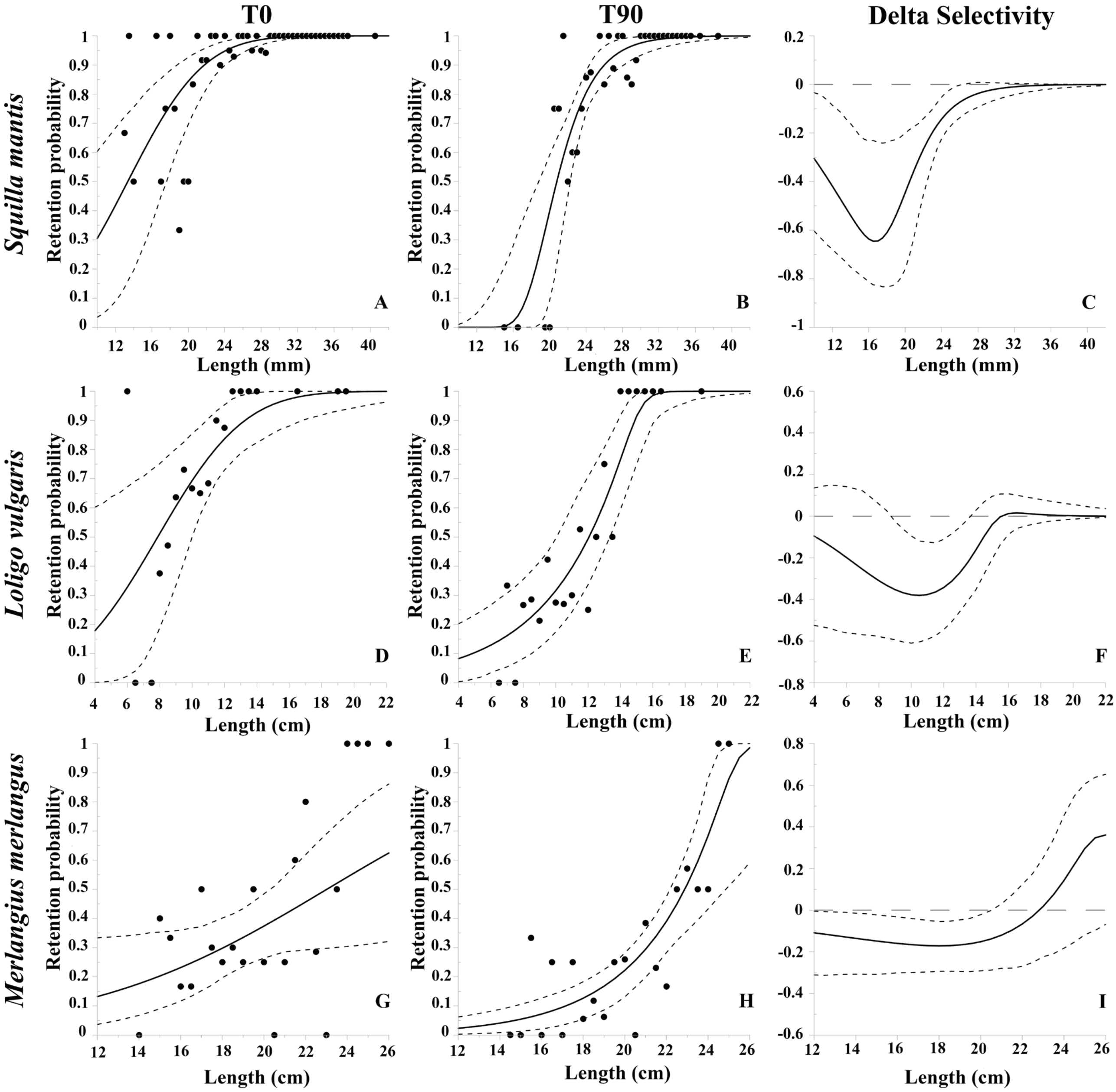

Fig. 3: Selectivity diagrams for *Squilla mantis* (A, B, C), *Loligo vulgaris* (D, E, F) and *Merlangius merlangus* (G, H, I). The first two columns show the size selectivity curves (full lines) with confidence intervals (dashed lines) and the experimental retention data (black dots) obtained with the T0 (A, D, G,) and the T90 (B, E, H) codends. The right column shows the delta selectivity curve (full line) with confidence intervals (dashed lines) representing the differences between the curves of the two codends for each species.

age L50 value above the MCRS of 20 cm (STECF, 2015), obtained with the T90 configuration, whereas the higher values reported in the literature have been obtained with a 60 mm DM (19.50 cm, Aldebert & Carries, 1991; 16.64 cm, Soldo, 2004; 18.10 cm, Belcari *et al.,* 2007). The size selection properties of the T90 mesh described herein are much greater than those found by Genç *et al.* (2018), who tested a 40 mm and 44 mm mesh (average L50 values, 12 - 13 cm). To our knowledge, no other published data on the selectivity of the T90 mesh are available for this species. We found that the selectivity for European hake strongly depended on mesh configuration. The poor size selectivity of the T0 mesh, found in this study, contrasts with the data reported by Sala & Lucchetti (2011) with a 56 mm DM. The authors found that reducing the number of meshes in the codend circumference from 280 to 240 involved an increase in L50 from 11.99 ± 1.50 to 16.25 ± 0.63 cm. In theory, the even lower number of meshes (222) used in our T0 codend should have involved a higher L50 for European hake (Sala & Lucchetti, 2011). The most likely explanation is that, at the high catch rates encountered, closing of the mesh holes occurred; as a result, our SR was much wider than those found by Sala & Lucchetti (2011) thus clearly indicating a nonselective net. In contrast, the T90 meshes may have closed less tightly under the weight of the catch, resulting in an average L50 greater than 20 cm, thus efficiently excluding hake juveniles.

The 54 mm nominal mesh size was excessively selective for red mullet and Mediterranean horse mackerel regardless of the mesh configuration, being inefficient at retaining specimens of commercial size. In fact, the size selection process with both codends often occurred at lengths greater than the MCRS of the two species. These data agree with those reported for red mullet by Sala *et al.* (2015), who found that even the current legal codend mesh sizes (40 mm SM and 50 mm DM) led to a predicted L50 value that was higher than the MCRS (11 cm). The same is true of Mediterranean horse mackerel, where an average L50 of 15.60 cm (MCRS, 15 cm) and an SR of 5.50 cm have been described by Tosunoğlu *et al.* (2008) a 50 mm DM. Moreover, Dereli & Aydin (2016) have found that L50 increased from a 50 mm DM (12.9 cm for *M. barbatus*, 14.2 cm for *T. trachurus*) to a 40 mm T90 mesh (13.6 cm for *M. barbatus*, 17.1 cm for *T. trachurus*), demonstrating how a 40 mm turned mesh already avoids catching undersized individuals.

Mantis shrimp, common squid and whiting are major species targeted by the Adriatic bottom trawl fishery and have no MCRS (EU, 2006). Mantis shrimp is especially abundant in the north-western Adriatic (Sánchez *et al.,* 2007). In our study the T90 codend proved to be more effective than the T0 codend in avoiding smaller specimens (< 26 mm CL), which are usually discarded due to their scarce commercial value (Scarcella *et al.,* 2007). This is in line with the findings of a Mediterranean study (Deval *et al.,* 2016), where the comparison of a T0 and a T90 codend demonstrated a higher percentage of juvenile escapees of four crustacean species from the T90 gear. With regard to common squid, previous studies have shown how selectivity increased from a DM to a SM codend, since its body shape can be approximated to that of a round fish (Ordines *et al.,* 2006; Tosunoğlu *et al.,* 2009); similarly, in our study the L50 of squid was significantly higher in the T90 codend. Moreover, the average L50 value reported herein for the T90 codend is greater than the length at first maturity (LFM) of males (11 cm), but still well below the LFM of females (18.5 cm) according to Roper *et al.* (1984). However, since common squid caught with the current legal codend mesh size, though being mostly immature (Tosunoğlu *et al.,* 2009), are of high commercial value, the greater size selection provided by our T90 codend would result in significant economic losses. Commercially valuable whiting were also lost with both codends, since their average L50 values predicted in the present study are more than double those reported by Sala, *et al.* (2007) with a 44 mm DM codend.

In conclusion, the T90 codend provided significantly greater size selection for all the species analysed, at least for some length classes, compared with the traditional DM codend. Most of these species have a rounded body cross-section, for which the T90 codend consistently showed greater selection improvements, as reported in other studies (Wienbeck *et al.,* 2011; Herrmann *et al.,* 2013; Tokaç *et al.,* 2014; Bayse *et al.,* 2016; Kaykac *et al.,* 2018). In contrast, the 54 mm nominal mesh size used in our study was too large for red mullet, Mediterranean horse mackerel, common squid and whiting, which are key species targeted by the Adriatic bottom trawl fishery. The latter finding is unlikely to encourage the adoption of the codends tested, at least in the short term. Further work is needed to investigate the selection properties of the T90 mesh for flat fish such as common sole *Solea solea*, a major target species in the area. Notably, the present study did not test changing the number of meshes in the codend circumference. Although fewer meshes provide greater selectivity (Sala & Lucchetti, 2011), the combined effect of the T90 mesh and a reduced mesh number in the circumference, as assessed in the Baltic cod fishery (Herrmann *et al.,* 2007; Wienbeck *et al.,* 2011), is well worth exploring. Finally, factors such as the codend twine material, twine thickness (Madsen *et al.,* 2012) and catch size also have the potential to affect the selectivity of the T90 mesh.

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