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Effect of a lateral square-mesh panel on the catch pattern and catch efficiency in a Mediterranean bottom trawl fishery

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Abstract

The current legal codends used in Mediterranean bottom trawl fisheries are at high risk of retaining undersized individuals of several commercial fish species. This entails that codends alone are unable to provide the desired exploitation pattern. A simple technological measure that potentially can provide higher release efficiency of undersized fish are Square-Mesh Panels (SMPs). SMPs are often applied in the upper section of the trawl belly, just ahead the codend. However, recent studies in the Mediterranean have demonstrated that SMPs mounted in this position provided limited release efficiency, because very few fish came into contact with their meshes. In attempt to improve SMPs efficiency in the Mediterranean bottom trawl fisheries, we applied them on the lateral sides of the last tapered section of the trawl belly, just ahead of the codend, and fitted two guiding panels in the trawl belly to enhance fish-SMP contact. We compared the catch performance of a standard commercial trawl with a 52 mm diamond-mesh codend and of a similar trawl fitted with lateral SMPs (70 mm mesh size) in the belly using a twin trawl. The study focused on red mullet (*Mullus barbatus*), a commercially important species, but data for gurnard (*Chelidonichthys lucerna* and *Chelidonichthys cuculus*) were also obtained and analysed. In contrast to previous research on SMPs mounted in the top panel of the trawl, in this study SMPs induced a significant effect on catch performance for red mullet, demonstrating that their lateral position involved greater fish-SMP contact. However, since the test trawl lost a significant amount of legal-sized red mullet compared with the standard trawl, the effect was not wholly positive, possibly due to an excessively large mesh size. Therefore, future studies should be encouraged to test lateral SMPs with smaller mesh sizes.

Keywords: Mediterranean bottom trawl; square-mesh panels; release efficiency; exploitation pattern; discard.

Introduction

Multi-species trawl fisheries are known for often discarding substantial portions of undersized fish (Feekings *et al.,* 2012; Tsagarakis *et al.,* 2017). The main reasons include insufficiently selective fishing techniques, excess fishing effort, and the patchy distribution of target species (Johnsen & Eliasen, 2011; Sala & Lucchetti, 2011). In the past decades, numerous attempts have been made to improve fishing gear selectivity and to reduce the bycatch of undersize fish and discarding (Glass, 2000; Catchpole & Revill, 2008; Sala *et al.,* 2008; 2015; 2016; Brčić *et al.*, 2015; Santos et *al.,* 2016; Vitale *et al.,* 2018). It has been estimated that in the Mediterranean Sea about 19% of the catch is discarded, mostly by trawls (Tsagarakis *et al.,* 2014). Current regulations allow EU bottom trawlers operating in the Mediterranean to use either a 40 mm square mesh or a 50 mm diamond mesh in the codend (Council Regulation (EC) No. 1967/2006). However, a recent study (Brčić *et al.,* 2018) has predicted a high risk of retention of undersized individuals of several species with both mesh types, highlighting the need for additional measures, besides codend size selection, to improve the exploitation pattern of Mediterranean bottom trawls. Square-Mesh Panels (SMPs) are among the simplest technological measures that can be applied to bottom trawls when codend size selection alone does not prevent retention of undersized individuals. SMPs are used in many different fisheries over the world and are now mandatory in several EU fisheries (Suuronen & Sardà, 2007).

Although their effectiveness in the Mediterranean has extensively been evaluated (Özbilgin *et al.,* 2005; Metin *et al.,* 2005; Kaykac, 2010; Tokaç *et al.,* 2010), most studies have tested SMPs placed in the upper part of the tapered trawl belly or in the upper panel of the codend, often with unsatisfactory outcomes. Brčić *et al.* (2016) demonstrated that a 50 mm SMP fitted in the upper panel of a Mediterranean bottom trawl contributed little to overall release efficiency, a finding that according to the authors was probably due to the poor probability of contact between the fish and the SMP; indeed, a later study found that the contact probability never exceeded 9% for any of the species analysed (Brčić *et al.,* 2018). Similar results were obtained in the Bay of Biscay, where only 1-15% of the fish actually came into contact with the SMP as they drifted towards the codend (Alzorriz *et al.,* 2016).

SMP positioning is known to affect selectivity, hence bottom trawl exploitation patterns. For instance, Santos *et al.* (2016) found that SMPs mounted on the lateral sides of the trawl belly significantly improved the release efficiency of bottom trawls in western Galician waters. The present study was inspired by the findings of Santos *et al.* (2016) and was designed to establish whether SMPs fitted on the lateral sides of the trawl body can change the exploitation pattern of Mediterranean bottom trawls.

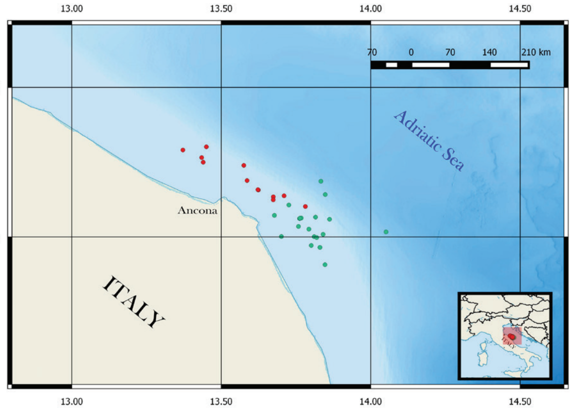

Fig. 1: Location of the fishing trials: red dots, R/V Dallaporta (RV); green dots, F/V Albatros Selvaggio (FV).

Materials and Methods

Fishing trials

Red mullet (*Mullus barbatus*) is a major commercial species in multi-species Mediterranean demersal trawl fisheries. In the past two decades several studies have investigated codend size selectivity for red mullet (Sala *et al.,* 2006; Özbilgin *et al.,* 2011; Sala *et al.,* 2015; Tokaç *et al.,* 2016). Furthermore, it is known, that SMP fitted in the top panel of a trawl does not efficiently release red mullet (Alzorriz *et al.*, 2016; Brčić *et al.*, 2016; 2018), therefore it is relevant to investigate whether placing it in a lateral position would lead to better performance for this species. Accordingly, in the present study, fishing grounds and periods were selected when red mullet would be abundant. Sea trials were conducted in the central Adriatic Sea in two different areas (Fig. 1): from 27th to 31st July 2015 on board the fishing vessel (F/V) Albatros Selvaggio (62 GT, 21.30 m LOA, 366.18 kW) between 43° 23’ 60” N 13° 40’ 12” E - 43° 40’ 48” N 14° 3’ 0” E and from 19th to 20th October 2016 and from 14th to 21st September 2017 on board the research vessel (R/V) G. Dallaporta (286 GT, 35.70 m LOA, 810 kW) between 43° 36’ 0” N 13° 25’ 48” – 43° 47’ 60” N 13° 46’ 48” E. Testing two vessel types in two areas aimed at identifying differences in SMP performance in different conditions and at investigating how diverse population size structures affected the trawl’s exploitation pattern. A typical twin trawl made of knotless polyamide with a low vertical opening was used for the trials (Fig. 2, Fig. S1). The test trawl was fitted with two 173-mesh long and 83-mesh wide SMPs (mesh size, 70 mm) mounted on the

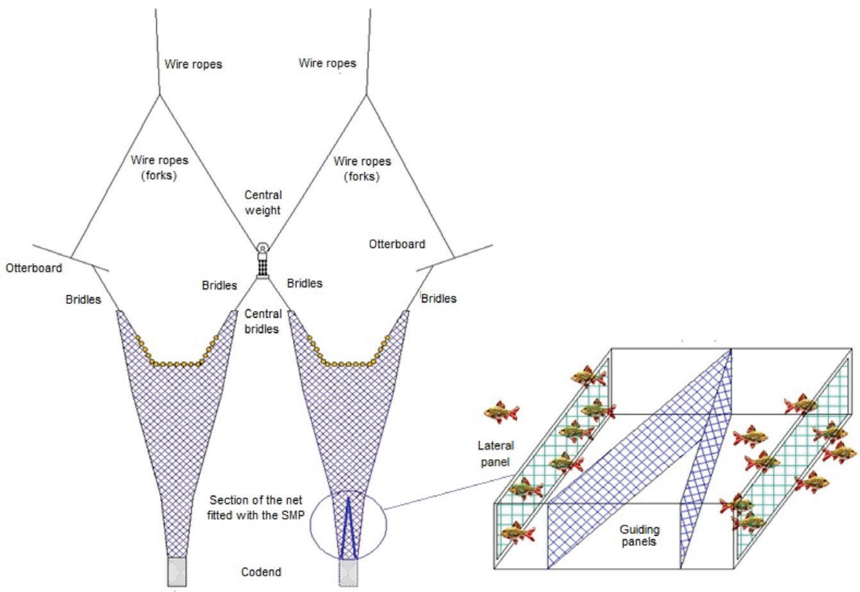

Fig. 2*:* Schematic drawing of the twin-trawl setup used in the study.

lateral sides of the last tapered section of the trawl belly, just ahead of the 52 mm diamond-mesh codend (Fig. 2, Fig. S1). Two guiding panels were also fitted in the trawl belly to enhance fish contact with the SMPs (Fig. 2). This design was adapted from the one described by Santos *et al.* (2016), who used long lateral SMPs supplemented with a pentagon-shaped device to guide the fish towards the SMPs. In the twin-trawl setup, the nets were equipped with 25 m long bridles made of combined rope (plastic and a central stainless-steel wire) and the footrope was rigged with ballast chains and a tickler chain. The horizontal opening of the net was provided by a single pair of Grilli AR cambered otterboards (length 1.80 m, weight in water, 320 kg); its vertical opening was ensured by floats and hydrodynamic devices (kites) applied to the upper edge (floatline) and by weights attached to the groundrope. The horizontal and vertical opening of the net was monitored by spread and height PX acoustic sensors (Simrad Spain Ltd) fitted to each net. Two further spread sensors were mounted on the otterboards, to monitor the horizontal door spread and ensure the correct gear deployment. The inner wings were attached to a central weight and a pulley, which were towed simultaneously with the otterboards by a wire fork. The headline and the footrope were respectively 32.8 m and 40.2 m long with a hanging ratio of 0.62 (horizontal hanging ratio, calculated as the length of the bosom divided by the length of the portion of stretched panel corresponding to the bosom).

After each haul, the catch from each trawl was sorted separately and the length of all fish or, in the case of large catches, a representative subsample, was measured to the nearest 0.5 cm.

Data analysis

A catch comparison and catch ratio analysis (Santos *et al.,* 2016; Herrmann *et al.,* 2017) was performed to investigate the size dependent effect on the capture efficiency by introducing the lateral SMPs in the trawl. In addition, the catch pattern and profile of each trawl was quantified and compared for each fishing trip, to provide information for fisheries management. Three further types of analysis were performed: catch distribution analysis (total fish number in relation to length), cumulative catch weight analysis and gear usability indicator analysis. Each is described in detail below. All analyses were performed separately for red mullet and any other species caught in sufficient numbers to be included in the study. SELNET software (Herrmann *et al.,* 2012; 2017) was employed for all analyses.

Catch comparison and catch ratio analysis

The catch comparison and catch ratio were analysed separately for each species investigated and for each fishing trip as described by Herrmann *et al.* (2017), except that use of the twin trawl involved that in this study the data of each haul were collected in pairs (Fig. 2).

Let nT_l be the number of fish of length l of a given species retained by the codend of the test trawl, and nS_l the number of fish of length l of a given species retained by the codend of the standard trawl. The experimental length-dependent catch comparison rate can then be calculated as:

$$cc_l = \frac{\sum_{i=1}^{m} \left\{ \frac{nT_{li}}{qT_i} \right\}}{\sum_{i=1}^{m} \left\{ \frac{nT_{li}}{qT_i} + \frac{nS_{li}}{qS_i} \right\}} \tag{1}$$

The summation in (1) is over the m hauls conducted during a given cruise. qT_i and qS_i (hereafter sampling ratios) are the ratio of the measured to the total number of individuals retained by the test and the standard gear.

The experimental length-dependent catch comparison rate was modelled by:

$$cc(l,\boldsymbol{q}) = \frac{e^{f(l,\boldsymbol{q}_0,\ldots,\boldsymbol{q}_k)}}{1+e^{f(l,\boldsymbol{q}_0,\ldots,\boldsymbol{q}_k)}} \tag{2}$$

where f is a polynomial of order k with coefficients q_0 to q_k. The values of the parameters $\boldsymbol{q}$ describing $cc(l,\boldsymbol{q})$ are estimated by minimizing expression (3), which is equivalent to maximizing the likelihood of the observed data. f was considered to be up to an order of 4 with parameters q_0, q_1, q_2, q_3 and q_4. Leaving out one or more of parameters $q_0 \ldots q_4$ yielded 31 additional models that were also considered as potential models for the catch comparison rate $cc(l,\boldsymbol{q})$. Based on the 32 models the catch comparison rate was estimated using multi-model inference to obtain a combined model (Anderson & Burnham, 2002; Herrmann *et al.,* 2017).

$$-\sum_{l}\sum_{i=1}^{m}\left\{ \frac{nT_{li}}{qT_i} \times \ln\left(cc(l,\boldsymbol{q})\right) + \frac{nS_{li}}{qS_i} \times \ln\left(1 - cc(l,\boldsymbol{q})\right)\right\} \tag{3}$$

where the inner summation is over the m hauls conducted during the specific cruise, and outer summation is over length classes l in the experimental dataset. $cc(l,\boldsymbol{q})$ quantifies the probability that a fish of length l is retained by the codend of the test trawl, provided that it is retained in one of the trawls. When $cc(l) = 0.5$, a fish of length l has the same probability of being retained by either gear, which entails that the lateral SMPs would not affect the catch performance for a fish of that length.

The ability of the model to provide a good description of the data was based on the p-value, which expresses the likelihood of obtaining at least as large a discrepancy between the fitted model and the experimental data by coincidence and the model deviance versus the degrees of freedom (DOF). In case of poor-fit statistics (p-value < 0.05 and deviance/DOF $>> 1$), the residuals were inspected to determine whether this was due to structural problems or overdispersion in the data (Wileman *et al.,* 1996; Alzorriz *et al.,* 2016). The models were also evaluated by plotting the fitted curves against the experimental length-dependent catch comparison rates, to obtain a visual representation of whether the curves reflected the main trend in the experimental data.

Since $cc(l,\boldsymbol{q})$ cannot be used to quantify directly the catch efficiency of the test relative to the standard trawl (Herrmann *et al.,* 2017), we used a length-dependent catch ratio ($cr(l)$), which can be derived from the $cc(l,\boldsymbol{q})$ (Veiga-Malta *et al.,* 2019):

$$cr(l,\boldsymbol{q})=\frac{cc(l,\boldsymbol{q})}{1-cc(l,\boldsymbol{q})} \tag{4}$$

If $cr(l,\boldsymbol{q}) = 1.0$, the two trawls are equally efficient in catching fish of length l, i.e. the SMPs do not affect catch efficiency. In contrast, if $cr(l,\boldsymbol{q}) = 0.75$, then the experimental trawl catches only 75% of the fish of length l compared with the standard trawl.

Uncertainties for the $cc(l,\boldsymbol{q})$ and the $cr(l,\boldsymbol{q})$ curves were quantified in terms of Efron 95% percentile confidence intervals (CIs) (Efron, 1982), which were estimated using a double bootstrap method with 1000 repetitions (Veiga-Malta *et al.,* 2019). This approach accounts for between- and within-haul variation in catch efficiency as well as for uncertainty in model selection by multi-model inference in each bootstrap.

Potential differences in catch ratios (hereafter referred to as delta) between cruises were investigated as described by Veiga-Malta *et al.* (2019). Specifically:

$$\Delta cr(l,\boldsymbol{q})_{FV-RV}=cr(l,\boldsymbol{q})_{FV}-cr(l,\boldsymbol{q})_{RV} \tag{5}$$

The uncertainty for $\Delta cr\,(l,\boldsymbol{q})_{FV-RV}$ was estimated based on the populations of bootstrap results for $cr(l,\boldsymbol{q})_{FV}$ and $cr(l,\boldsymbol{q})_{RV}$. Since resampling for $cr(l,\boldsymbol{q})_{FV}$ and $cr(l,\boldsymbol{q})_{RV}$ was independent, it was possible to create a new population of bootstrap results for $\Delta cr\,(l,\boldsymbol{q})_{FV-RV}$ accordingly:

$$\Delta cr(l,\boldsymbol{q})_{FV-RVi}=cr(l,\boldsymbol{q})_{FVi}-cr(l,\boldsymbol{q})_{RVi}\; i\in[1,\ldots,1000] \tag{6}$$

where i is the bootstrap iteration index. This new population of 1000 bootstrap results was then used to obtain the 95% CI for $\Delta cr(l,\boldsymbol{q})_{FV-RV.}$

Catch distribution analysis

Summed catch population curves were estimated for each gear and fishing trip as follows:

$$NX_l=\sum_{i=1}^{m}\left\{\frac{nX_{il}}{qX_i}\right\} \tag{7}$$

where nX_{il} and qX_i represent nT_{il} and qT_i if the estimation is made for the test trawl, or nS_{il} and qS_i if it is made for the standard trawl. The summations of i are over the m hauls conducted during a given cruise. 95% CI's were estimated for catch population curves using the double bootstrap method reported above. The delta approach mentioned above was used to infer whether there was a significant difference in the catch population curves of the two gears.

Cumulative catch weight analysis

Cumulative catch weight analysis was performed by estimating the proportion (in weight) of a total catch up to a given length class L (Veiga-Malta *et al.,* 2019):

$$CDF_w(L)=\frac{\sum_{i=1}^{m}\sum_{l=0}^{L}\left\{\frac{a\times l^b\times nX_{il}}{qX_i}\right\}}{\sum_{i=1}^{m}\sum_{l}\left\{\frac{a\times l^b\times nX_{il}}{qX_i}\right\}} \tag{8}$$

where nX_{il} and qX_i represent nT_{il} and qT_i if the estimation is made for the test trawl, or nS_{il} and qS_i if it is made for the standard trawl. The summations of i and l in (8) are over the m hauls conducted during a given cruise and length *classes* l, respectively. Estimation of the 95% CI of $CDF_w(L)$ with the double bootstrap method then allowed estimating potential differences between the *CDF*s ($\Delta CDF_w(l)_{test\text{-}standard}$) of the test and the standard trawl. The 95% CI for $\Delta CDF_w(l)_{test\text{-}standard}$ was estimated by the same approach as for $\Delta CR(l,\boldsymbol{q})_{FV\text{-}RV}$.

Gear usability indicator analysis

Gear usability indicators for catch comparison data were used to summarize the performance of the two gears and their relative performance. Most of the indicators were adopted from Veiga-Malta *et al.* (2019). Since only red mullet is subject to the Minimum Conservation Reference Size (MCRS) (11 cm), different indicators were used for red mullet and the other species that was caught in sufficient numbers. For the red mullet, the average percentage of individuals below and above MCRS retained by test, compared to standard trawl, both in terms of numbers (*nP-, nP+*) and weights (*wP-, wP+*) were estimated as follows:

$$nP-=\frac{\sum_{i=1}^{m}\left\{\sum_{l<MCRS}\frac{nT_{il}}{qT_i}\right\}}{\sum_{i=1}^{m}\left\{\sum_{l<MCRS}\frac{nS_{il}}{qS_i}\right\}} \tag{9}$$

$$nP+=\frac{\sum_{i=1}^{m}\left\{\sum_{l\geq MCRS}\frac{nT_{il}}{qT_i}\right\}}{\sum_{i=1}^{m}\left\{\sum_{l\geq MCRS}\frac{nS_{il}}{qS_i}\right\}} \tag{10}$$

$$wP-=\frac{\sum_{i=1}^{m}\left\{\sum_{l<MCRS}\frac{nT_{il}}{qT_i}\times\left(a\times l^b\right)\right\}}{\sum_{i=1}^{m}\left\{\sum_{l<MCRS}\frac{nS_{il}}{qS_i}\times\left(a\times l^b\right)\right\}} \tag{11}$$

$$wP+=\frac{\sum_{i=1}^{m}\left\{\sum_{l\geq MCRS}\frac{nT_{il}}{qT_i}\times\left(a\times l^b\right)\right\}}{\sum_{i=1}^{m}\left\{\sum_{l\geq MCRS}\frac{nS_{il}}{qS_i}\times\left(a\times l^b\right)\right\}} \tag{12}$$

The summations of i and l in (9), (10), (11) and (12) are over the hauls m and length *classes* l, respectively. An indicator value of 100% would entail that the test trawl caught an equal number and weight of individuals under (*nP-*, *wP-*) and above (*nP+*, *wP+*) the MCRS, respectively compared to the standard trawl. *nP-* and *wP-* values should preferably be as close to 0% as possible, whereas *nP+* and *wP+* should be as high as possible (close to 100% or higher).

Furthermore, discard ratios were estimated for each gear in terms of number (*ndRatio*) and weight (*wdRatio*), as follows:

$$nDRatio = 100 \times \frac{\sum_{i=1}^{m} \left\{ \sum_{l<MCRS} \frac{nX_{il}}{qX_i} \right\}}{\sum_{i=1}^{m} \left\{ \sum_{l} \frac{nX_{il}}{qX_i} \right\}} \tag{13}$$

$$wDRatio = 100 \times \frac{\sum_{i=1}^{m} \left\{ \sum_{l<MCRS} \frac{nX_{il}}{qX_i} \times \left(a \times l^b\right) \right\}}{\sum_{i=1}^{m} \left\{ \sum_{l} \frac{nX_{il}}{qX_i} \times \left(a \times l^b\right) \right\}} \tag{14}$$

where nX_{il} and qX_i represent nT_{il} and qT_i if the estimation is made for the test trawl, or nS_{il} and qS_i if it is made for the standard trawl. The summations of i and l are over the hauls m and length *classes* l, respectively. a and b are length-weight relationship coefficients taken from Bolognini *et al.* (2013). The values of these indicators should preferably be equal to 0%, what would imply that no discarding is taking place.

For species not subject to the MCRS, the mean percentage of all individuals retained by the test compared to the standard trawl was estimated both in terms of number (*nPTotal*) and weight (*wPTotal*):

$$nPTotal = \frac{\sum_{i=1}^{m} \left\{ \sum_{l} \frac{nT_{il}}{qT_i} \right\}}{\sum_{i=1}^{m} \left\{ \sum_{l} \frac{nS_{il}}{qS_i} \right\}} \tag{15}$$

$$wPTotal = \frac{\sum_{i=1}^{m} \left\{ \sum_{l} \frac{nT_{il}}{qT_i} \times \left(a \times l^b\right) \right\}}{\sum_{i=1}^{m} \left\{ \sum_{l} \frac{nS_{il}}{qS_i} \times \left(a \times l^b\right) \right\}} \tag{16}$$

A value of 100% would mean that the test trawl catches the same total number (*nPTotal*) and weight (*wPTotal*) of the species analysed as the standard trawl. The 95% CI was estimated for each indicator using the double bootstrap method (Veiga-Malta *et al.,* 2019).

Results

A total of 33 valid hauls, 21 aboard the FV and 12 aboard the RV, were performed during the fishing trials. Towing duration ranged from 51 to 112 min (FV) and from 49 to 72 min (RV); towing speed ranged from 3.4 to 3.9 kn (FV) and from 3.3 to 3.9 kn (RV); bottom depth ranged from 15.7 to 76.3 m (FV) and from 22.5 to 42.0 m (RV). Apart from the red mullet, gurnards were also caught in sufficient numbers and they mainly consisted of *Chelidonichthys lucerna* and a small fraction of *Che-*

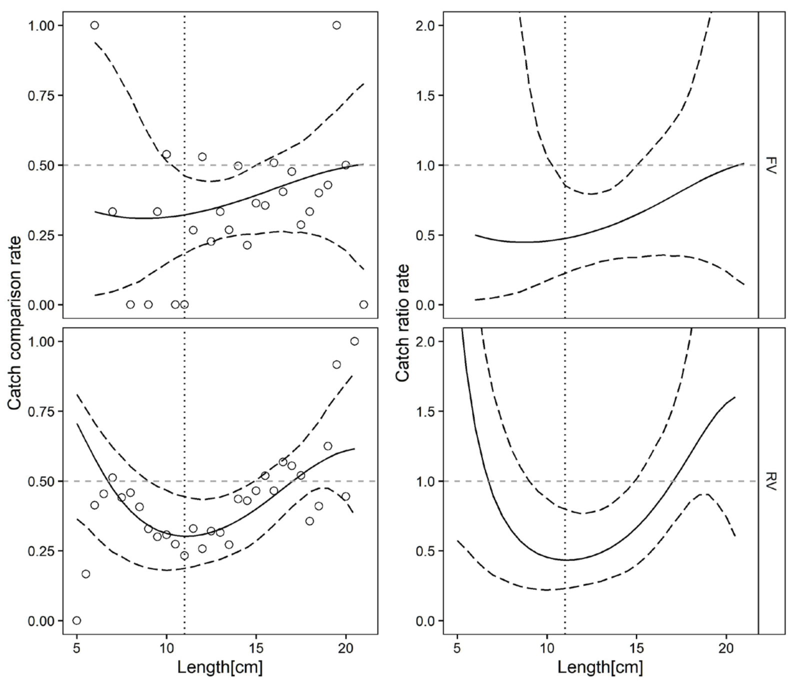

Fig. 3*:* Catch comparison rate (left) and catch ratio rate (right) for the test trawl compared to the standard trawl for red mullet (MUT) during fishing (FV) and the research vessel (RV) cruises. Circles: experimental rates. Dashed black curves: 95% CIs of the catch comparison and catch ratio curves. Horizontal grey dashed line: expected catch comparison (left) or catch ratio (right) rate in case of equal catch efficiency of the two trawls. Vertical dashed grey line: MCRS.

Table 1. Number (n) of fish length-measured per gear (test and standard) and per vessel (fishing vessel, FV and research vessel, RV). q represents the sampling factor. MUT: red mullet; GUR: gurnard.

Haul number	Vessel	MUT				GUR			
		Standard		Test		Standard		Test	
		n	q	n	q	n	q	n	q
1	FV	14	1.0000	4	1.0000	96	1.0000	86	1.0000
2		50	1.0000	4	1.0000	176	1.0000	158	1.0000
3		16	1.0000	1	1.0000	102	0.4000	98	0.5000
4		41	1.0000	27	1.0000	169	1.0000	129	1.0000
5		-	-	-	-	118	1.0000	61	1.0000
6		-	-	-	-	70	1.0000	79	1.0000
7		9	1.0000	17	1.0000	21	1.0000	32	1.0000
8		27	1.0000	12	1.0000	22	1.0000	37	1.0000
9		79	1.0000	74	1.0000	35	1.0000	29	1.0000
10		29	1.0000	24	1.0000	40	1.0000	106	1.0000
11		-	-	-	-	114	1.0000	92	1.0000
12		-	-	-	-	111	1.0000	78	1.0000
13		67	1.0000	55	1.0000	133	1.0000	90	0.5000
14		22	1.0000	22	1.0000	87	1.0000	67	1.0000
15		34	1.0000	3	1.0000	166	1.0000	87	1.0000
16		14	1.0000	3	1.0000	20	0.0700	105	1.0000
17		35	1.0000	7	1.0000	22	0.0700	69	1.0000
18		52	1.0000	18	1.0000	19	0.1000	72	0.4000
19		51	1.0000	81	1.0000	73	0.2000	55	0.2000
20		33	1.0000	1	1.0000	-	-	-	-
21		-	-	-	-	74	0.5000	63	1.0000
1	RV	93	0.2000	122	0.6000	-	-	-	-
2		-	-	-	-	41	1.0000	53	1.0000
3		11	1.0000	128	0.5000	101	1.0000	102	1.0000
4		140	1.0000	122	1.0000	113	1.0000	142	1.0000
5		1087	0.7000	794	0.3000	99	1.0000	120	1.0000
6		516	0.2000	484	1.0000	125	1.0000	82	1.0000
7		474	0.4	207	0.4	24	1.0000	25	1.0000
8		312	0.2	382	0.5	-	-	-	-
9		376	0.5	590	1	-	-	-	-
10		359	0.5	332	1	-	-	-	-
11		242	0.2	183	0.4	-	-	-	-
12		245	0.5	35	1	-	-	-	-

lidonichthys cuculus. Since these two species belong to the same family and have similar morphology, for practical reasons they were treated as one.

During the FV cruise, 353 and 573 red mullet and 2111 and 2917 gurnard were caught with the test and the standard trawl, respectively; during the RV cruises, 6409 and 10663 red mullet and 524 and 503 gurnard from the test and the standard trawl, respectively, were measured for length. Hake (*Merluccius merluccius*), common pandora (*Pagellus erythrinus*) and sole (*Solea solea*) were also caught, but they were too few to be included in the analyses. The number of red mullet and gurnard specimens found in the codend and measured for length is re-

Table 2. Fit statistics results for the catch comparison curves for red mullet (MUT) and gurnard (GUR). FV=fishing vessel; RV=research vessel; DOF: degrees of freedom.

Species	Vessel	*P*-Value	Deviance	DOF
MUT	FV	< 0.0001	65.52	22
	RV	< 0.0001	114.76	27
GUR	FV	0.0129	57.48	36
	RV	0.4867	25.57	26

ported in Table 1 according to haul, gear type and cruise.

The estimated catch comparison curve for red mullet reflects the main trend in the experimental data in a satisfactory way (Fig. 3). However, the *p*-values obtained for the model fit for the cruises of both vessels were lower than 0.05 (Table 2), but since there was no clear pattern in the deviations between the experimental points and the model curves, this was probably due to overdispersion in the data (Wileman *et al.,* 1996). This enabled the confident use of the models to assess the difference in length-dependent catch efficiency for red mullet between the test and the standard gear.

From the catch comparison and catch ratio curves (Fig. 3), a significant reduction of red mullet sizes from ~10 to ~15 cm in catches of test, compared to standard gear was observed. The FV and RV catch comparison and catch ratio curves exhibited a similar pattern (Fig. 3). The 95% CIs of the two curves were widest outside the bulk of the data, especially in the case of the FV cruise. A number reduction in the catches was found not only for the sizes under the MCRS but also for those above it, showing that the test gear caught fewer legal-sized fish than the standard gear. Comparison of the FV and RV catch ratio curves for red mullet showed no significant differences (Fig. 4). The *nP+* indicator values estimated for red mullet (Table 3) in both cruises showed that the experimental trawl caught respectively 62.57% and 54.14% of individuals above the MCRS compared with the standard gear. In both cases, the 95% CI of the indicator values did not contain 100, reflecting a statistically significant reduction. The *nP-* values also showed that the test gear had caught a smaller number of individuals under the MCRS compared to the standard gear in both cruises, but since the 95% CIs contained 100, the reduction was not statistically significant. A similar pattern was observed for the catch weight of red mullet in the test trawl compared with the standard gear under (*wP-*) and above (*wP+*) the MCRS (Table 3).

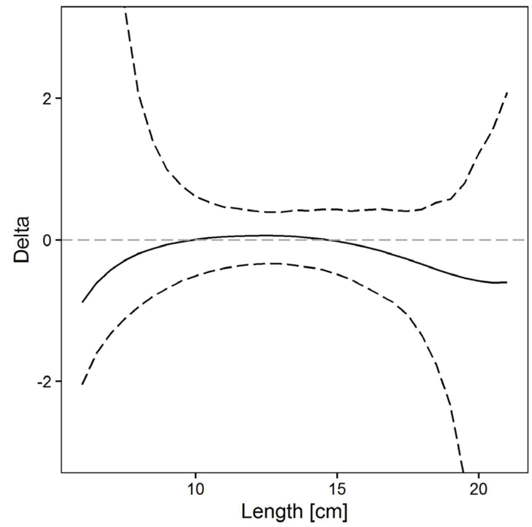

Fig. 4: Comparison of the fishing vessel (FV) and research vessel (RV) catch ratio curves for red mullet (MUT).

Table 3. Values of the exploitation pattern indicators (and 95% confidence intervals) for red mullet (MUT) and gurnard (GUR) caught by trawls towed by the fishing (FV) and the research vessel (RV). All values are percent.

Species	Vessel	Indicator	Mean (95% CI)
MUT	FV	*nP-*	42.86 (14.29-287.50)
		nP+	62.57 (36.74-93.91)
		ndRatioTest	3.40 (0.80-6.06)
		ndRatioStandard	4.89 (0.73-11.38)
		wP-	38.66 (14.75-162.03)
		wP+	65.73 (36.03-98.58)
		wdRatioTest	0.84 (0.16-1.70)
		wdRatioStandard	1.42 (0.30-3.18)
	RV	*nP-*	65.18 (27.73-125.28)
		nP+	54.14 (32.8-84.25)
		ndRatioTest	58.64 (39.00-69.53)
		ndRatioStandard	54.07 (46.17-61.90)
		wP-	57.47 (24.98-111.54)
		wP+	64.71 (40.64-97.27)
		wdRatioTest	22.25 (11.16-33.11)
		wdRatioStandard	24.37 (17.73-31.31)
GUR	FV	*nPTotal*	72.37 (57.12-91.50)
		wpTotal	73.43 (55.74-91.12)
	RV	*nPTotal*	104.18 (80.99-131.31)
		wpTotal	101.68 (78.92-130.95)

The size structure of the red mullet population caught by the trawls towed in the two cruises differed significantly, as clearly shown in Fig. 5 (upper left panel), which also demonstrates that both trawls of the RV cruises had a considerably higher risk of catching individuals under the MCRS. This directly impacted the discard ratio both in terms of number and of weight, which were estimated to be lower in the FV cruise than in the RV cruises. This difference is reflected in the mean cumulative catch weight curves shown in Fig. 5, where the intersection between the MCRS vertical line and the mean cumulative catch weight curves corresponds to the values of the *wdRatio*. The mean discard rate in weight (*wdRatio*) for the test and the standard gear was estimated to be respectively 22.25% and 24.37% in the RV cruises and only 0.84% and 1.42%, respectively, in the FV cruise. Since the 95% CIs estimated for the *wdRatio* indicators during FV and RV cruise did not overlap (Table 3), it can be argued that the average discard ratios were significantly lower in the FV cruise. The diagrams in Figure 5 also highlight significant differences between the mean cumulative catch weight curves of the test and the standard trawl for the RV cruises (delta curves).

The results obtained for gurnard were less clear. The estimated catch comparison curves for the FV and RV cruises reflected the main trend in the experimental data in a satisfactory way (Fig. 6). However, the *p*-value obtained for the model fit for gurnard in the FV cruise was less than 0.05 (Table 2), but no systematic pattern was observed after inspection of the residuals of fit. Therefore, in this case the poor-fit statistics can be attributed

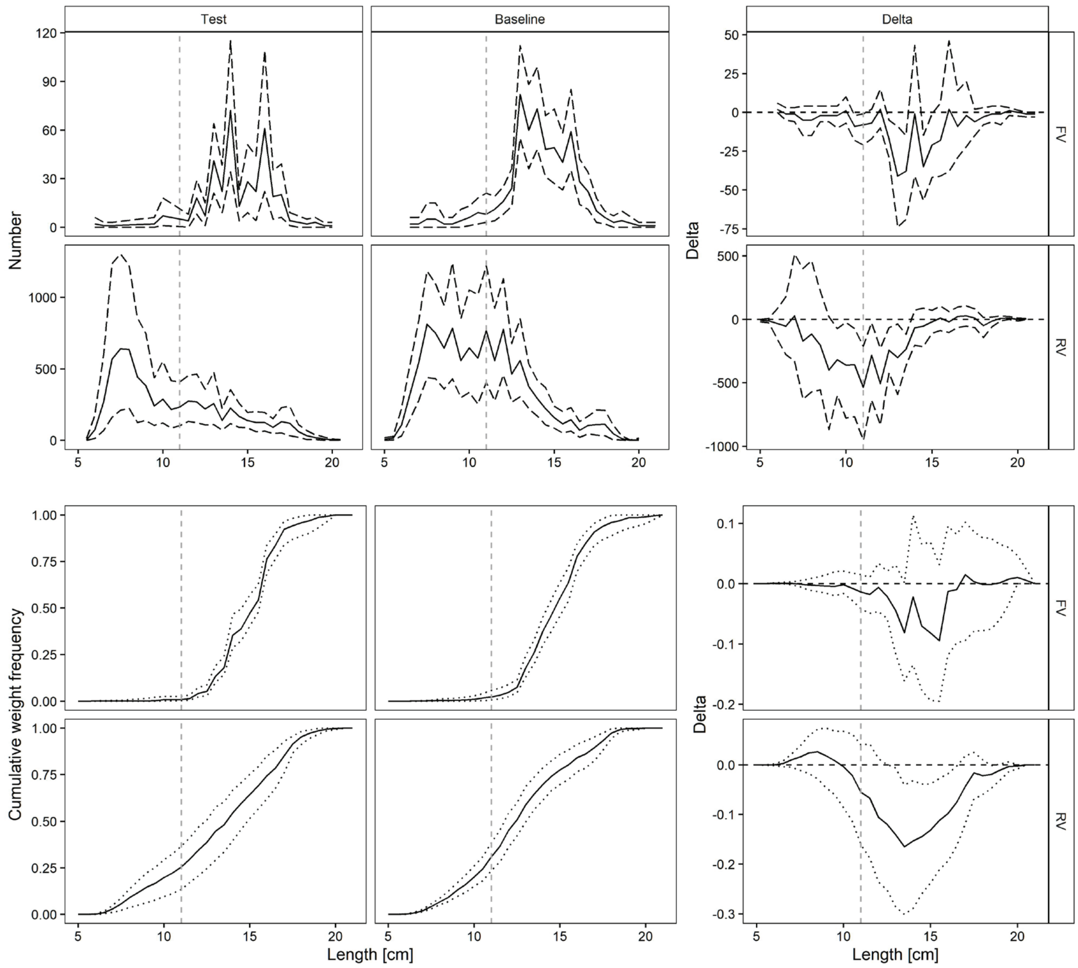

***Fig. 5**:* Comparison of the total red mullet (MUT) population, in terms of number (two top rows) and cumulative catch weight distribution (two bottom rows), retained by the test and the standard gear towed by the fishing (FV) and the research vessel (RV) and respective deltas. Vertical dashed grey line: MCRS. Dashed black curves: 95% CIs.

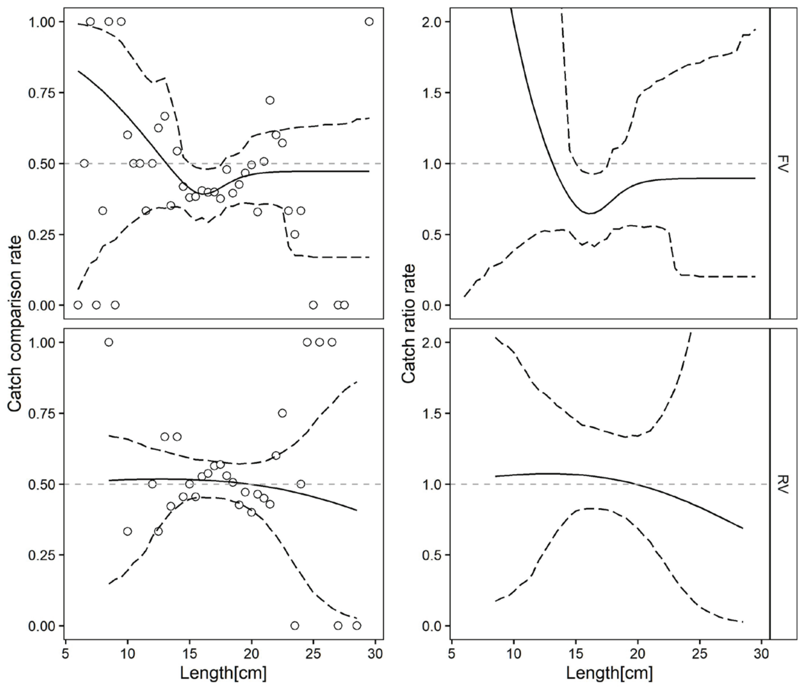

***Fig. 6**:* Catch comparison rate (left) and catch ratio rate (right) for the test trawl compared to the standard trawl for gurnard (GUR) during fishing (FV) and the research vessel (RV) cruises. Circles: experimental rates. Dashed black curves: 95% CIs of the catch comparison and catch ratio curves. Horizontal grey dashed line: expected catch comparison (left) or catch ratio (right) rate in case of equal catch efficiency of the two trawls.

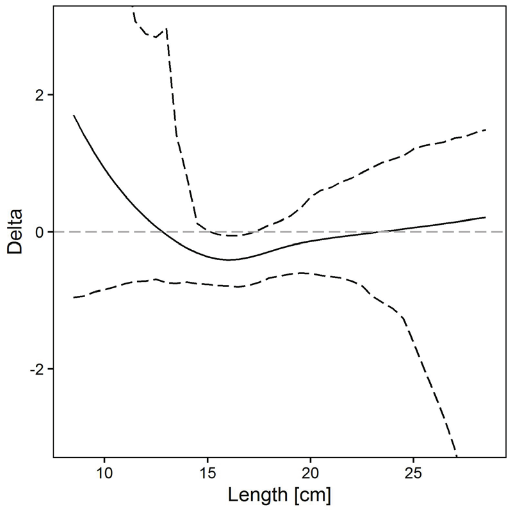

Fig 7: Comparison of the fishing vessel (FV) and research vessel (RV) catch ratio curves for gurnard (GUR).

to overdispersion in the data (Wileman *et al.,* 1996). The *p*-value obtained for the model fit for gurnard in the RV cruises exceeded 0.05 (Table 2) and there was no concern using the models to assess the difference in catch performance between the gears also for gurnard.

Inspection of the catch comparison and catch ratio curves demonstrated a significant reduction in the catches of the test gear towed by the FV, although only for a narrow length range (~15-17 cm). This pattern was not observed in the RV data. Compared to red mullet (Fig. 3), the catch comparison and catch ratio curves for gurnard had much wider 95% CIs, especially outside the bulk of the data (Fig. 6), but they showed a small but significant difference between the FV and RV catch ratio (delta) curves (Fig. 7). As regards the size distribution of the gurnard captured in the FV cruise, the test trawl caught on average fewer individuals compared to standard trawl (Fig. 8). This was confirmed and quantified by the values of *nPTotal* and *wPTotal*, which revealed that the test trawl captured on average 72.37% and 73.43% less gurnard in terms of both number and weight, respectively, compared with the standard trawl (Table 3). Since the 95% CIs of the *nPTotal* and *wPTotal* indicators did not contain 100, the difference was statistically significant. This pattern was not observed in the RV cruises (Table 3). Comparison of the cumulative catch weight (delta) curve failed to prove statistically significant differences (Fig. 8).

Discussion

In this present study, the catch efficiency of a bottom trawl equipped with 70 mm SMPs applied laterally in the last tapered section of the trawl belly was tested in a twin-

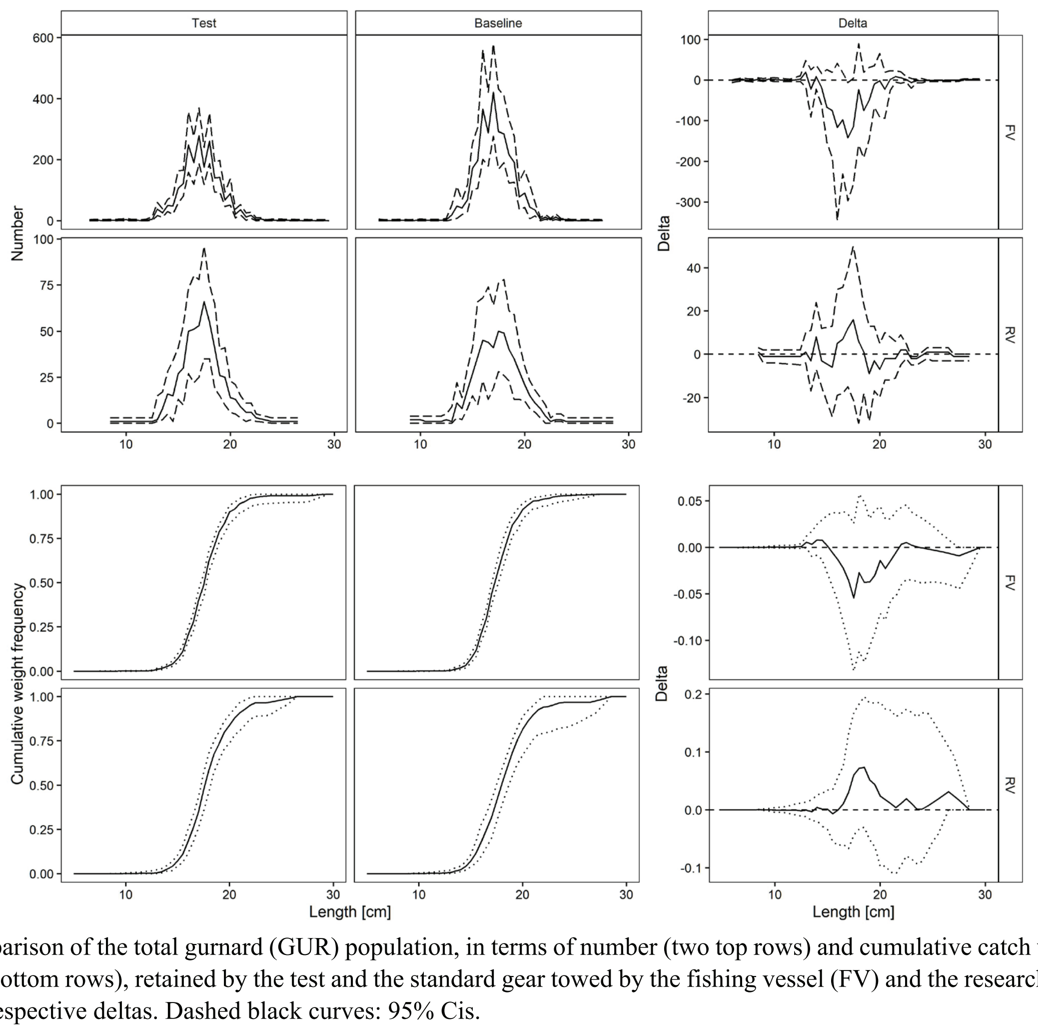

***Fig. 8**:* Comparison of the total gurnard (GUR) population, in terms of number (two top rows) and cumulative catch weight distribution (two bottom rows), retained by the test and the standard gear towed by the fishing vessel (FV) and the research vessel (RV) cruises and respective deltas. Dashed black curves: 95% Cis.

trawl setup in cruises performed on board a commercial fishing vessel (FV) and a research vessel (RV).

The results demonstrate that the SMPs significantly affected the catch performance for some red mullet sizes (from 10 to 15 cm) with both vessels, and for some gurnard sizes (from 15 to 17 cm) with the FV. The present data clearly show that fish did make contact with the SMPs and managed to escape through their meshes. However, outside the above-mentioned red mullet and gurnard length sizes, no significant difference in catch efficiency between the test and standard gear was detected for both species. This implies that those length sizes are either equally released or equally retained by the test and standard trawls. There is little available information on the selectivity of a 70 mm square mesh in Mediterranean bottom trawl fisheries. According to the predictions made by Tokaç *et al.* (2016), red mullet individuals up to at least 20 cm should be able to escape through the SMP meshes meaning that all individuals up to this size should have a greater probability of being retained in the standard trawl than the test trawl. However, analysis of the catch comparison and catch ratio curves demonstrated only a significant difference in the catch of individuals up to 15 cm. This is probably due to the angle at which the fish body comes into contact with the panel (angle of attack). Krag *et al.* (2014) showed that lower angles of attack reduce size selectivity in trawl. Since in the present study the SMPs were mounted in the low tapering section of the trawl belly, a fish drifting towards the codend will likely met them at a low angle of attack, thus potentially reducing SMP selectivity. Nonetheless, the catch efficiency of the two trawls was neither significantly different for smaller red mullet (< 10 cm) in all cruises nor for gurnard less than 15 cm long in the FV cruise. Considering that the codends of both trawls were made of the same netting and shared the same selection potential, most of the small fish that did not manage to escape through the SMP meshes were probably then released by the codend meshes of both trawls.

The effect of the guiding panels could not be quantified in this study. It can only be speculated that it may have enhanced the probability of fish-SMP contact and influenced the contact angle, but the scope of the study was not to test and quantify this effect. Nevertheless, the present data show that the lateral SMPs combined with the guiding panels significantly affected the catch pattern of the Mediterranean bottom trawl. Notably, the effect was not wholly positive, since the SMPs also released legal-sized red mullet. Further work is clearly warranted to investigate the effect of lateral SMPs with smaller mesh sizes before SMPs can be recommended to fishermen and fisheries managers (Soma *et al.,* 2018).

The results of this catch comparison and catch ratio analysis of the efficiency of a Mediterranean bottom trawl can be extrapolated to other fisheries that do not depend on fish population structure. In contrast, the results of catch distribution, cumulative catch weight and gear usability indicator analyses are population-dependent and cannot be extrapolated to other fisheries; they are nonetheless important, because they specifically quantified the consequences of fishing with each gear on the population structure fished. The results of all four analyses can provide fisheries managers with a much broader picture of the implications of using each of the two trawls.

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The following supplementary information is available for the article online:

Figure S1: Design of the trawl adopted in the study.