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

Sara BONANOMI1, Jure BRČIĆ2, Bent HERRMANN3,4, Emilio NOTTI1, Alessandro COLOMBELLI1, Fabrizio MORO1, Jacopo PULCINELLA1 and Antonello SALA1

1 Italian National Research Council (CNR), Institute of Marine Biological Resources and Biotechnologies (IRBIM), Largo Fiera della Pesca 1, 60125, Ancona, Italy
2 University of Split, Department of Marine Studies, Rudera Boškovića 37, 2100, Split, Croatia
3 The Arctic University of Norway UIT, Hansine Hansens veg 18, 9019, Tromsø, Norway
4 SINTEF Ocean, Fishing Gear Technology, Willemoesvej 2, 9850, Hirtshals, Denmark

Corresponding author: sara.bonanomi@cnr.it

Handling Editor: Stelios SOMARAKIS

Received: 4 December 2019; Accepted: 3 February 2020; Published online: 31 March 2020

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.

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

**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; Herrmann et al., 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 \( n_T \) be the number of fish of length \( l \) of a given species retained by the codend of the test trawl, and \( n_S \) 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:

\[
cc_l \text{ by } q = \frac{\sum_{i=1}^{m} \left( \frac{n_T_i}{q_T} \right)}{\sum_{i=1}^{m} \left( \frac{n_T_i}{q_T} + \frac{n_S_i}{q_S} \right)}
\]

(1)

The summation in (1) is over the \( m \) hauls conducted during a given cruise. \( q_T \) and \( q_S \) (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:

\[
cc \{l, q\} = \frac{e^f(l, q_0, \ldots, q_k)}{1 + e^f(l, q_0, \ldots, q_k)}
\]

(2)

where \( f \) is a polynomial of order \( k \) with coefficients \( q_{0} \) to \( q_{k} \). The values of the parameters \( q \) describing \( cc \{l, q\} \) 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 \( q_{0}, q_{1}, q_{2}, q_{3}, q_{4}, \ldots, q_{k} \). Leaving out one or more of parameters \( q_{0}, q_{1}, q_{2}, q_{3}, q_{4}, \ldots, q_{k} \) yielded 31 additional models that were also considered as potential models for the catch comparison rate \( cc \{l, q\} \). 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).

\[
- \sum_{l} \sum_{i=1}^{m} \left( \frac{n_T_i}{q_T} \times \ln \left( cc \{l, q\} \right) + \frac{n_S_i}{q_S} \times \ln \left( 1 - cc \{l, q\} \right) \right)
\]

(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. \( cc \{l, q\} \) 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 \( \gg 1 \)), the residuals were inspected to determine whether this was due to structural problems or overdispersion in the data (Wileman et al., 1996; Alzorri 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 \( cc(l, q) \) 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 \( cc(l, q) \) (Veiga-Malta et al., 2019):

\[
    cr(l, q) = \frac{cc(l, q)}{1 - cc(l, q)} 
\]  

(4)

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

Uncertainties for the \( cc(l, q) \) and the \( cr(l, q) \) 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:

\[
    \Delta cr(l, q)_{FV-RV} = cr(l, q)_{FV} - cr(l, q)_{RV} 
\]  

(5)

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

\[
    \Delta cr(l, q)_{FV-RV} = cr(l, q)_{FV} - cr(l, q)_{RV} \quad i \in [1, \ldots, 1000] 
\]  

(6)

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

**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):

\[
    CD F_w(L) = \sum_{i=1}^{m} \sum_{l=1}^{L} \frac{a \times l^b \times nX_i}{qX_i} 
\]  

(8)

where \( nX_i \) and \( qX_i \) represent \( nT_i \) and \( qT_i \), if the estimation is made for the test trawl, or \( nS_i \) 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. The 95% CI for \( \Delta cr(l, q)_{FV-RV} \) was estimated by the same approach as for \( \Delta cr(l, q)_{FV-RV} \).

**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 (\( nP^- \)), weights (\( wP^- \)) and weights (\( wP^+ \)) were estimated as follows:

\[
    nP^- = \frac{\sum_{i=1}^{m} \left( \frac{nT_i}{qT_i} \right) \left[ \sum_{i=1}^{m} \left( \frac{nT_i}{qT_i} \right) \right]}{\sum_{i=1}^{m} \left( \frac{nS_i}{qS_i} \right) \left[ \sum_{i=1}^{m} \left( \frac{nS_i}{qS_i} \right) \right]} 
\]  

(9)

\[
    nP^+ = \frac{\sum_{i=1}^{m} \left( \frac{nT_i}{qT_i} \right) \left[ \sum_{i=1}^{m} \left( \frac{nT_i}{qT_i} \right) \right]}{\sum_{i=1}^{m} \left( \frac{nS_i}{qS_i} \right) \left[ \sum_{i=1}^{m} \left( \frac{nS_i}{qS_i} \right) \right]} 
\]  

(10)

\[
    wP^- = \frac{\sum_{i=1}^{m} \left( \frac{nT_i}{qT_i} \right) \left[ \sum_{i=1}^{m} \left( \frac{nT_i}{qT_i} \right) \right]}{\sum_{i=1}^{m} \left( \frac{nS_i}{qS_i} \right) \left[ \sum_{i=1}^{m} \left( \frac{nS_i}{qS_i} \right) \right]} 
\]  

(11)

\[
    wP^+ = \frac{\sum_{i=1}^{m} \left( \frac{nT_i}{qT_i} \right) \left[ \sum_{i=1}^{m} \left( \frac{nT_i}{qT_i} \right) \right]}{\sum_{i=1}^{m} \left( \frac{nS_i}{qS_i} \right) \left[ \sum_{i=1}^{m} \left( \frac{nS_i}{qS_i} \right) \right]} 
\]  

(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 $(n_{P-}, w_{P-})$ and above $(n_{P+}, w_{P+})$ the MCRS, respectively compared to the standard trawl. $n_{P-}$ and $w_{P-}$ values should preferably be as close to 0% as possible, whereas $n_{P+}$ and $w_{P+}$ 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:

$$n_{DRatio} = 100 \times \frac{\sum_{i=1}^{m} \left( \sum_{l \leq \text{MCRS}} \frac{nX_{il}}{qX_{i}} \right)}{\sum_{i=1}^{m} \left( \sum_{l} \frac{nX_{il}}{qX_{i}} \right)}$$

$$w_{DRatio} = 100 \times \frac{\sum_{i=1}^{m} \left( \sum_{l \leq \text{MCRS}} \frac{nX_{il}}{qX_{i}} \times (a \times l^{b}) \right)}{\sum_{i=1}^{m} \left( \sum_{l} \frac{nX_{il}}{qX_{i}} \times (a \times l^{b}) \right)}$$

where $nX_{i}$ and $qX_{i}$ represent $nT_{i}$ and $qT_{i}$ if the estimation is made for the test trawl, or $nS_{i}$ 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 ($n_{PTotal}$) and weight ($w_{PTotal}$):

$$n_{PTotal} = \frac{\sum_{i=1}^{m} \left( \sum_{l \leq \text{MCRS}} \frac{nT_{il}}{qT_{i}} \right)}{\sum_{i=1}^{m} \left( \sum_{l} \frac{nS_{il}}{qS_{i}} \right)}$$

$$w_{PTotal} = \frac{\sum_{i=1}^{m} \left( \sum_{l \leq \text{MCRS}} \frac{nT_{il}}{qT_{i}} \times (a \times l^{b}) \right)}{\sum_{i=1}^{m} \left( \sum_{l} \frac{nS_{il}}{qS_{i}} \times (a \times l^{b}) \right)}$$

A value of 100% would mean that the test trawl catches the same total number ($n_{PTotal}$) and weight ($w_{PTotal}$) 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-
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 reported in Table 1.

| Haul number | Vessel | MUT Standard | Test | GUR Standard | Test |
|-------------|--------|--------------|------|--------------|------|
| 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     | - -          | - -        |

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  |
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).

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

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

Inspection of the catch comparison and catch ratio
curves demonstrated a significant reduction in the catch-
es 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). Compari-
son 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 7: Comparison of the fishing vessel (FV) and research ves-
sel (RV) catch ratio curves for gurnard (GUR).](image)

![Fig 8: Comparison of the total gurnard (GUR) population, in terms of number (two top rows) and cumulative catch weight distri-
bution (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.](image)
troll 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 meet 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.

Acknowledgements

This study was supported by the European project “BENTHIS: Benthic ecosystem fisheries impact study” (KBBE 2012.1.2-09, Grant Agreement No. 312088), financed by the European Commission through the Seventh Framework Programme. The authors are grateful to the crew of R/V G. Dallaporta and to the fishermen of F/V Albatros Selvaggio. We are also grateful to the two anonymous reviewers for their constructive comments.

References

Alzorriz, N., Arregi, L., Herrmann, B., Sistiaga, M., Casey, J. et al., 2016. Questioning the effectiveness of technical measures implemented by the Basque bottom otter trawl fleet: implications under the EU landing obligation. Fisheries Research, 175, 116-126.

Anderson, D., Burnham, K., 2004. Model selection and multi-model inference. Second Edition. Springer-Verlag, New York, 488 pp.

Bolognini, L., Domenichetti, F., Grati, F., Polidori, P., Scarcel la, G. et al., 2013. Weight-length relationships for 20 fish species in the Adriatic Sea. Turkish Journal of Fisheries and Aquatic Sciences, 13 (3), 555-560.

Brčić, J., Herrmann, B., De Carlo, F., Sala, A., 2015. Selective characteristics of a shark-excluding grid device in a Mediterranean trawl. Fisheries Research, 172, 352-360.

Brčić, J., Herrmann, B., Sala, A., 2016. Can a square-mesh panel inserted in front of the codend improve the exploitation pattern in Mediterranean bottom trawl fisheries? Fisheries Research, 183, 13-18.

Brčić, J., Herrmann, B., Sala, A., 2018. Can a square-mesh panel inserted in front of the cod end improve size and species selectivity in Mediterranean trawl fisheries? Canadian Journal of Fisheries and Aquatic Sciences, 75 (5), 704-713.

Catchpole T., Revill A., 2008. Gear technology in Nephrops trawl fisheries. Reviews in Fish Biology and Fisheries, 18 (1), 17-31.

Feekings, J., Bartolino, V., Madsen, N., Catchpole T., 2012. Fishery discards: factors affecting their variability within a demersal trawl fishery. PLoS ONE, 7 (4), e36409.

Efron, B., 1982. The jackknife, the bootstrap, and other resampling plans. Vol. 38. Siam, Philadelphia, 100 pp.

EU, 2006. Council Regulation (EC) No. 1967/2006 of 21 December 2006, concerning management measures for the sustainable exploitation of fishery resources in the Mediterranean Sea, amending Regulation (EC) No. 2847/93 and repealing Regulation (EC) No. 1626/94. Official Journal of the European Union L. 409

Glass, C.W., 2000. Conservation of fish stocks through bycatch reduction: a review. Northeastern Naturalist, 7 (4), 395-411.

Johnsen, J.P, Eliasen, S., 2011. Solving complex fisheries man-
agement problems: what the EU can learn from the Nordic experiences of reduction of discards. Marine Policy, 35 (2), 130-139.

Herrmann, B., Sistiaga, M., Nielsen, K.N., Larsen, R.B., 2012. Understanding the size selectivity of redfish (Sebastes spp.) in North Atlantic trawl codends. Journal of Northwest Atlantic Fishery Science, 44, 1-13.

Herrmann, B., Sistiaga, M., Rindahl, L., Tatone, I., 2017. Estimation of the effect of gear design changes on catch efficiency: methodology and a case study for a Spanish longline fishery targeting Hake (Merluccius merluccius). Fisheries Research, 185, 153-160.

Kaykac, H., 2010. Size selectivity of commercial (300 MC) and larger square mesh top panel (LSMTPC) trawl codends for blue whiting (Micromesistius poutassou Risso, 1826) in the Aegean Sea. African Journal of Biotechnology, 9 (53), 9037-9041.

Krag, L.A., Herrmann, B., Karlsen, J.D., 2014. Inferring fish escape behaviour in trawls based on catch comparison data: model development and evaluation based on data from Skagerrak, Denmark. PLoS One, 9 (2), e88819.

Metin, C., Özbilgin, H., Tosunoğlu, Z., Gökçe, G., Aydin et al., (2005). Effect of square mesh escape window on codend selectivity for three fish species in the Aegean Sea. Turkish Journal of Veterinary and Animal Sciences, 29 (2), 461-468.

Özbilgin, H., Tosunoğlu, Z., Aydin, C., Kaykac, H. and Tokaç, A., 2005. Selectivity of standard, narrow and square mesh panel trawl codends for hake (Merluccius merluccius) and poor cod (Trisopterus minutus capelanus). Turkish Journal of Veterinary and Animal Sciences, 29 (4), 967-973.

Özbilgin, H., Tosunoğlu, Z., Tokaç, A., Metin, G., 2011. Seasonal variation in the trawl codend selectivity of red mullet (Mullus barbatus). Turkish Journal of Fisheries and Aquatic Sciences, 11 (2), 191-1.

Sala, A., Lucchetti, A., 2011. Effect of mesh size and codend circumference on selectivity in the Mediterranean demersal trawl fisheries. Fisheries Research, 110, 252-258.98.

Sala, A., Priour, D., Herrmann, B., 2006. Experimental and theoretical study of red mullet (Mullus barbatus) selectivity in codends of Mediterranean bottom trawls. Aquatic Living Resources, 19 (4), 317-327.

Sala, A., Lucchetti, A., Piccinetti, C., Ferretti, M., 2008. Size selection by diamond- and square-mesh codends in multi-species Mediterranean demersal trawl fisheries. Fisheries Research, 93, 8-21.

Sala, A., Lucchetti, A., Perdichizzi, A., Herrmann, B., Rinelli, P., 2015. Is square-mesh better selective than larger mesh? A perspective on the management for Mediterranean trawl fisheries. Fisheries Research, 161, 182-190.

Sala, A., Herrmann, B., De Carlo, F., Lucchetti, A., Brčić, J., 2016. Effect of codend circumference on the size selection of square-mesh codends in trawl fisheries. PLoS ONE, 11 (7), e0160354.

Santos, J., Herrmann, B., Otero, P., Fernandez, J., Pérez, N., 2016. Square mesh panels in demersal trawls: does lateral positioning enhance fish contact probability? Aquatic Living Resources, 29 (3), 1-10.

Soma, K., Nielsen, J.R., Papadopoulou, N., Polet, H., Zengin, M. et al., 2018. Stakeholder perceptions in fisheries management - Sectors with benthic impacts. Marine Policy, 92, 73-85.

Suuronen P., Sardá F., 2007. By-catch Reduction Techniques in European Fisheries: Traditional Methods and Potential Innovations. p. 37-74. In: By-catch Reduction in the World’s Fisheries. Reviews: Methods and Technologies in Fish Biology and Fisheries. Kennelly, S.J., (Eds). Springer, Dordrecht.

Tokaç, A., Özbilgin, H., Kaykac, H., 2010. Selectivity of conventional and alternative codend design for five fish species in the Aegean Sea. Journal of Applied Ichthyology, 26 (3), 403-409.

Tokaç, A., Herrmann, B., Gökçe, G., Krag, L.A., Nezhad, D. et al., 2016. Understanding the size selectivity of red mullet (Mullus barbatus) in Mediterranean trawl codends: A study based on fish morphology. Fisheries Research, 174, 81-93.

Tsagarakis, K., Palialexis, A., Vassilopoulou, V., 2014. Mediterranean fishery discards: review of the existing knowledge. ICES Journal of Marine Science, 71 (5), 1219-1234.

Tsagarakis, K., Carbonell, A., Brčić, J., Bellido, J.M., Carbonara, P. et al., 2017. Old Info for a New Fisheries Policy: Discard Ratios and Lengths at Discarding in EU Mediterranean Bottom Trawl Fisheries. Frontiers in Marine Science, 4, 99.

Veiga-Malta, T., Seekings, J., Herrmann, B., Krag, L.A., 2019. Industry-led fishing gear development: Can it facilitate the process? Ocean & Coastal Management, 177, 148-155.

Vitale, S., Milisenda, G., Gristina, M., Baiata, P., Bonanomi, S. et al., 2018. Towards more selective Mediterranean trawl fisheries: are juveniles and trash excluder devices effective tools for reducing undersized catches? Scientia Marina, 82 (S1), 215-223.

Wileman, D., Ferro, R.S.T., Fonteyne, R., Millar, R.B., 1996. Manual of methods of measuring the selectivity of towed fishing gear. ICES Cooperative Research Report, 215, 132.

The following supplementary information is available for the article online:

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