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Relative Catch Performance of Two Gear Modifications Used to Reduce Bycatch of Undersized Fish and Shrimp in Mediterranean Bottom Trawl Fisheries

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Abstract

The catch of large quantities of sublegal-sized fish and shrimp is a pervasive feature of bottom trawl fisheries, particularly in the Mediterranean demersal mixed fisheries where regulations traditionally allow small mesh sizes. To address these concerns, two bottom trawl net selectivity trials were carried out in 2019 and 2020 on fishing grounds worked by the trawl fleet of Spanish Mediterranean, under normal commercial operating conditions with volunteer trawlers of the local fleet. The traditional otter bottom trawl employed in the demersal mixed fishery was modified with a 50-mm T90 panel on the extension piece under two different configurations (front of the extension piece and back of the extension piece). A second modification consisted of inserting a selective grid in the extension piece of the standard bottom trawl net. The species investigated in the demersal mixed fishery were European Hake *Merluccius merluccius*, Red Mullet *Mullus barbatus*, Striped Red Mullet *Mullus surmuletus*, and the deepwater rose shrimp *Parapenaeus longirostris*. Important selectivity improvements were observed for European Hake and deepwater rose shrimp, particularly in the selective grid trial, where 95% and 100%, respectively, of undersize specimens escaped through the grid. The design with the T90 panel in the back of the extension piece allowed for a reduction of 35% of sublegal-sized individuals of European Hake, but no difference was gained in the sizes of both *Mullus* spp. retained in the cod end. The adoption of these gear modifications might contribute to reducing discards of sublegal-sized fractions of the fisheries target species.

The production of large quantities of unwanted bycatch is a pervasive feature of bottom trawl fisheries, particularly in the Mediterranean demersal mixed fisheries where regulations traditionally allow small net mesh sizes (currently 40-mm square mesh or 50-mm diamond mesh, Council Regulation 1967/2006; Sala et al. 2015).

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Unwanted bycatch is a general term to encompass both catches of individuals under regulatory size and other marine organisms that cannot be commercialized for any reason (e.g., from nonedible invertebrates to damaged fish of commercial categories). In Mediterranean trawl fisheries the amount of unwanted bycatch that is discarded at sea is variously estimated to between 20% and 65% of the total catch (from several studies summarized in Tsagarakis et al. 2014), and it is difficult to be any more precise because of the many factors affecting discard rates (Uhlmann et al. 2014). Both the fishing industry and fisheries managers are interested in the minimization of the amount of unwanted bycatch for a variety of reasons, such as compliance with regulations, but also reduced costs of sorting the catch or conservation of fisheries resources by reducing mortality on juvenile fish. The landing obligation enshrined in Article 15 of the European Common Fisheries Policy (Council Regulation 1386/2013), implementing a ban on discards of regulated species, should incentivize the design and adoption of technical solutions that diminish the amount of unwanted bycatch (Condie et al. 2014; Prellezo et al. 2016).

Modifying fishing gear to ensure better selectivity is a well-tested option to help reduce the amount of unwanted bycatch, with many experimental studies reporting enhanced escapement of the smaller-size fraction of commercial species (e.g., Sala and Lucchetti 2011; Sola and Maynou 2018a; Robert et al. 2020). Of special concern in Mediterranean bottom trawl fisheries are species such as European Hake *Merluccius merluccius* with mean retention lengths (10–16 cm TL; Sánchez et al. 2004; Sala and Lucchetti 2011) that are significantly lower than the legal landing size (20 cm TL) or the deepwater rose shrimp *Parapenaeus longirostris*, where approximately half of the catch taken with regulatory meshes is composed of undersized individuals (by number; <20 mm carapace length [CL]; Vitale et al. 2018b).

It is well-known that selection in standard (unmodified) bottom trawls occurs at the cod end (Wileman et al. 1996) and that suitably large meshes should allow the escape of juveniles of most commercial species. The need to increase the size of the regulatory mesh employed in the Mediterranean bottom trawl fisheries has been advocated (Quetglas et al. 2017; Russo et al. 2017) because it retains undersize individuals (Brčić et al. 2018). However, it is likely that increasing the mesh size of cod ends in Mediterranean fisheries to align with mesh sizes used in European Atlantic fisheries (e.g., 80 mm, 100 mm or more) would result in excessive short-term losses to the fishing industry. Solutions to increase selection in bottom trawls can alternatively be based on modifications to the body of the trawl by using panels of different meshes (Campos and Fonseca 2004), changing the cod end mesh netting (Deval et al. 2016), or fitting bycatch reduction devices (Fonseca et al. 2005; Aydin et al. 2011). Among the solutions tested, square mesh panels (Campos and Fonseca 2007), selective grids (Fonseca et al. 2005; Vitale et al. 2018b) or escape light rings (Southworth et al. 2020) have shown good technical results, with an observed decrease in the fraction of unwanted bycatch of at least some commercial target species. In addition to good selection properties, desirable properties of bycatch reduction devices are low cost, ease of operation, low environmental impact, being easily enforceable, and having acceptable losses of commercial fish fractions (Catchpole et al. 2008). In this sense, design and trial of solutions inspired by the fishing industry and tested in real commercial conditions are key to facilitate wide adoption (O’Neill et al. 2019). Among the existing technical solutions related to the type of mesh netting, the use of 90° turned mesh (T90) has proved interesting and has been shown in some studies to increase the size at selection and the quality of fish (Tokaç et al. 2014; Sola and Maynou 2018a; Robert et al. 2020). The insertion of selective or sorting grids in the body of the trawl has also been repeatedly trialed with good results in terms of species and size selection (Nordmore grid: Isaksen et al. 1992; juvenile and trash exclusion device grids: Eayrs et al. 2007; Vitale et al. 2018b). However, previous trials with grids based on the Nordmore design in the relatively small trawls employed in Mediterranean fisheries showed handling problems onboard and likely low acceptance by fishers (Suuronen and Sardà 2007; Vitale et al. 2018b), and for these reasons we opted to trial the latter authors’ design based on a variation of the juvenile and trash exclusion device grid.

The objectives of this work were to test two technical modifications of the traditional trawl net used in western Mediterranean demersal fisheries by: (1) fitting a T90 panel on the trawl net extension and (2) inserting a selective grid. The study focused on the main target species of the fishery, which includes European Hake, Red Mullet *Mullus barbatus*, Striped Red Mullet *Mullus surmuletus*, and deepwater rose shrimp, and examined the size selectivity and catch patterns of these technical solutions on board commercial trawlers, replicating their normal working conditions.

**METHODS**

**Experimental fishing trials.**—The study was carried out on commercial fishing grounds off the east coast of Spain, referred to as the Spanish Mediterranean (Figure 1), in two sampling locations with a local trawl vessel. In the north, sampling was carried out from the port of Blanes (Figure 1A), while in the southern location the sampling was on fishing grounds of the Puerto de Mazarrón trawlers (Figure 1B). The fishing grounds are located at depths between 50 and 250 m.

Two separate modifications to the regulatory otter bottom trawl generally employed for demersal fishing were
trialed: (1) a panel in the extension piece of the trawl made with 90° turned mesh (T90) before the cod end following the same design and specifications as in Sola and Maynou (2018a), and (2) a selective grid placed in the middle of the extension piece, following design G1-SM40 of Vitale et al. (2018b; Figure 2).

The T90 experiments consisted of substituting the type of netting for part of the trawl extension (tubular piece of net between the body of the trawl and the cod end; Figures 2, 3). The standard netting of the extension piece used by the sampling trawler was constructed from 53-mm (nominal) diamond mesh netting. The test piece was constructed from 50-mm mesh knotted at 90° (T90). Both in the standard and the experimental trawl, the cod end used was built from the regulatory mesh in Mediterranean fisheries of 40-mm mesh knotted at 45° (“square mesh”). The T90 panel was tested in two different configurations: it was placed at the end of the extension piece in the north sampling experiments (T90a) and at the beginning of the extension piece in the south sampling trials (T90b; Figure 2). The selection properties of the T90 net piece are based on the ability of this net to keep open under tension, allowing small fish to swim upwards and escape through the mesh.

The selective grid experiments consisted of fitting an experimental selective grid in the trawl extension. The selective grid consisted of an oval steel frame (120 cm high × 90 cm wide) with SM40 mesh in the upper two-thirds and left open in the lower one-third, positioned at an angle of 35° from the vertical towards the front (Figures 2, 4). The principle of the selective grid is to guide larger fish downwards towards the grid opening, while allowing small-sized fish to escape through the mesh. For the experimental trials, a 5-m piece of small mesh net was used to retain small fish escaping through the selective grid (Figure 2). Specific details and the main dimensions of the T90 and the selective grid modifications are provided in Table 1 and Figure 2; for more details, refer to Sola and Maynou (2018a) and Vitale et al. (2018b).

Experimental T90 net trials.—In the northern area, the sampling strategy for the T90 assessment was comprised of alternate hauls using a local commercial vessel, fishing with the standard “control” trawl and the experimental T90 net on consecutive days over the same geographical coordinates. On these continental shelf fishing grounds, the target species were European Hake, Red Mullet, and Striped Red Mullet. The experiments were carried out in July 2019 with the same commercial vessel as in Sola and Maynou (2018a), a 15-m length-over-all bottom trawler with a 261-kW main engine. In total, 12 pairs of trawl hauls were conducted (12 hauls with the standard net as control and 12 hauls with the T90 modified net).

In the southern area, the T90 sampling also followed the alternate haul strategy onboard a local commercial vessel of 18-m length-over-all and a 280-kW main engine. The target species were European Hake and deepwater rose shrimp on fishing grounds over the deep continental slope and shelf edge (Figure 1). A total of six pair hauls were carried out in November 2019 (deepwater rose shrimp) and six more pairs in October 2020 (European Hake).

For the catch analysis, it was assumed that individuals in the population had equal probability (0.5) of being captured by the test trawl net and the standard trawl net, but retention by each net could differ. The individuals retained in the cod end of the test trawl net are denoted “nT,” and those retained in the cod end of the standard net are denoted “nS.”

Selective grid trials.—In July 2020, the same continental fishing grounds of the northern area were sampled with the standard trawl incorporating a selective grid. The
sampling strategy consisted of six trawl hauls on each of two fishing grounds without control hauls (Figure 1). The catch analysis was based on the null hypothesis that once fish entered the trawl net they had equal probability of escaping through the sorting grid or being retained in the cod end. The sorting grid was fitted with a small-mesh net (20 mm stretched) cover to retain escaping fish (Figure 2) (naturally, in normal fishing conditions this small-mesh net would not be present). All fish entering the trawl consisted of two fractions: the fish sorted by the grid (nS), which were retained in the small-mesh cover, and the fish retained by the normal cod end (nT).

The trawl nets were towed at 3 knots for a duration of 2 h effective fishing time. After hauling in the catch, all individuals of the target species (European Hake, Red Mullet, Striped Red Mullet, deepwater rose shrimp) were sorted, measured (nearest 0.5 cm TL for the finfish, nearest 0.1 mm CL for the shrimp) and weighed (nearest 1 g for the finfish, nearest 0.1 g for the shrimp) individually, while the rest of the catch was identified to species level, counted, and weighed. No subsampling of the catch was necessary given the number of specimens caught.

**Data analysis.**—The analysis of the paired haul experiments assessing the effect of the T90 aimed to compare, for each target species, the catch efficiency of the standard trawl (nS) against that of the modified trawl (nT). In the case of the selective grid experiments, the analysis was framed as a comparison of the catch efficiency of the small-mesh cod end (nS) retaining the fish that escaped through the grid against the catch of the normal cod end (nT). In both cases, the catch comparison method (Holst and Revill 2009; Krag et al. 2014; Sistiaga et al. 2015) was used to estimate the average relative change in length-dependent catch efficiency for each species. For a set of p comparisons (pairs of trawl hauls in the T90 experiments or single trawl hauls in the selective-grid experiment), the experimental average catch comparison rate (CCl) is given by the following expression (Sistiaga et al. 2015; Veiga-Malta et al. 2019):

\[
CC_l = \frac{\sum_{i=1}^{p} nT_{li}}{\sum_{i=1}^{p} nS_{li} + \sum_{i=1}^{p} nT_{li}},
\]

where, for each species, nSli and nTli are the number of fish measured in each length class l in the standard net cod end and experimental cod end, respectively, in the case of the T90 experiment, or the small-mesh net and the trawl cod end in the sorting grid experiment, respectively.
The experimental $CC_I$ was modelled with the equation (Krag et al. 2014):

$$CC(l, v) = \frac{e^{f(l, q_0, \ldots, q_k)}}{1 + e^{f(l, q_0, \ldots, q_k)}},$$ (2)

where $f$ is a polynomial of order $k$ with coefficients $q_0$ to $q_k$; that is, the parameter space of equation (2) is $v = (q_0, \ldots, q_k)$. Equation (2) gives the probability of retaining an individual of length $l$ in the experimental cod end provided it entered any of the two trawls in the T90 experiments, or the probability of being retained in the trawl cod end in the single-trawl sorting grid experiment. A value of $CC(l, v) = 0.5$ implies that the likelihood of retaining a fish of size $l$ is the same in both cases (i.e., both trawl nets would have the same catch efficiency in the T90 experiments, while in the selective grid experiment it represents equal probability of exiting through the selective grid or being retained in the cod end). Values significantly lower than 0.5 for a given length $l$ mean that the modified trawl with the T90 retains less individuals of that length class compared with the control trawl. In the selective-grid experiment, values $<0.5$ correspond to increased escapement through the selective grid. The values of the polynomial coefficients in $v$ were estimated by minimizing the log-likelihood:

$$LL = -\sum_i\{nS_i \cdot \log[1 - CC(l, v)] + nT_i \cdot \log[CC(l, v)]\},$$ (3)
where \( n_{S_i} \) and \( n_{T_i} \) are the numbers of fish of length \( l \) summed over hauls.

Following Krag et al. (2014), we tested all possible polynomials up to the third degree, i.e., \( 2^4 \) combinations of parameters \( q_0, q_1, q_2, q_3 \). The parameters were estimated using linear mixed models, with the size-class as a fixed factor and haul as a random factor. Selection of the best model among the 16 candidate models followed a model-based inference approach (Burnham and Anderson 2013). Briefly, we ranked the candidate models according to the value of Akaike information criterion (AIC) and selected the model configuration with lowest AIC. The computations were carried out with lme4 version 1.1.21 and MuMIn version 1.43.15 libraries of the R language. The goodness of fit of the selected model for each species and experiment was checked with a chi-square test for two different statistics, the Pearson residuals and the deviance residuals, with the degrees of freedom corresponding to the difference between the number of size-classes and the number of parameters in the model, following Wileman et al. (1996). Acceptable fit of the model to the data was indicated by \( P \)-values \( >0.05 \) and ratio statistic to degrees of freedom of the order of 1.

Additionally, for each species, the ratio (CR) between the catch efficiency of the control cod end and the experimental cod end in the T90 experiments for a given length \( l \) was computed. In the selective-grid experiments, CR represents the efficiency in retaining fish in the trawl cod end. We computed CR with the following expression, for the experimental data (“catch ratio analysis”):

\[
CR_l = \frac{\sum_{i=1}^{p} n_{T_{li}}}{\sum_{i=1}^{p} n_{S_{li}}},
\]

with the following functional form, based on equations (1) and (4) and following Veiga-Malta et al. (2019):

\[
CR(l, v) = \frac{CC(l, v)}{1 - CC(l, v)}.
\]

If the catch efficiency were the same in both the test and the standard nets (or the selective-grid cover net and the trawl cod end), the CR would be equal to 1. Catch ratio values significantly lower than 1 represent lower retention in the cod end of the T90 nets or enhanced escapement in the experiment with the selective grid. The catch comparison and catch ratio models were fitted with the computing package for R (version 3.6.2), using an ad hoc script.

A summary of the relative performance of the technical modifications can be obtained with the indicators provided by the catch usability analysis (Veiga-Malta et al. 2019; Bonanomi et al. 2020). In particular, the indicators on the relative catches above or below minimum landing size (MLS) can be of interest to industry and fisheries managers. The fractions above and below MLS were computed for each species in number and weight (see Table 2 for MLS). The fraction in number of individuals below \( (nP−) \) and above \( (nP+) \) MLS was obtained by

\[
nP− = 100 \cdot \frac{\sum_{i \leq MLS} n_{T_{li}}}{\sum_{i \leq MLS} n_{S_{li}}},
\]

\[
nP+ = 100 \cdot \frac{\sum_{i \geq MLS} n_{T_{li}}}{\sum_{i \geq MLS} n_{S_{li}}},
\]

and the ratio (nRatio) of undersize to legal size in numbers between the standard and modified gear per species and experiment:

\[
n\text{Ratio} = 100 \cdot \frac{\sum_{i \leq MLS} n_{T_{li}}}{\sum_{i \leq MLS} n_{S_{li}}} / \frac{\sum_{i \leq MLS} n_{S_{li}}}{\sum_{i \leq MLS} n_{T_{li}}},
\]

Likewise, the fractions below or above legal size in weight were the results of

\[
wP− = 100 \cdot \frac{\sum_{i \leq MLS} w_{T_{li}}}{\sum_{i \leq MLS} w_{S_{li}}},
\]

\[
wP+ = 100 \cdot \frac{\sum_{i \geq MLS} w_{T_{li}}}{\sum_{i \geq MLS} w_{S_{li}}},
\]

where \( w_{S_{li}} \) and \( w_{T_{li}} \) are the results of.
TABLE 2. Trawl selection experiments for reducing bycatch in Mediterranean trawl fisheries with species investigated and their minimum landing size (MLS), where TL is total length and CL is carapace length.

| MLS            | Number of hauls | European Hake | Red Mullet | Striped Red Mullet | Deepwater rose shrimp |
|----------------|-----------------|---------------|------------|--------------------|-----------------------|
| T90, north     | 12 pairs        | 20 cm TL      | x          | x                  | x                     |
| T90, south     | 6 + 6 pairs     | 11 cm TL      | x          | x                  | x                     |
| Selective grid | 12 hauls        | x             | x          | x                  | x                     |

\[ wP^+ = 100 \cdot \frac{\sum_i \sum_{l \geq \text{MLS}} wT_i^+}{\sum_i \sum_{l \geq \text{MLS}} wS_i^+} \]

and the ratio of undersize to legal size in weight \((w\text{Ratio})\):

\[ w\text{Ratio} = 100 \frac{\sum_i \sum_{l < \text{MLS}} wT_i^-}{\sum_i \sum_{l < \text{MLS}} wS_i^-} / \frac{\sum_i \sum_{l \geq \text{MLS}} wS_i^-}{\sum_i \sum_{l \geq \text{MLS}} wS_i^-} \]

RESULTS

Experimental Trials with T90 Trawls

Northern area: European Hake, Red Mullet and Striped Red Mullet.— In the T90 experimental trawls in the northern study area, there were 130 and 104 European Hake caught by the standard net and the modified net, respectively (Figure 5A). Both nets caught predominantly undersized individuals (136 out of the combined 234, or 58%), although in all size-classes <20 cm TL (the MLS), the number of individuals caught by the modified net was equal to or lower than the number of individuals caught with the standard net.

In the case of Red Mullet, the total number of 1,736 individuals caught was almost equally split between the two nets: 865 individuals in the standard net and 871 in the modified net (Figure 5B). The number of individuals below 11 cm TL (the MLS) was very low (six fish or 0.3%) for both nets combined. For sizes 10–14 cm TL, the catches of Red Mullet were lower for the modified net compared to the standard net, and for the size-class 14–18 cm TL, the contrary was observed.

The catches of Striped Red Mullet (Figure 5C) amounted to 207 individuals, very nearly in the same amount in both nets: 98 in the standard trawl and 109 in the modified trawl, and no undersize fish were observed. The bulk of individuals was between 10 and 16 cm TL, with higher catches of fish between 12.5 and 16 cm TL in the modified net.

Southern area: European Hake and deepwater rose shrimp.— In the T90 experiments for the southern area, the catches of European Hake (Figure 5D) were higher in the standard net \((n = 570)\) than in the modified net \((n = 428)\), and the proportion of undersized hake (<20 cm) was very high in both cases: 89% and 82%, respectively.

For the deepwater rose shrimp, the catches of the standard net totaled 650 individuals, larger than the 567 individuals caught by the modified trawl (total 1,217; Figure 5E). Both nets had very similar catches per size-class over the range of about 15 to 25 mm CL. The modified net retained considerably fewer individuals smaller than 15 mm CL but more individuals larger than 25 mm CL, compared to the standard net. The proportion of undersized shrimp was 33%, approximately equally split between the two nets, because most sublegal individuals were in the range of 16–19 mm CL with no statistical differences between the two nets.

Selective-Grid Experiments: European Hake, Red Mullet, and Striped Red Mullet

For the selective-grid experiments, the size frequencies of the three species considered were markedly different between the fraction recovered in the cod end and the fraction escaping through the sorting grid (retained in the experimental small mesh cover; Figures 5F, G, H). A total of 126 European Hake were caught, very nearly equally split between the selective grid cover and the trawl cod end (65 and 61 individuals, respectively), but only 3 out of the 65 individuals (4.6%) were undersized (<20 cm TL) in the cod end, while all individuals sorted through the selective grid were undersized (Figure 3F). In the case of Red Mullet, the total number of fish was 441, with 42% retained in the selective grid cover. No undersized individuals were retained in the net cod end, while 52% of those in the selective grid cover were undersized. For Striped Red Mullet, 599 were retained in the net cod end (74% of the catch), and 208 were retained in the selective grid cover (total 807). The proportion of undersized fish was much lower in the case of Red Mullet; just 14 individuals of the 208 escaping through the sorting grid were undersized (6.7%), and no undersized individuals were caught in the trawl cod end.

Catch Comparisons

In the length-dependent catch comparison analysis for the three species, most models fitted the data reasonably well (Figure 6; Table 3) except the selected model for
FIGURE 5. Size-frequency data for each target species and experiment examining bycatch reduction in Mediterranean trawl fisheries. The blue line shows catches retained in the standard net cod end (T90 experiments) or in the selective grid cover (selective-grid experiments). The red line shows catches retained in the modified-trawl cod end (T90 experiments) or in the net cod end (selective-grid experiments). The minimum landing size for each species is shown in red on the x-axis.
Striped Red Mullet in the T90 experiment (north) and that for European Hake in the selective-grid experiment. In the first case, the chi-square test on the Pearson residuals statistics had a $P$-value <0.05, and the poor fit is probably due to the low number of individuals caught ($n = 207$) and the wide dispersal of the data (Figure 6C). On the contrary, in the case of European Hake in the selective grid (Figure 6F), the high contrast between the small sizes caught in the selective grid cover and the cod end resulted in only two size-classes (10.5 and 16.5 cm TL) having a value different from 0 or 1, and the residuals statistics were then based just on this pair of values. In this case, even if the model diagnostics are poor, the effect of the selective grid is clear.

In the case of the European Hake and Red Mullet in the northern T90 experiments, the best models selected were the models including polynomial terms 0, 1, 2, and 3, while in the case of the Striped Red Mullet, a 1-degree polynomial produced the most parsimonious model based on AIC (Table 4). In the southern T90 experiments, the best model for deepwater rose shrimp was based on a polynomial of terms 0, 1, 2, and 3, while in the case of the European Hake it was a 1-degree polynomial (Table 4).

The experiments with the trawl net fitted with the selective grid produced clearly separate fractions of small fish escaping through the grid bars and larger fish retained in the trawl cod end. This was particularly apparent for European Hake, where only three undersize individuals were retained in the cod end (Figure 5F). The best-fitting selection model for European Hake was based on a 3rd degree polynomial, for Red Mullet a polynomial with terms 0 and 3, and for Striped Red Mullet a polynomial with terms 1 and 3 (Table 4).

Northern area with T90 modifications.—From the catch comparison curve (Figure 6A) and the catch ratio curve (Figure 7A), a significant reduction in the modelled catch of European Hake when fishing with the T90-modified trawl was apparent for individuals in the range of ~10 to ~17 cm TL. The curves show no statistical difference for catches of European Hake individuals in the length range of ~18 to ~32 cm TL and increasing catch rates for larger sizes. The catch usability indicators (Table 5) showed that the number of undersized fish retained in the cod end of the modified trawl ($nP_-$) was 64.60% of the number retained in the standard cod end (i.e., a 35.40% reduction from the expected equal proportion of undersize fish in both nets under the null hypothesis of no effect). In terms of weight ($wP_-$), the reduction was 14.80%. The relative importance of undersized catches in the cod end of the T90-modified trawl were 71.20% in numbers ($n$Ratio) and 57.70% in weight ($w$Ratio) compared to the cod end of the standard trawl.

In the case of Red Mullet, the catch comparison curve (Figure 6B) and the catch ratio curve (Figure 7B) show that the number of individuals retained in the T90-modified trawl were lower than in the standard cod end for the size range of ~10 to ~15 cm TL. The catch ratio curve for sizes larger than ~15 cm TL was significantly higher than 1, suggesting that the modified trawl caught higher numbers of larger individuals. However, most of the individuals caught were of legal size (>11 cm TL) and resulted in very low difference in the catch usability indicators (Table 5).

In the case of the Striped Red Mullet (Figures 6C, 7C), the statistical model fitted did not show significant differences in catches by size between the T90-modified net and the standard net. Additionally, no individuals smaller than 11 cm TL were caught and the catch usability indicators ($nP_-, wP_-, n$Ratio, $w$Ratio) were 0.

Southern area with T90 modifications.—The catch comparison (Figure 6D) and catch ratio (Figure 7D) curves for European Hake show that the sizes retained in the standard and the modified nets were not markedly different. Hake smaller than 12 cm TL had statistically lower retention in the modified net (Figure 7D), but the bulk of samples was in the range of size-classes ~13 to ~18 cm TL. The catch usability analysis showed that the modified net produced overall a lower proportion of undersized hake ($nP_- = 73.70\%$ and $wP_- = 71.20\%$), but the ratios of undersized hake between the modified and the standard gear were not highly different ($n$Ratio = 92.70%).

The catch comparison (Figure 6E) and catch ratio (Figure 7E) curves for the deepwater rose shrimp showed that the number of individuals retained in the cod end of the T90-modified trawl was lower than in the standard trawl in the size range of ~12 to ~17 mm CL. From ~17 to ~30 mm CL, the catches of both nets were not significantly different. The catches of deepwater rose shrimp larger than ~30 mm CL were higher in the modified net. The catch usability indicators (Table 5) showed that the proportion of undersized shrimp was slightly lower in the T90 cod end than in the standard cod end, both in numbers ($nP_- = 89.50\%$) and weight ($wP_- = 88.40\%$).

Selective grids.—In the case of the experiments with the trawl fitted with a selective grid, the catch comparison (Figure 6F) and catch ratio (Figure 7F) curves for European Hake showed a very sharp theoretical selection for undersize hake by the selective grid. The model curves showed no catches of hake individuals smaller than ~16 cm TL in the cod end of the trawl net. This corresponds to very low values of the usability indicators $nP_-$ (4.92%) and $wP_-$ (15.30%). The relative ratio of undersized fish between the trawl cod end and the selective grid cover was 4.6% in number and 1.7% in weight, meaning that more than 95% of undersized hake entering the trawl would escape through the selective grid.

The catch comparison (Figure 6G) and catch ratio (Figure 7G) curves for Red Mullet also showed a steep
FIGURE 6. Catch comparison analysis showing observed experimental-to-control ratios (blue dots) and the theoretical model (black line) with 95% confidence intervals (dotted lines) for trawl modifications to reduce bycatch.
selection by the selective grid, with no catches of individuals smaller than ~13 cm TL retained in the trawl cod end. Additionally, no undersized Red Mullet were observed in the cod end, and the value of the catch usability indicators ($nP_-, wP_-, nRatio, wRatio$) were 0.

The results of the catch comparison and catch ratio analysis was practically the same in the Striped Red Mullet (Figures 6H, 7H) as in the Red Mullet in the experiment with the selective grid, and likewise there were no undersized individuals caught in the trawl cod end.

**TABLE 3.** Fit statistics of the model selected for catch comparison rates for each species and gear modification for reducing trawl bycatch in Mediterranean fisheries, based on the chi-square test. $P$-values >0.05 (denoted with an asterisk) indicate an acceptable fit of the model to the data.

| Experiment       | Species               | df | Pearson residuals statistic | $P$-value | Deviance residuals statistic | $P$-value |
|------------------|-----------------------|----|------------------------------|-----------|------------------------------|-----------|
| T90, north       | European Hake         | 28 | 20.365                       | 0.845     | 15.892                       | 0.967     |
|                  | Red Mullet            | 16 | 3.256                        | 0.999     | 15.892                       | 0.461     |
|                  | Striped Red Mullet    | 15 | 32.882                       | 0.005*    | 14.326                       | 0.501     |
| T90, south       | European Hake         | 49 | 41.822                       | 0.005     | 25.073                       | 0.998     |
|                  | Deepwater rose shrimp | 8  | 4.443                        | 0.815     | 4.530                        | 0.806     |
| Selective grid   | European Hake         | 21 | 88.540                       | <0.0001*  | 82.020                       | <0.0001*  |
|                  | Red Mullet            | 19 | 4.711                        | 0.999     | 4.268                        | 0.999     |
|                  | Striped Red Mullet    | 20 | 0.688                        | 1.000     | 0.537                        | 1.000     |

**TABLE 4.** Model coefficients of the selected catch comparison model (coefficients of the polynomials in equation 2) for each species and gear modification for reducing trawl bycatch in Mediterranean fisheries.

| Experiment       | Species               | Model Parameter | Estimate | SE |
|------------------|-----------------------|-----------------|----------|----|
| T90, north       | European Hake         | $q_0$           | -22.36   | 2.17|
|                  |                       | $q_1$           | 2.72     | 0.19|
|                  |                       | $q_2$           | -0.11    | 4.41 x 10^{-3}   |
|                  |                       | $q_3$           | 1.36 x 10^{-3}  | 3.44 x 10^{-5}  |
|                  | Red Mullet            | $q_0$           | -16.41   | 1.41|
|                  |                       | $q_1$           | 2.40     | 0.16|
|                  |                       | $q_2$           | -0.11    | 5.48 x 10^{-3}   |
|                  |                       | $q_3$           | 1.74 x 10^{-3}  | 7.55 x 10^{-5}  |
|                  | Striped Red Mullet    | $q_1$           | 8.80 x 10^{-3}  | 0.01|
| T90, south       | European Hake         | $q_0$           | -10.21   | 2.58|
|                  |                       | $q_1$           | 0.06     | 0.02|
|                  |                       | $q_2$           | -0.16    | 3.31 x 10^{-3}   |
|                  |                       | $q_3$           | 2.24 x 10^{-3}  | 2.28 x 10^{-5}  |
|                  | Deepwater rose shrimp | $q_0$           | -26.82   | 1.60|
|                  |                       | $q_1$           | 3.58     | 0.14|
|                  |                       | $q_2$           | -0.16    | 3.31 x 10^{-3}   |
|                  |                       | $q_3$           | 2.24 x 10^{-3}  | 2.28 x 10^{-5}  |
| Selective grid   | European Hake         | $q_0$           | 1.85 x 10^{-3}  | 5.74 x 10^{-4}  |
|                  |                       | $q_1$           | 1.85 x 10^{-3}  | 5.74 x 10^{-4}  |
|                  |                       | $q_2$           | 4.52 x 10^{-3}  | 9.48 x 10^{-4}  |
|                  |                       | $q_3$           | 8.26 x 10^{-3}  | 1.52 x 10^{-3}  |

The results of the catch comparison and catch ratio analysis was practically the same in the Striped Red Mullet (Figures 6H, 7H) as in the Red Mullet in the experiment with the selective grid, and likewise there were no undersized individuals caught in the trawl cod end.
FIGURE 7. Catch ratio analysis showing empirical size frequencies (as in Figure 5) with fitted theoretical models (black line) and their 95% confidence intervals (dotted lines). Catches retained in the standard net cod end (T90 experiments) or in the selective grid small-mesh cover (selective-grid experiments) are shown by a blue line, whereas catches retained in the modified trawl cod end (T90 experiments) or in the net cod end (selective grid experiments) are shown by a red line. The horizontal line at $y = 1$ shows expected equal catches in the modified and the standard fishing gears.
TABLE 5. Catch usability indicators for each species and gear modification for reducing bycatch in Mediterranean trawl fisheries. The table shows the mean value and the minimum and maximum values in brackets (all values as percents).

| Experiment | T90, north | T90, south | Selective grid |
|------------|------------|------------|----------------|
| Species    | European Hake | Red Mullet | Striped Red Mullet | European Hake | Deepwater rose shrimp | European Hake | Red Mullet | Striped Red Mullet |
| Standard gear: % under MLS (number) | 63.08 (0–93) | 0.23 (0–3.33) | 0 | 89.01 (82.02–94.34) | 33.86 (7.41–51.35) |
| Standard gear: % under MLS (weight) | 24.85 (0–53) | 0.05 (0–1.12) | 0 | 59.54 (36.52–64.78) | 19.32 (4.68–28.96) |
| Modified gear: % under MLS (number) | 44.91 (0–83) | 0.23 (0–1.96) | 0 | 82.54 (75.36–86.89) |
| Modified gear: % under MLS (weight) | 14.35 (0–37) | 0.04 (0–0.08) | 0 | 45.13 (39.76–57.93) |
| $nP-$ | 64.60 (8–143) | 100 (0–100) | 0 | 73.70 (29.66–145.21) | 102.60 (45.45–134.21) | 4.92 (0–33.33) |
| $nP+$ | 135.40 (18–1,100) | 100.70 (39.81–137.93) | 111.20 (42.86–700) | 126.20 (52.94–566.67) | 289.70 (70.59–1,300) | 142.50 (25.25–7,533) |
| $wP-$ | 85.20 (0–189) | 86.30 (0–86.30) | 0 | 71.20 (28.65–140.28) | 109.80 (42.93–148.75) | 111.20 (44.55–727.70) |
| $wP+$ | 168.20 (23–1,366) | 108.60 (42.93–148.75) | 115.60 (44.55–727.70) | 127.50 (53.49–572.50) | 1017.30 (52.49–134.21) | 556.10 (247.88–4,565) |
| $nRatio$ | 71.20 (13–142) | 99.30 (0–103.92) | 0 | 79.88 (39.88–105.93) | 89.50 (43.03–119.79) | 4.62 (0–12.50) |
| $wRatio$ | 57.70 (0–115) | 79.50 (0–83.20) | 0 | 75.80 (65.32–86.62) | 88.40 (42.50–118.32) | 1.69 (0–36.58) | 40.50 (28.45–77.59) |
In addition to the detailed analysis of the difference in catches of the target species, the loss of commercial catch was also empirically estimated in volume and value. This was done by considering the species composition of the standard and test nets, including both the target species and the commercial bycatch, and the average ex-vessel price fetched at the auction on the same days of the field trials. We estimated a loss of 20% in volume and 12% in value with the use of the T90 net in the northern area, and 14% and 13% (in volume and value, respectively) in the southern area. With the use of the selective grid, the loss in volume was estimated at 12% and 14% in value. These immediate losses cannot be translated directly into loss of economic profitability because, according to the vessel skippers, the selective devices also resulted in lower sorting time and lower fuel consumption.

**DISCUSSION**

Our results show that relatively simple modifications to trawl design can facilitate the escape of juvenile individuals of important commercial species of Mediterranean fisheries. In particular, the modification of the extension piece of the trawl with a panel of T90 netting or inserting a bycatch reduction device (selective grid) can make a bottom trawl more selective for larger individuals of target species such as the European Hake, Red Mullet, and deepwater rose shrimp. This is relevant in terms of fisheries management because stocks of these species in the Mediterranean suffer excessive exploitation rates on juveniles with the regulatory 40-mm square mesh cod end (Quetglas et al. 2017).

At the same time, undersized catches of these species cannot be discarded under the Landing Obligation of the reformed Common Fisheries Policy (Article 15 of EU Regulation 1386/2012). The adoption of these or similar technical solutions would help reduce the problem of generating unwanted catches, while at the same time permitting fishers to align the size at mean capture (L50) closer to the regulated minimum landing size. In the case of European Hake, the bulk of the catches with the regulatory mesh is typically higher than 20% in weight. In our T90 experiments, 24.85% in the north area and 59.54% in the south area (in weight) were under 20 cm TL when using the standard trawl net, and the addition of the T90 panel helped reduce this amount to 14.35% and 45.13%, respectively (Table 5). The position of the T90 panel was, however, important: placing it forwards in the extension piece (as in our T90 experiment in the south area) did not improve selectivity as much as placing it immediately in front of the cod end. Direct comparison between the two T90 designs should, however, take into account the different size structure in the north and south areas (compare Figures 5A and 5D).

In the southern area, the European Hake catches are dominated by a single mode of undersize individuals between 10 and 20 cm TL, while in the north a relatively large fraction of the catches have sizes between 20 and 30 cm TL. In the case of Red Mullet, the proportion of undersized individuals in the unmodified trawl was already low or 0, but nevertheless the T90 panel helped reduce significantly the catches of the smallest fraction (Table 5). Naturally, the introduction of a technological gear modification does not necessarily benefit all species equally. While the experiments with the T90 net in the north area showed clear selective effects for European Hake and Red Mullet, there was no evidence of changes to the selectivity of Striped Red Mullet. Likewise, the T90 design tested in the south area showed an improvement in the selectivity of deepwater rose shrimp but not for European Hake. Achieving good selective properties overall for demersal mixed fisheries will remain a complex issue (Sala et al. 2015), but modifying standard trawls to decrease retention of unwanted sizes for the main and highly overexploited target species in Mediterranean trawl fisheries is a necessary first step.

The choice of T90 mesh netting to modify trawls in demersal mixed fisheries has proved successful to facilitate escapement of juvenile fish of target species elsewhere, such as in Atlantic French mixed demersal fisheries (Robert et al. 2020), where both the extension piece and the cod end were built with T90 mesh. The use of T90 mesh in cod ends has been shown to result in trawls with better selective properties previously for other bottom trawl fisheries in the Mediterranean (Deval et al. 2016), Barents (Digre et al. 2010) or Baltic seas (Moderhak 1999) and helped also improve the quality of the fish product, resulting in better economic returns for the fisher (Hansen 2004; Digre et al. 2010).

In our experimental fishing trials, the selective grid was successful in separating the smaller fish fraction, which escaped through the grid, from the largest individuals which were retained in the cod end. This bycatch reduction device resulted in negligible retention of undersized European Hake in the cod end (4.92% in number and 15.30% in weight) compared with the control hauls in the T90 experiments (63.08% in number and 24.85% in weight). It has been shown that inserting selective grids in trawls can significantly reduce the proportion of unwanted catches, both in experimental and commercial conditions (Isaksen et al. 1992; Campos and Fonseca 2004, 2007).

The good selection properties of different designs of selective grids have been demonstrated in demersal mixed fisheries where, depending on the configuration, the technical modification can take advantage of the behavior of different species to facilitate selection. For example, in the Portuguese crustacean trawl fishery, a selective grid permitted the separation of the target crustaceans (deepwater rose shrimp and Norway lobsters *Nephrops norvegicus*) from unwanted fish bycatch, facilitating the escapement of 70% and 95%, respectively, of European Hake and Blue
more selective social and economic measures to facilitate the adoption of Sola and Maynou 2018b; Vitale et al. 2018a). Therefore, economic losses are amply compensated with mid- to gadoids. On the other hand, these potential short-term small-bodied bycatch, such as cephalopods and certain involving from 12% to 14%. Robert et al. (2020) showed also that a selective grid produced comparable economic losses, ranging from 12% to 14%. Robert et al. (2020) showed also that their modified trawl with the combined T90 extension and T90 cod end mesh reduced the catches of valuable, small-bodied bycatch, such as cephalopods and certain gadoids. On the other hand, these potential short-term economic losses are amply compensated with mid- to long-term gains, according to the results of bioeconomic projection models simulating the adoption of more selective fishing gear (Raveau et al. 2012; Prellezo et al. 2017; Sola and Maynou 2018b; Vitale et al. 2018a). Therefore, social and economic measures to facilitate the adoption of more selective fishing gear must accompany the strictly technical work. In this sense, technical solutions originating from a dialogue between the fishing industry and fisheries technologists and tested in commercial conditions (O’Neill et al. 2019; Veiga-Malta et al. 2019) are advantageous. For instance, the classical Nordmøre separator grid was quickly and widely adopted by Norwegian shrimp fisheries because it led to a strong reduction in unwanted bycatch, but also because it resulted in reduced sorting time and enhanced quality of the product (Isaksen et al. 1992).

Another important aspect to be taken into consideration when analyzing the selectivity of the trawl gears is linked to the protection of the exploited sensitive and productive habitats that are part of fishing grounds. The evidence of less capture of undersized or juvenile demersal target species (as well as noncommercial invertebrates) offers reasonable and positive perspectives that suggest that these modified trawl designs have a lower impact on exploited populations. Decreasing these effects on habitats is also beneficial to the communities and species without economic value that are part of the discard, such as for the majority of invertebrates that easily can escape both T90 and selective grids.

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