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SPECIALTY SECTION

This article was submitted to
Marine Fisheries, Aquaculture and
Living Resources, a section of the journal
Frontiers in Marine Science

RECEIVED 04 August 2022

ACCEPTED 06 March 2023

PUBLISHED 26 April 2023

CITATION

Geraci ML, Sardo G, Scannella D, Falsone F,
Di Maio F, Gancitano V, Fiorentino F,
Chirco P, Massi D and Vitale S (2023)
Exploring the feasibility of technological
transfers of two by-catch reduction
devices in the crustacean bottom trawling
of the central Mediterranean.
Front. Mar. Sci. 10:1011605.
doi: 10.3389/fmars.2023.1011605

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Exploring the feasibility of technological transfers of two by-catch reduction devices in the crustacean bottom trawling of the central Mediterranean

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Introduction: Most Mediterranean fish stocks are overexploited owing to high fishing efforts and poor exploitation patterns. Demersal trawl fisheries are considered the most impactful fishery type because of the high quantities of unwanted catch that is then routinely discarded at sea.

Methods: In the present study, two types of by-catch reduction devices (BRDs), that is a sorting grid (Grid-T45 40 mm) and a T90 50 mm codend, were compared to a typical commercial bottom trawl net (control) in terms of size structures and catch per unit effort to assess the effect of gear modification on the selectivity of crustacean fisheries in the central Mediterranean Sea. In particular, three randomly selected trawlers were involved in a paired hauls experiment fishing at the same time in the same fishing ground. Each trawler carried out four hauls per day during a 3-day campaign for a total of 36 hauls. The target species of the fishery is *Parapenaeus longirostris* (herein DPS), and the main commercial by-catch is *Merluccius merluccius* (herein HKE).

Results: The results showed that the landing per unit effort (LPUE) of DPS was higher for Grid-T45 40 mm net, although it did not differ significantly from that of the control net. Conversely, the discard per unit effort (DPUE) of the control net was significantly higher than of both BRD configurations. For HKE, a slightly higher LPUE was recorded using the T90 50 mm codend compared to that of the control, but this result was not statistically significant. The lowest DPUE was found for the T90 50 mm codend, with significant differences compared to that of the control and Grid-T45 40 mm net. The catch comparison of the size structures analysed through generalised linear mixed models highlighted that the Grid-T45 40 mm net was more effective in catching adult DPS, whereas the T90 50 mm codend was more selective for adult HKE.

Discussion: In conclusion, although further studies should be carried out in future to test the performance of the BRDs in different areas and seasons, the investigated gear seems to be promising for reducing the catch of undersized individuals and contributing to mitigating the current overfishing of DPS and HKE.

KEYWORDS

selectivity, discard, *Parapenaeus longirostris*, *Merluccius merluccius*, T90 codend, sorting grid

1 Introduction

The Mediterranean Basin is affected by a very high level of human pressure (Micheli et al., 2013). Among these pressures, fisheries are considered one of the main sources of impact on marine ecosystems, with most of the exploited stocks being overfished (Colloca et al., 2013; Vasilakopoulos et al., 2014; Colloca et al., 2017). Despite efforts to establish an effective legal framework and ensure the implementation and compliance of the fishery sector, 75% of the assessed stocks in the Mediterranean are still considered to be threatened by overfishing (Food and Agriculture Organization (FAO), 2020). Furthermore, the increasing level of fishing effort applied in the last three decades has led to profound modification of the marine ecosystem in terms of loss of biodiversity (Coll and Libralato, 2012; Piroddi et al., 2017).

Among the different fisheries, bottom trawling is considered one of the most impactful techniques in the Mediterranean, due to high quantities of unwanted catch, including the incidental catch of non-target species and juveniles of both target and non-target species, which are either discarded because of their low economic value or because of legal restrictions (Pravin et al., 2011; Gorelli et al., 2016; Tsagarakis et al., 2017; GFCM, 2018; Sardo et al., 2020a).

In the Strait of Sicily, one of the most productive areas for demersal resources in the Mediterranean Sea, a large trawler fleet is present, where 785 trawlers from Italy, Malta, and Tunisia exploit shared resources in international waters (Colloca et al., 2017). Among the different species targeted by bottom trawling, the deep-water rose shrimp *Parapenaeus longirostris* Lucas, 1846 (herein DPS) is one of the most important in terms of landings and revenue (Di Maio et al., 2022). However, in the DPS trawl fisheries of the Strait of Sicily, a discarded fraction of 25–40% of the total catch has been reported (Milisenda et al., 2017). Therefore, the General Fisheries Commission for the Mediterranean (GFCM) adopted the Recommendation GFCM/44/2021/12 on a multiannual management plan for bottom trawl fisheries exploiting demersal stocks in the Strait of Sicily, which aims to ensure the sustainable use of marine living resources through measures to prevent overfishing, including selectivity to minimise discard. In addition, according to Reg. UE 1241/2019, fishermen must use square mesh codends (terminal end of the net) with a minimum mesh size of 40 mm or, only upon approval of a request, a 50 mm diamond mesh. These legal codend mesh sizes allow the catching

adults of small to medium sized species, such as shrimps, red mullet, and cephalopods, but do not prevent the catching of undersized specimens of medium to large sized species, such as European hake (*Merluccius merluccius*, herein HKE), monkfish, and horse mackerel (Vitale et al., 2018a; Vitale et al., 2018b; Lucchetti et al., 2021). Because adopting a larger mesh size in the codend implies a strong reduction in the valuable fraction of catch, different technical solutions are being tested to modify the mesh shape to reduce the unwanted by-catch from trawling in the Mediterranean Sea. Considering the selectivity of the T90 (i.e., a diamond mesh turned 90°) codend, this solution was tested in the Adriatic Sea (Petetta et al., 2020) and the Aegean Sea (Dereli and Aydin, 2016; Deval et al., 2016; Genç et al., 2018), but not in the Strait of Sicily. The T90 codend, compared to other meshes currently used by trawlers, should remain more open during fishing operations, allowing undersized fishes and shrimps to escape. Given that the T90 codend is a very simple modification that does not involve any technical handling problems or any safety risk, it could be more easily accepted by fishing communities of the Strait of Sicily. Other promising by-catch reduction devices (BRDs) are the sorting grids, which are placed in the extension section of the trawl net. In the Mediterranean, the adoption of sorting grids in bottom trawling fisheries was tested to avoid catching undersized specimens of the target species, such as DPS and HKE (e.g., Sardà et al., 2004; Sardà et al., 2005; Bahamon et al., 2007; Aydin and Tosunoğlu, 2012; Vitale et al., 2018a; Vitale et al., 2018b), as well as to reduce the unwanted by-catch of sharks (Brčić et al., 2015) and sea turtles (Lucchetti et al., 2016; Lucchetti et al., 2019). The grid tested in the present study was similar to that tested by Vitale et al. (2018a); Vitale et al. (2018a), but the novelty was that, for the first time, to our knowledge, it was installed in a commercial, rather than an experimental, trawl net. In particular, it was constructed with a steel frame and a stretched 40 mm square mesh in the selective area. The fishes and shrimps were conveyed toward the selective area of the grid through a funnel, allowing them to pass through this area, thus by-catch could be released, while the individuals that did not pass through the grid meshes were pushed down and retained by the codend mesh. Although the previous finding of all relevant studies point to a generally positive impact of sorting grids on the size at capture of commercial species as well as reducing the amount of unwanted by-catch, their adoption in Mediterranean trawl fisheries remains very low. The lack of sorting grid implementation could be linked to several causes, including fishers' resistance to changing their behaviour and,

consequently, their unwillingness to modify their fishing gear (Vitale et al., 2018a). Other possible causes are linked to the lack of efficient technology transfer from researchers to fishers (e.g., Morrissey and Almonacid, 2005) as well as the overall weakness of fishing management in the Mediterranean region (Colloca et al., 2017).

To reduce the catch of undersized DPS and of HKE (unwanted by-catch according to the definition provided by ICES, 2020), the present study explored options to facilitate the transfer of BRDs to DPS trawl fisheries, showing important implications for their long-term sustainability, in-line with the management goals of the EU Common Fisheries Policy, CFP (reg. EC 1380/2013).

2 Material and methods

2.1 Study area

The study area, located in the northern part of the Strait of Sicily, belongs to Geographical Sub-Area 16 (GSA16 - South of Sicily), according to the GFCM classification (GFCM, 2007; Figure 1). GSA16 is characterised by a wide continental shelf with an intense hydrographic circulation pattern, a stable upwelling system, and high biodiversity (Di Lorenzo et al., 2018). These abiotic and biotic features lead to high productivity of fish resources, which are exploited by a multinational fleet in national and international waters (Di Maio et al., 2022; Falsone et al., 2022; Jarboui et al., 2022).

2.2 Sampling design

In December 2020, a 3-day selectivity campaign was conducted with three trawlers based at the Mazara del Vallo harbour. The fishing vessels operated simultaneously and in parallel according to a paired hauls design (Wileman et al., 1996) in a DPS fishing ground where the main commercial by-catch, according to the definition of ICES (2020), is HKE (Figure 1).

Given that the involved trawlers were not exactly the same in terms of overall length, to assess the potential variability among them, the swept area (A) of each haul to which the catch was estimated according to the formula proposed by Sparre and Venema (1998):

$$A = D * Hr * X, \quad (1)$$

where D is the distance covered during the haul, Hr is the length of the head-rope, and X is a fraction of Hr . Multiplying $X * Hr$ gives the width of the path swept by the trawl, the so-called wing 'spread'. According to Pauly (1980), a value of X of 0.5 is the best compromise for a demersal otter trawl. Finally, for each haul, the higher swept area recorded by a vessel was compared to the other areas as a percentage difference ($\Delta\%$) (Table S1).

On a daily basis, each vessel carried out four hauls of 90 min (usually in the commercial fishery, the haul duration ranged between 120 and 150 min) for a total of 12 hauls per day per vessel and 36 hauls over the campaign. In particular, one vessel used a control net; namely, a typical trawl net used by the Italian fleet in the Strait of Sicily with a 40 mm square mesh codend, whereas the other two vessels rigged the nets (test) with a sorting grid (i.e., Grid-T45 40 mm; see section 2.3 and Vitale et al., 2018a, for details) in the extension section (just in front of the codend) and a T90 50 mm codend, respectively. Due to the SARS-CoV-2 pandemic, scientific observers were unable to follow fishing operations on board. To overcome this problem, a video camera was installed on the stern of each vessel to register all fishing operations. The fishers were trained on the aims of the project and the sampling procedures of the commercial and discarded fractions of DPS and HKE. In particular, for the purpose of the study, for each haul the on-board activity included: i) recording of the geographical coordinates, depth, and fishing time (start and end); ii) sorting the catch and sampling the commercial fraction of DPS and HKE selected according to the fishers' habits; iii) recording the weight (in kg) of the commercial catch of DPS and HKE by counting the box number (a box of DPS corresponded to 2 kg, while a box of HKE corresponded to 6 kg), iv) sampling the discarded marine organism fraction (including undersized specimens of DPS and HKE); and v) recording the total amount of marine organisms rejected and returned to the sea, the so-called discard. Each fishing trip was monitored remotely using an AIS tracking system. The sorting of the catch on-board and how fishers sub-sampled discard were assessed through visual inspection of the frame recorded by the video camera. The recordings of discard sampling were compared to the fishers' self-reported data. In addition, given that the number of hauls carried out on each fishing day was known (i.e., four), the number of boxes of both species was counted at the landing port, which was compared with the fishers' self-reported data by summing the number of boxes reported in each haul. Representative samples of DPS and HKE commercial (one box per category) and discarded

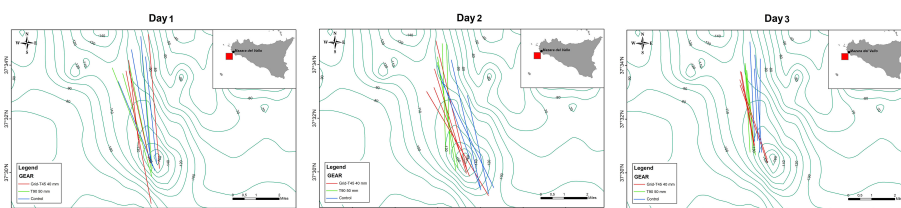


FIGURE 1

Maps of the hauls carried out with the control (blue line), T90 50 mm codend (green line), and Grid-T45 40 mm (red line) nets over 3 days of the survey. The study area is highlighted with a red square box.

(5–10 kg, min–max, of discard) fractions by haul were brought to the National Research Council (CNR) laboratory, weighed (0.1-gram accuracy), and measured (to the nearest 5 mm total length [TL] for HKE and to the nearest 1 mm for carapace length [CL] of DPS) individually.

2.3 Gear description

During the campaign, the vessels used very similar trawl nets, except for the BRDs (Supplementary Figures 1–3).

2.3.1 Control trawl with a T45 40 mm codend

The control trawl was built with a nominal 50 mm diamond mesh and polyamide nylon netting in the main body and extension sections of the net whereas the codend had a 40 mm square mesh. The control trawl had an overall length of 54.75 m, a 57 m-long headrope (diameter, hereinafter \varnothing , 24 mm, polyamide–stainless-steel combined material), a 64.90 m-long footrope (\varnothing 36 mm, polyamide–stainless-steel combined material) with steel chain, and 800 and 900 meshes of circumference in the upper and lower part of the net, respectively (Supplementary Figure 1). It was rigged with two bottom trawl doors high yield type (150×95 cm, 200 kg each).

2.3.2 Test trawl mounting Grid-T45 40 mm

The design of the test trawl, which mounted the grid system in the extension section, was equivalent to that of the control trawl. Therefore, the only major difference between the two trawls was the presence of the grid in the test one. The sorting grid was similar to that tested by Vitale et al. (2018a), including a funnel panel (opening 20 mm, square mesh) of approximately 3 m, adapting its size to the local trawl nets (Figure 2). Specifically, the grid was built with a stretched net of 40 mm square mesh (selective area of the grid) directly sewn to a steel frame (150 × 110 cm) and placed in the extension part of the trawl net. Other slight differences to the control trawl were their overall length (54.75 m control vs 56 m Grid-T45 40 mm), the headrope length (57 m control vs 60 m Grid-T45 40 mm), and the footrope length (64.90 m control vs 68 m Grid-T45 40 mm) (Supplementary Figure 2). It was rigged with two bottom trawl doors high yield type (158 × 97 cm, 230 kg each).

2.3.3 Test trawl mounting T90 50 mm codend

The design and dimensions of this test gear were similar to those used in the DPS fishery, except for the T90 50 mm codend. The trawl slightly differed from the control one for the overall length (54.75 m control vs 55.15 m T90 50 mm codend), the headrope length (57 m control vs 58 m T90 50 mm codend), and the footrope length (64.90 m control vs 66 m T90 50 mm codend) (Supplementary Figure 3). The trawl was spread using the same trawl doors as the Grid-T45 40 mm.

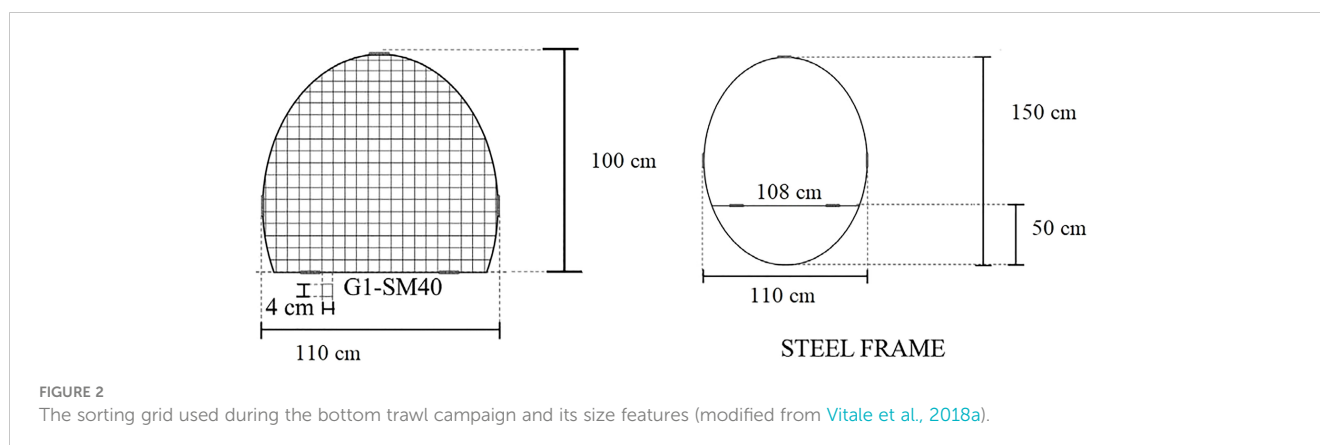
Notably, the extension pieces of the three trawl nets were cylindrical, with a total length of 10 m and 500 meshes in circumference, whereas the codend was 6 m long, with a twine \varnothing of 3 mm and 350 meshes in circumference. The sweeps of the three trawls were approximately 652 m long (slightly changing according to the depth of the fishing ground) and had a \varnothing of 14 mm, while warps were approximately 250 m long and had a \varnothing of 30 mm.

The mesh openings of the extension pieces and the codends of the three types of gears were measured 30 times each in wet conditions with a digital Vernier calliper, with a 4 kg weight tied vertically to the stationary jaw (Cárdenas et al., 1997; Aydın and Tosunoğlu, 2012). The meshes in the extension section of the three nets were equal to 48.95 ± 2.10 mm (control; mean \pm standard error), 49.10 ± 1.56 mm (Grid-T45 40 mm), and 50.21 ± 1.34 mm (T90 50 mm codend). The meshes in the codends were 39.45 ± 1.13 mm (control), 38.95 ± 1.56 mm (Grid-T45 40 mm), and 49.65 ± 1.45 mm (T90 50 mm codend).

2.4 Catch comparison analysis

2.4.1 Landing per unit effort and discard per unit effort

The commercial and discarded DPS and HKE fractions classified according to the fishers' habits had two different subsampling ratios (where the subsampling ratio was calculated as sample in kg/total catch in kg). To ensure that the global subsampling was correctly calculated, the methodology proposed by Cosgrove et al. (2019) was applied. The required sub-sampling ratio q_l for the combined discarded (q_d) and commercial (q_c) fractions solves the following equation:



$$\frac{nd_{li}}{qd_i} + \frac{nc_{li}}{qc_i} = \frac{n_{cli} + n_{dli}}{q_l}, \quad (2)$$

where $\frac{nd_{li}}{qd_i}$ is the raised count of the discard and $\frac{nc_{li}}{qc_i}$ is the raised count of the commercial fraction. Re-arranging (2) gives the following equation:

$$q_l = \frac{q_{dl}q_{cl}(nd_{li} + nc_{li})}{q_{cl}nd_{li} + q_{dl}n_{dli}} \quad (3)$$

This demonstrates that the combined sub-sampling ratio of the combined fractions was length-dependent. This ensures that the raised counts for the total (right-hand side of Equation 2) were equal to the sum of the separately raised counts (left-hand side of Equation 2). After being raised, the DPS and HKE individuals were re-classified into commercial and discarded fractions according to the minimum conservation reference size (MCRS) defined by Reg. EU 1241/2019, that is, above (commercial) and below (discarded) 20 mm CL and 200 mm TL, respectively. Then, their total weight in kg was standardized to 1 h to obtain the catch per unit effort (CPUE) expressed as kg/h by species. In particular, the catch rates of the commercial fraction were herein named landing per unit effort (LPUE) while the catch rates of the discard fraction were herein named discard per unit effort (DPUE). Linear mixed models (LMMs) were applied by species to evaluate whether the control and test nets differed significantly, without any assumption regarding the direction (i.e., two-tailed). The catch rates were contrasted against gear on a logarithmic scale, including the hauls as a random intercept, i.e., assuming that an intercept was different for each level of the variable 'gear'. To check the significance of the variable 'gear' in the model, a likelihood ratio test was applied. In the case of significant differences, *post-hoc* Tukey HSD tests were performed to compare the gear to one another. To directly interpret the coefficient estimates of the LMMs and Tukey HSD tests, they were transformed as antilogs. The LMMs were run through the 'lme4' package (Bates et al., 2015) whereas the Tukey HSD test used the 'multcomp' package (Hothorn et al., 2008). All analyses were carried out in R Studio version 3.6.3 (R Core Team, 2020).

2.4.2 Size structures

The probability of retaining a fish of a given length in the test net in relation to the total catch was assessed according to the method proposed by Fryer et al. (2003) and Holst and Revill (2009). A comparison was made between 12 hauls (i.e., 12 in the test and 12 in the control nets), and the length classes were set at 2 mm CL and 20 mm TL for DPS and HKE, respectively. The undersized specimens were identified as fish with lengths below the MCRS.

The observed average catch comparison for each length class (CC_l) was expressed as follows:

$$CC_l = \frac{\sum_{i=1}^{12} n_t}{\sum_{i=1}^{12} n_t + \sum_{i=1}^{12} n_c}, \quad (4)$$

where n_c and n_t are the number of fish caught in each length class l in the control and test nets, respectively (e.g., Vitale et al., 2018a; Geraci et al., 2021a). The observed proportion of catch caught in the

test gear of each selected species was modelled to obtain a catch comparison curve using generalised linear mixed models (GLMMs) with a binomial distribution, where hauls were included as random intercept, using the Laplace approximation, to remove the variance linked to the expected change in abundance/catchability of the investigated species during the days and timeframes (Holst and Revill, 2009). A value of 0.5 for the catch comparison curves, $CC(l)$, indicates that there is the same probability of capturing a fish of length l in the test and control. A value above 0.5 indicates a higher probability of catching a fish of length l in the test compared to the control, and vice versa for a value below 0.5. The global sub-sampling ratio (q_b , see Section 2.4.1) in the test and control nets was also included as an offset in the model (Fryer et al., 2003; Holst and Revill, 2009). In addition, the models were fitted using splines with different degrees of freedom (df). The df in the model were assigned based on the fitting of predictions and observations. Subsequently, the model fit was checked by assessing the residuals.

To directly quantify the relative length-dependent gear catch efficiency of the test versus control net, the so-called 'catch ratio' (CR), that is, the ratio between the catch of the control and test trawl nets of a given length, l , was estimated (e.g., Melli et al., 2020; Lomeli et al., 2021; Geraci et al., 2021a). In particular, $CR(l)$ was computed as:

$$CR(l) = \frac{CC(l)}{1 - CC(l)}, \quad (5)$$

being $CC(l)$ the predicted values of the catch comparison model (based on Equation 4). A value of 1.0 for $CR(l)$ indicates no difference in catch efficiency between the test and the control. On the other hand, a value of 0.60 or 1.45 indicates that the probability of fish being caught for a given length with the test net is 40% less or 45% more, respectively, than that sampled with a control net. To provide a global idea of the effect of the tested BRDs, the $CR(l)$ has been shown as the overall mean. The 95% confidence intervals of $CC(l)$ and mean $CR(l)$ were estimated from the model predictions and using the $qt()$ function in R language to return the inverse probability cumulative density of the Student t -distribution. All size structure analyses were carried out with R version 3.6.3 using the package 'glmmTMB' (Brooks et al., 2017).

3 Results

3.1 Operational information and catches

The depth of the surveyed fishing grounds ranged between 89 and 170 m (i.e., the continental shelf). The commercial sub-sampled fraction for DPS ranged between 2 and 15 whereas no subsampling was required for the commercial fraction of HKE. The sub-sampling fraction of the discard for DPS ranged between 2 and 16, whereas that for HKE ranged between 2 and 6. The size ranges of the DPS specimens caught by the control and T90 50 mm codend (5/6–31 mm CL) were very similar, while specimens retained by the Grid-T45 40 mm net were slightly bigger (10–34 mm CL). The size ranges of HKE specimens were 55–700 mm TL for the control, 55–570 mm TL for Grid-T45 40 mm, and 75–635 mm TL for the T90 50 mm codend (Table 1).

TABLE 1 Description of the fishing operations by haul carried out during the survey.

Gear	Day	N haul	Start	Duration (minutes)	Depth range (m)	Species	G	N. measured samples-discard	q _d	N. measured samples-commercial	q _c	Length range (mm)
Control	1	1	06:45	90	139-139	DPS	22824	130	0.33	495	0.10	10-28
						HKE	6186	5	0.50	124	//	95-425
Grid-T45 40 mm	1	1	06:40	90	141-145	DPS	25933	38	//	459	0.10	11-32
						HKE	13027	10	//	160	//	90-520
T90 50 mm codend	1	1	06:45	90	140-143	DPS	2282	4	0.17	354	//	13-31
						HKE	10585	//	//	42	//	80-520
Control	1	2	08:40	90	145-97	DPS	25145	64	0.17	560	0.10	5-29
						HKE	7705	2	//	117	//	90-530
Grid-T45 40 mm	1	2	08:45	90	147-100	DPS	28581	62	//	458	0.10	11-32
						HKE	8875	11	//	70	//	115-530
T90 50 mm codend	1	2	08:50	90	145-98	DPS	3186	4	0.33	563	//	12-28
						HKE	11584	//	//	40	//	215-445
Control	1	3	10:50	90	143-148	DPS	24077	54	0.12	522	0.10	9-28
						HKE	6460	5	0.17	35		55-575
Grid-T45 40 mm	1	3	10:50	90	146-152	DPS	28781	19	//	519	0.10	12-34
						HKE	6056	12	//	71	//	120-400
T90 50 mm codend	1	3	10:45	90	150-153	DPS	3070	11	0.50	548	//	13-28
						HKE	10427	3	0.50	49	//	125-590
Control	1	4	12:40	90	148-119	DPS	30034	114	0.17	548	0.08	9-29
						HKE	7054	3	//	27	//	60-530
Grid-T45 40 mm	1	4	12:35	90	145-117	DPS	35652	43	//	459	0.07	11-28
						HKE	4743	9	//	47	//	55-570
T90 50 mm codend	1	4	12:35	90	146-120	DPS	8817	//	//	360	0.25	13-31
						HKE	9745	//	//	32	//	135-605
Control	2	1	06:00	90	143-143	DPS	16292	199	0.17	584	0.20	10-31
						HKE	8583	5	0.33	126	//	65-400
Grid-T45 40 mm	2	1	06:00	90	145-147	DPS	16292	//	//	535	0.17	10-32
						HKE	2439	//	//	42	//	60-505
T90 50 mm codend	2	1	06:00	90	143-146	DPS	4289	//	//	450	0.50	6-28
						HKE	5276	//	//	15	//	210-505
Control	2	2	08:00	90	146-117	DPS	39615	33	0.06	555	0.07	10-28
						HKE	19663	3	0.20	143	//	75-700
Grid-T45 40 mm	2	2	08:05	90	145-120	DPS	44889	26	//	556	0.07	12-32
						HKE	5066	9	//	23	//	120-470
T90 50 mm codend	2	2	08:05	90	143-118	DPS	4424	16	0.50	711	//	13-30
						HKE	12255	//	//	31	//	215-495

(Continued)

TABLE 1 Continued

Gear	Day	N haul	Start	Duration (minutes)	Depth range (m)	Species	G	N. measured samples-discard	q _d	N. measured samples-commercial	q _c	Length range (mm)
Control	2	3	10:15	90	150-170	DPS	34733	65	0.17	486	0.07	10-29
						HKE	4759	5	0.50	20	//	75-460
Grid-T45 40 mm	2	3	10:20	90	145-168	DPS	40311	36	//	497	0.07	12-31
						HKE	2371	13	//	40	//	110-250
T90 50 mm codend	2	3	10:15	90	143-172	DPS	5867	//	//	543	0.50	11-29
						HKE	6063	//	//	27	//	220-485
Control	2	4	12:10	90	155-110	DPS	22909	113	0.33	579	0.12	10-27
						HKE	2002	3	0.25	99	//	100-165
Grid-T45 40 mm	2	4	12:10	90	152-113	DPS	25994	25	//	477	0.10	11-29
						HKE	3795	15	//	26	//	85-510
T90 50 mm codend	2	4	12:05	90	146-110	DPS	1447	77	0.33	122	//	13-27
						HKE	1208	//	//	4	//	295-385
Control	3	1	06:15	90	137-152	DPS	14233	94	0.33	595	0.20	8-29
						HKE	6293	4	//	27	//	85-640
Grid-T45 40 mm	3	1	06:15	90	139-150	DPS	14618	//	//	563	0.20	13-29
						HKE	5781	//	//	19	//	145-570
T90 50 mm codend	3	1	06:10	90	146-155	DPS	3205	45	0.50	638	//	12-26
						HKE	5112	//	//	18	//	75-550
Control	3	2	07:55	90	146-95	DPS	23932	155	0.25	496	0.10	10-28
						HKE	10720	//	//	71	//	125-505
Grid-T45 40 mm	3	2	08:00	90	144-89	DPS	24462	9	//	458	0.10	12-33
						HKE	1962	4	//	18	//	130-370
T90 50 mm codend	3	2	07:55	90	141-93	DPS	5335	//	//	487	0.50	13-29
						HKE	5066	//	//	15	//	295-445
Control	3	3	09:30	90	126-148	DPS	17335	351	0.25	599	0.20	9-28
						HKE	2287	//	//	8	//	265-420
Grid-T45 40 mm	3	3	09:35	90	127-150	DPS	17137	21	//	542	0.17	12-31
						HKE	1578	4	//	7	//	125-405
T90 50 mm codend	3	3	09:30	90	132-145	DPS	1106	//	//	254	//	11-25
						HKE	3005	//	//	7	//	270-535
Control	3	4	11:15	90	145-117	DPS	15961	133	0.25	544	0.17	10-30
						HKE	2500	//	//	26	//	70-345
Grid-T45 40 mm	3	4	11:10	90	144-118	DPS	15529	28	//	498	//	10-30
						HKE	1463	5	//	3	//	110-440
T90 50 mm codend	3	4	11:10	90	139-115	DPS	5089	10	0.50	460	0.50	14-27
						HKE	5243	//	//	8	//	280-635

q_d: subsampling fraction of the discard according to fishers' habits; q_c: subsampling fraction of the commercial catch according to fishers' habits; //: not available.

3.2 LPUE and DPUE

The LPUEs of the DPS, were higher for the Grid-T45 40 mm configuration than for either the control or T90 50 mm codend, whereas the DPUEs were highest for the control gear. Conversely, the lowest catch rates were recorded for the T90 50 mm codend, for both LPUE and DPUE (Figure 3; Table 2). The LMMs considering LPUEs and DPUEs of DPS showed significant differences between

the gear (LPUE, $p < 4.045^{-13}$; DPUE, $p < 2.2^{-16}$). In particular, for LPUEs the HSD Tukey *post-hoc* test revealed significant differences between the T90 50 mm codend and control net and between the two BRDs, whereas no significant difference between the Grid-T45 40 mm and control net was recognized. The DPUEs differed significantly for all gear (Table 3).

For HKE, slightly higher median LPUEs were recorded using the T90 50 mm codend, followed by the control net, whereas the

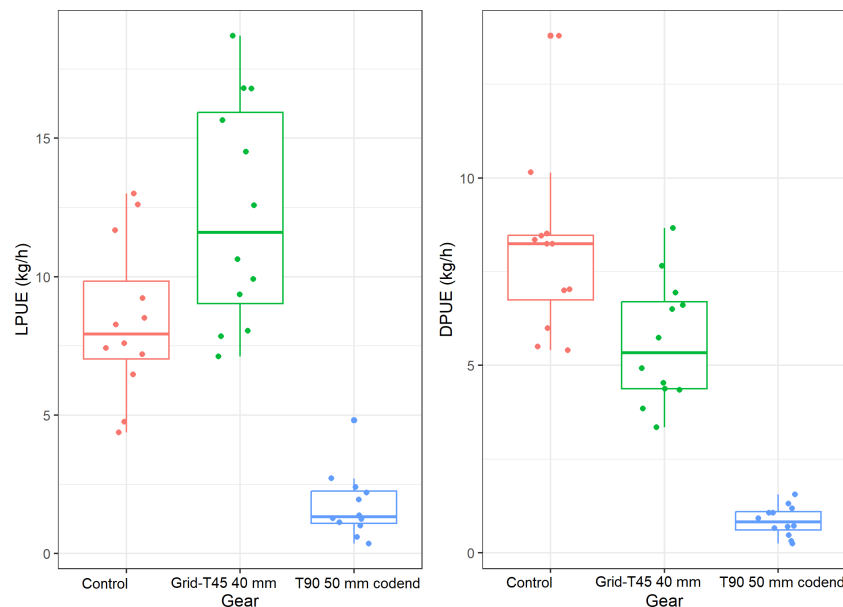


FIGURE 3

Boxplots of *Parapenaeus longirostris* (herein DPS) catch rates (kg/h) per gear caught during the campaign classified in landing per unit effort (LPUE; commercial) – left – and discard per unit effort (DPUE; discard) – right – according to the minimum conservation reference size (MCRS) established by the Reg. EU 1241/2019.

TABLE 2 Coefficient estimates for the catch rates of DPS and HKE modelled through linear mixed models in the catch fraction (commercial, LPUE and discard, DPUE).

Fraction		Gear	Estimate	s.e.	t value	<i>p</i>
LPUE	DPS	Intercept	7.995	1.152	14.691	4.045 ⁻¹³
		Grid T45 40mm	1.465	1.204	2.060	
		T90 50 mm codend	0.179	1.204	-9.271	
	HKE	Intercept	3.611	1.224	6.362	0.025
		Grid T45 40mm	0.571	1.262	-2.407	
		T90 50 mm codend	1.033	1.269	0.137	
DPUE	DPS	Intercept	7.793	1.127	17.199	< 2.2 ⁻¹⁶
		Grid T45 40mm	0.694	1.163	-2.415	
		T90 50 mm codend	0.096	1.163	-15.514	
	HKE	Intercept	0.529	1.485	-1.611	0.001
		Grid T45 40mm	0.746	1.728	-0.535	
		T90 50 mm codend	0.031	2.348	-4.058	

s.e. is the standard error.

TABLE 3 Outcomes of the Tukey HSD *post-hoc* test of the catch rates of DPS and HKE, classified in catch fraction (commercial, LPUE and discard, LPUE), among different gear.

Fraction		Contrast	Estimate	s.e.	z value	<i>p</i>
LPUE	DPS	Grid-T45 40 mm – Control	1.465	1.203	2.060	0.098
		T90 50 mm codend – Control	0.179	1.203	-9.271	<0.001
		T90 50 mm codend – GRID-T45 40 MM	0.122	1.203	-11.332	<0.001
	HKE	Grid T45 40mm – Control	0.571	1.262	-2.407	0.042
		T90 50 mm codend – Control	1.034	1.269	0.137	0.9897
		T90 50 mm codend – Grid T45 40mm	1.809	1.262	2.547	0.029
DPUE	DPS	Grid T45 40mm – Control	0.694	1.163	-2.415	0.042
		T90 50 mm codend – Control	0.096	1.163	-15.514	<0.001
		T90 50 mm codend – Grid T45 40mm	0.138	1.163	-13.099	<0.001
	HKE	Grid T45 40mm – Control	0.746	1.728	-0.535	0.851
		T90 50 mm codend – Control	0.031	2.347	-4.058	<0.001
		T90 50 mm codend – Grid T45 40mm	0.042	2.330	-3.749	<0.001

In bold are significant differences.

DPUEs were higher for the control gear and negligible for the T90 50 mm codend (Figure 4). The LMMs for LPUEs and DPUEs of HKE showed significant differences among the gear (LPUE, $p = 0.025$; DPUE, $p = 0.001$). Specifically, for LPUEs, the Tukey HSD *post-hoc* test revealed significant differences between Grid-T45 40 mm and control net and between the two BRDs, whereas no significant difference between the T90 50 mm codend and control net was recognised. For DPUEs, significant differences between the

pairwise comparison of Grid-T45 40 mm–T90 50 mm codend and T90 50 mm codend–control were detected (Table 3).

3.3 Size structures analyses

The length-frequency distributions of DPS and HKE showed that the bulk of the catch of the control was mainly composed of

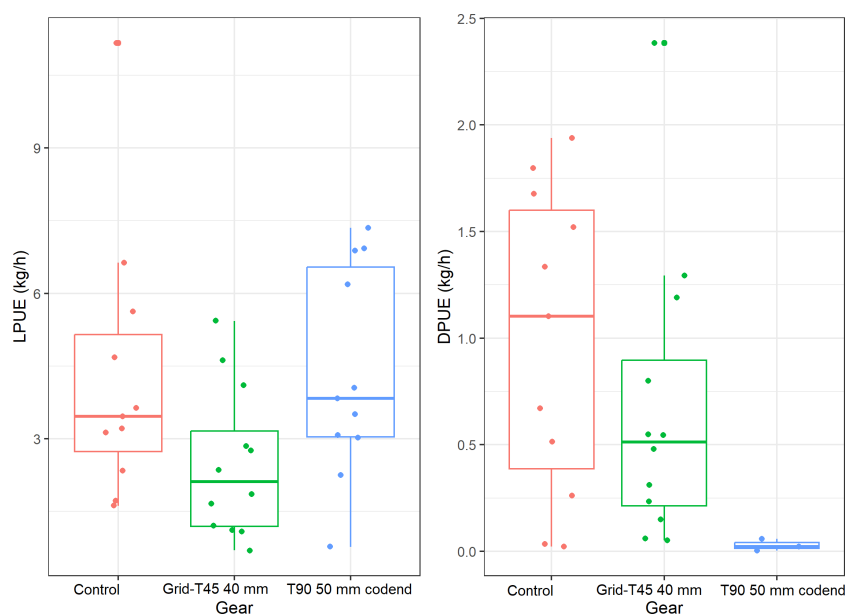


FIGURE 4

Boxplots of *Merluccius merluccius* (herein HKE) catch rates (kg/h) per gear caught during the campaign classified in landing per unit effort (LPUE; commercial) – left – and discard per unit effort (DPUE; discard) – right – according to the minimum conservation reference size (MCRS) established by the Reg. EU 1241/2019.

undersized specimens, indicating a potentially poor selectivity of the gear with legal mesh size in the codend. As for the BRDs, the Grid-T45 40 mm caught more commercial DPS whereas the T90 50 mm codend was more effective in catching adult HKE (Figures 5C, 6C).

The catch comparison, modelled through GLMMs for DPS, was run with 3 df when considering the Grid-T45 40 mm and control, whereas 4 df were set for the T90 50 mm codend vs. control. As for HKE concerns, 4 df (Grid-T45 40 mm vs Control) or 3 df (T90 50 mm codend vs Control) were used.

The final GLMMs by species, including their R codes, are presented in Table 4.

In particular, for DPS the Grid-T45 40 mm had a lower probability of catching undersized specimens compared to the control as the $CC(l)$ values were always lower than the level of no effect, that is, the same probability of catching an individual at a given length for both types of gear, or numerically $CC(l) = 0.5$. In contrast, there was an increase in the $CC(l)$ recorded for adults, showing that the Grid-T45 40 mm had a higher catch probability than the control, particularly for legal-sized specimens. An important increase in catch above the level of no effect was detected for individuals from 25 mm CL onward (Figure 5A). This trend is reflected in the mean $CR(l)$, which is very high (6.68, confidence interval: 6.63–6.77) (Figure 5D). However, the probability of catching DPS was always lower for the T90 50 mm codend configuration than for the control net (Figures 5B, D).

For HKE, the Grid-T45 40 mm showed lower efficiency than the control in capturing undersized fish. Conversely, the probability of

catching adults was equal to that of the control (Figure 6A). Importantly, the T90 50 mm codend showed a lower probability of catching undersized HKE specimens, whereas the $CC(l)$ values generally exceeded the level of no effect for commercial-sized specimens, except for a few individuals caught in the latest size classes (Figure 6B). The mean $CR(l)$ was below and above the level of no effect ($CR(l) = 1.00$) for Grid-T45 40 mm and T90 50 mm codend, respectively (Figure 6D).

4 Discussion

The adoption of both BRDs in DPS fisheries resulted in a reduction in the number of undersized DPS and HKE specimens in the catches, suggesting a potential overall enhancement in the exploitation pattern. In particular, the Grid-T45 40 mm seems to be a technological solution that could be capitalised on by commercial trawlers targeting DPS. In fact, the Grid-T45 40 mm provided a higher LPUE and a significant reduction in undersized DPS when compared to the other trawl net configurations. However, the T90 50 mm codend, tested in the Strait of Sicily for the first time, strongly reduced the catch of both legal and undersized DPS, thus, would not ensure the economic sustainability of the DPS fisheries. Regarding HKE, the most efficient gear was the T90 50 mm codend. It is worth noting that, although this device excluded almost all of the undersized HKE, higher catch rates were recorded for HKE due to an elevated number of legal-sized specimens. Given that the Tukey test did not detect significant differences between the LPUE of the T90 50 mm codend and the control, while overall the $CC(l)$

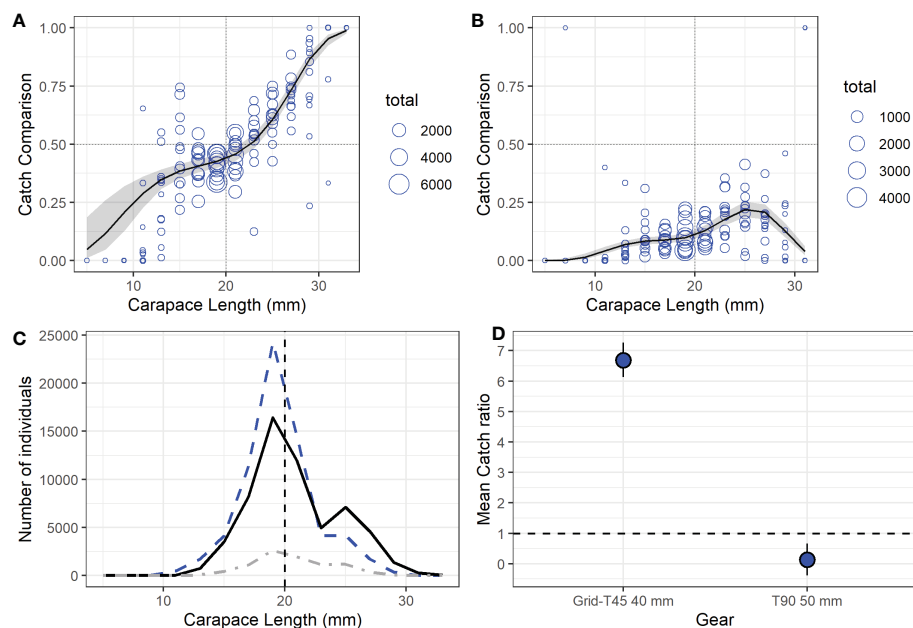


FIGURE 5

(A) Catch comparison curves for DPS caught with the Grid-T45 40 mm, and (B) with the T90 50 mm codend. Blue circles show observed proportions by haul, black dashed lines represent the model prediction, and the grey band indicates the 95% confidence limit. The level of no effect ($CC(l) = 0.5$) is shown by horizontal black dashed lines while the MCRS is shown by the black vertical dashed lines. (C) Length frequency distributions of DPS caught during the campaign. The blue dashed line represents the control, the continuous black line represents the Grid-T45 40 mm, and the dark grey line represents the T90 50 mm codend. Black vertical dashed lines depict the MCRS according to the Reg. EU 1241/2019. (D) The blue dots indicate the mean catch ratio ($CR(l)$), and horizontal bars indicate the 95% confidence limit. The level of no effect ($CR(l) = 1.0$) is depicted by horizontal black dashed lines.

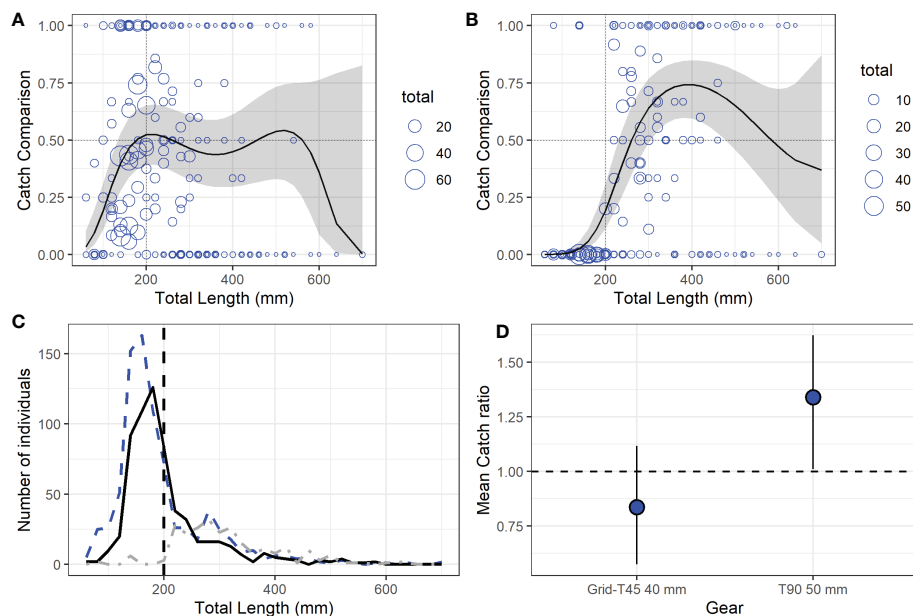


FIGURE 6

(A) Catch comparison curves for HKE caught with the Grid-T45 40 mm, and (B) with the T90 50 mm codend. Blue circles show observed proportions by haul, black dashed lines represent the model prediction, and the grey band indicates the 95% confidence limit. The level of no effect ($CC(l) = 0.5$) is shown by horizontal black dashed lines while the MCRS is shown by the black vertical dashed lines. (C) Length frequency distributions of DPS caught during the campaign. The blue dashed line represents the control, the continuous black line represents the Grid-T45 40 mm, and the dark grey line represents the T90 50 mm codend. Black vertical dashed lines depict the MCRS according to the Reg. EU 1241/2019. (D) The blue dots indicate the mean catch ratio ($CR(l)$), and horizontal bars indicate the 95% confidence limit. The level of no effect ($CR(l) = 1.0$) is depicted by horizontal black dashed lines.

highlighted a higher efficiency for the T90 50 mm codend in catching larger-sized HKE, an apparent inconsistency appeared. These differences were due to the different analyses applied; in particular, Tukey's test compared the mean value of catch regardless the size structure while $CC(l)$ described the variation of proportions in the catch of individuals by size, making it more informative in terms of selectivity aspects.

Considering the intrinsic relationship between the ecological purpose of the MCRS and mesh size, it seems clear that the common goal is to avoid catching juveniles until they are large enough to spawn (Beverton and Holt, 1957). From an economic standpoint, this means that juveniles are given time to grow to an economically valuable size before harvest. Indeed, according to Vasilakopoulos et al. (2014), overexploitation of HKE juveniles was particularly severe as they were being harvested during the first and second years of life before reaching sexual maturity. Despite the basic nature of this notion, the identification of an adequate legal mesh size could involve practical difficulties and management problems, mainly in fisheries where small-sized species, such as DPS, are caught together with fish that can reach a large size, such as HKE (Caddy, 1990; Fiorentino and Vitale, 2021). In other words, the adoption of a more selective mesh size for HKE would imply the loss of a large number of shrimp and other small-sized species, significantly reducing fishery profitability (Lucchetti et al., 2021).

For sorting grids, Vitale et al. (2018a) used an experimental trawl net with Grid-T45 40 mm in the same area and found a high sorting capability for DPS and HKE in the reduction of undersized

specimens with a minor loss of the marketable fraction for DPS; however, similar to the present study, a low amount of legal-sized HKE was retained by the Grid-T45 40 mm (Table 5; Vitale et al., 2018a). Similarly, Vitale et al. (2018a) further reported a higher number of larger-sized DPS individuals caught with the Grid-T45 40 mm compared to the control. These confirmed results could be due to the slightly higher vertical aperture of the trawl equipped with the Grid-T45 40 mm allowing the catching of larger DPS individuals while remaining at a greater height from the bottom. To support this hypothesis, by studying the catch of the lower, middle, and upper compartments in the codend of the bottom trawl fisheries of the Barents Sea, Larsen et al. (2021) found that the majority of deep-water shrimps (*Pandalus borealis* Krøyer, 1838) that entered the highest compartments of the trawl net were larger-sized individuals. Although further investigations through *ad-hoc* experiments are needed, the size-depth separation of the shrimps in the water column (vertical separation) can help improve the species/size selectivity of Mediterranean DPS bottom trawl fisheries, as suggested by oceanic studies (e.g. Engås et al., 1998; Graham and Fryer, 2006; Ferro et al., 2007; Karlsen et al., 2019).

In other Mediterranean demersal trawl fisheries, according to the present study, a substantial improvement in DPS and HKE selectivity was found through the incorporation of a sorting grid in the trawl net (Massutí et al., 2009; Aydın et al., 2011; Aydın and Tosunoğlu, 2012). Recently, in the Adriatic Sea, an improvement in the catch pattern of HKE was found even if a loss of marketable DPS was at the same time detected (Table 5; Sbrana et al., 2022).

TABLE 4 Selected GLMM models with coefficients estimates for the catch comparison curves (test vs control net) of DPS (*Parapenaeus longirostris*), and HKE (*Merluccius merluccius*) and the used R code to run them.

Species	Model (R code)	CC(I)	Estimate	Std. Error	z value	p
DPS	glmmTMB(prop~(bs(size, df=3))+(1 Haul)+offset(log(q_Grid/q_ctrl)), family = binomial(link = "logit"), weights = total, data= DPS_Grid)	Grid vs Control	(Intercept) 2.98	0.25	-11.77	$<2^{-16}$
			1 5.21	0.49	10.62	$<2^{-16}$
			2 -0.56	0.13	-4.21	2.53^{05}
			3 7.53	0.37	20.43	$<2^{-16}$
	glmmTMB(prop~(bs(size, df=4))+(1 Haul)+offset(log(q_T90/q_ctrl)), family = binomial(link = "logit"), weights = total, data= DPS_T90)	T90 vs Control	(Intercept) -8.95	1.30	-6.88	5.91^{12}
			1 7.92	1.51	5.26	1.45^{07}
			2 4.79	1.17	4.08	4.47^{05}
			3 9.17	1.37	6.69	2.19^{11}
HKE	glmmTMB(prop~(bs(size, df=4))+(1 Haul)+offset(log(q_Grid/q_ctrl)), family = binomial(link = "logit"), weights = total, data= HKE_Grid)	Grid vs Control	(Intercept) -3.34	0.62	-5.38	7.50^{08}
			1 4.00	0.81	4.93	8.28^{07}
			2 2.29	0.65	3.55	3.80^{04}
			3 4.25	1.47	2.89	3.83^{03}
	glmmTMB(prop~(bs(size, df=3))+(1 Haul)+offset(log(q_T90/q_ctrl)), family = binomial(link = "logit"), weights = total, data= HKE_Grid)	T90 vs Control	(Intercept) -7.94	0.96	-8.28	$<2^{-16}$
			1 13.98	2.29	6.10	1.05^{09}
			2 7.56	1.11	6.75	1.46^{11}
			3 7.41	1.80	4.12	3.70^{05}

prop, proportion; bs, b-spline; df, degree of freedom; q, subsampling fractions; CC(I): catch comparison curves; Std. Error: standard error. In bold, significant terms.

Similar to the present study, an improvement in the selectivity of HKE was found using a T90 50 mm codend in the Adriatic Sea, even if the nominal mesh size was inefficient at retaining specimens of commercial sizes of *Mullus barbatus* (Linnaeus, 1758), *Trachurus mediterraneus* (Steindachner, 1868), *Loligo vulgaris* (Lamarck, 1798), and *Merlangius merlangus* (Linnaeus, 1758; Petetta et al., 2020). Conversely, an increase in selectivity for mantis shrimp (*Squilla mantis*) (Linnaeus, 1758), allowing the escape of juvenile individuals often discarded by fishers, was reported. In the Aegean Sea, the T90 44 mm codend improved in the size of the first capture of HKE (Genç

et al., 2018) whereas the T90 40 mm improved selectivity for *M. barbatus* and *T. trachurus* (Dereli and Aydin, 2016). Recently, on the eastern coast of Spain, modifying trawl extension with a T90 50 mm panel resulted in decreased fishing mortality for younger age classes of HKE and *M. barbatus* (Maynou et al., 2021), while in the Adriatic Sea (Petetta et al., 2022), and northern Tyrrhenian Sea (Sbrana et al., 2022) the application of a T90 40 mm panel in the extension piece did not significantly reduce the catch of juveniles of the target species (Table 5).

Given that demersal twin trawls are not present in the Strait of Sicily, the trawlers involved in this study were as similar as possible to

TABLE 5 Results of research in the Mediterranean Sea during which the sorting grid or T90 mesh was tested.

Area	BRD	Codend (mesh size/ orientation)	Method	Target species	Result	Reference
Western Mediterranean (Balearic Islands)	Flexible sorting grids, 15 and 20 mm bar spacing	T0 40 mm, T45 40 mm	Divided bottom trawl	DPS, HKE, <i>Mullus</i> spp., <i>Zeus faber</i> , <i>Lophius</i> spp., <i>Raja</i> spp., <i>Nephrops norvegicus</i> , <i>Lepidorhombus bosci</i> , <i>Aristeus antennatus</i>	Increased L_{50} for DPS, HKE, and most commercial species whereas the unwanted by-catch species were decreased.	Massuti et al., 2009
Aegean Sea	Sorting grid with 20 mm bar spacing	T45 40 mm T0 44 mm	Covered codend	DPS	For DPS a loss of 23% and 25% was detected in the T0 44 mm and T45 40 mm codends, respectively; For HKE, it was found that a larger part was excluded in the T45 40-mm rather than in the T0 44-mm codends. For all other species, separation values were generally high and similar for both codends.	Aydın et al., 2011
Eastern Aegean Sea (Sigacık Bay)	Sorting grid mounted at the end of a funnel, 10 and 15 mm bar spacing	T0 44 mm	Double codend	DPS	Separation ratios for HKE were between 96.3 and 100% in terms of weight. Separation ratios for DPS of 37.0% and 44.4% by weight in 10 and 15 mm grids, respectively.	Aydın and Tosunoğlu, 2012
Aegean Sea (Mytilene and Chios Islands/ Karaburun Peninsula and Kusadası Bay)	T90 40 mm	T0 44 mm T0 50 mm T45 40 mm T90 40 mm	Covered codend	HKE, <i>Dentex maroccanus</i> , <i>Mullus barbatus</i> , <i>Trachurus trachurus</i>	T90 40 mm codends improved the selectivity of <i>M. barbatus</i> and <i>T. trachurus</i> .	Dereli and Aydın, 2016
Aegean Sea (Kuşadası Bay)	T90 44-mm	T90 44 mm, 300 meshes on its circumference; T90 44 mm, 150 meshes on its circumference; T90 40 mm, 165 meshes on its circumference.	Alternate hauls	DPS, HKE, <i>T. trachurus</i>	For DPS no significant differences between L_{50} values of T90 40 mm and T90 44 mm were found. For HKE the T90 40 mm and T90 44 mm codends improved the L_{50} .	Genç et al., 2018
Strait of Sicily	Grid G1-SM40 made with a net of 40-mm square mesh; Grid G2-ST20 and Grid G3-ST25 made from vertical steel bars spaced 20 and 25 mm apart, respectively	T45 40 mm	Alternate hauls	DPS, HKE	G1-SM40 showed a reduction of undersized individuals of about 60% and 44% for DPS and HKE, respectively. G2-ST20 showed a 34% catch decrease of HKE individuals smaller than 20 cm TL. G3-ST25 was efficient at reducing the catch of undersized specimens of both target species but showed the highest loss of marketable fractions.	Vitale et al., 2018a
North-western Adriatic Sea	T90 54 mm	T0 54 mm, T90 54 mm	Covered codend	HKE, <i>Merlangius merlangus</i> , <i>M. barbatus</i> , <i>Loligo vulgaris</i> , <i>Squilla mantis</i> ,	T90 54 mm significantly excluded undersized specimens of HKE, whose average L_{50} was above the MCRS, and <i>Squilla mantis</i> . Both codends showed an excessive size selectivity, which involves a commercial loss, especially for <i>M.</i>	Petetta et al., 2020

(Continued)

TABLE 5 Continued

Area	BRD	Codend (mesh size/ orientation)	Method	Target species	Result	Reference
				<i>T. mediterraneus</i>	<i>barbatus</i> , <i>T. mediterraneus</i> , <i>Loligo vulgaris</i> , and <i>M. merlangus</i> .	
Western Mediterranean (east coast of Spain)	Grid (G1-SM40) placed in the middle of the extension; T90 50 mm in the extension	T45 40 mm	Alternate hauls	DPS, HKE, <i>M. barbatus</i> , <i>M. surmuletus</i>	T90 50 mm extension panel allowed for a reduction of 35% of undersized specimens of HKE. Selective grid allowed for 95% and 100% of undersized specimens to escape for HKE and DPS, respectively	Maynou et al., 2021
North-western Adriatic Sea	T90 44 mm in the extension	T0 44 mm (standard extension piece); T0 44 mm, reduced number of meshes in circumference and reduced extension piece; T45 40 mm and 170 meshes in circumference	Paired hauls	HKE, <i>M. barbatus</i> , <i>Lophius</i> spp.	HKE and <i>Lophius</i> spp. showed no indication of improved selectivity or catch pattern compared to the standard extension piece of the trawl.	Petetta et al., 2022
Northern Tyrrhenian Sea	T90 44 mm, Grid (FLEXGRID) 20 mm bar spacing	T45 40 mm	Alternate hauls	DPS, HKE	No significant differences between the control and T90 44 mm Flexgrid showed a loss of marketable fractions for DPS, <i>M. barbatus</i> , and <i>Illex coindetii</i> but reduced the catch of undersized HKE	Sbrana et al., 2022

those available to collaborate. Therefore, to verify whether the slight differences among vessels could introduce a potential bias in the sampling design, the swept areas were estimated and compared by haul. The results showed negligible differences between the swept areas amounting to no more than 5% (Table S1). The inevitable slight differences in the allocation of the hauls were implicitly accommodated considering the random effect (the hauls) within matrix D, which measures the variation in relative catch rate between paired hauls, which are assumed to occur at random and to average out over a series of paired hauls (Fryer et al., 2003; Holst and Revill, 2009). In addition, to corroborate the minimal effect of haul spatial allocation, the distance (at the beginning, intermediate, and final haul points) among vessels by haul was measured. Except for the fourth haul of the second day, during which distance reached a maximum of 2.3 nm during the intermediate and final haul points, the distances among vessels during the survey were negligible, ranging between 0.02 and 1.5 nm (Figure S4). Moreover, all fishing operations were conducted on the same biocenosis (Table 3) ensuring that the differences in catch rates were due to the different selectivity of the gear. The shorter haul duration in the present study (90 min) compared to the commercial hauls' duration (120–150 min) might be considered a potential weakness. This shorter time was due to the trade-off between the logistics needed to carry out all of the hauls in 1 day and having a haul that was long enough to collect a sufficient number of specimens.

Overall, the findings of the present study are consistent with those of previous studies obtained in other areas of the Mediterranean Sea, emphasising DPS and HKE a selectivity improvement through the adoption of the Grid-T45 40 mm and T90 50 mm codend mounted on commercial trawl nets. These findings confirmed that in a multi-specific fishery, such as Mediterranean otter trawling, it is unrealistic to secure a gear configuration that is ideally suited for all species (Fiorentino and Vitale, 2021; Lucchetti et al., 2021). This is because to the different shapes, sizes, swimming abilities, and behaviours of the various species caught during trawling activities. Therefore, it is important to explore technological solutions that are selective for the main target species of trawl fishery, such as DPS in the Strait of Sicily, with acceptable levels of losses of valuable by-catch, such as HKE, and mitigation of the impact on benthic habitat and communities (Maynou et al., 2021), considering the different behaviour and vertical distribution from the seabed of the species.

In addition, given that the success of the adoption of gear is affected by the acceptance of fishers, their viewpoints are of paramount importance. During the campaign, no negative feedback toward the use of sorting grids from the involved fishers was detected, and no handling issues were raised from them. As for concerns relating to the T90 50 mm, even though it was a very simple modification without any possible handling issues, some concerns were raised by the fishers owing to the important loss of marketable DPS.

Therefore, in the future, it will be of vital importance to take into account the trade-off between the socio-economic and ecological points of view and to engage with as many fishers as possible in developing and optimising more selective gear (e.g., Geraci et al., 2019; Sardo et al., 2020b; Geraci et al., 2021b) to be translated into the decision-making process of the management regulations.

However, before transferring the tested BRDs to fishing enterprises and improving the selectivity of bottom trawling, is desirable to carry out generously planned surveys using commercial vessels fishing in different conditions (time, season, and grounds) with a shared protocol, and with fishing gear that is comparable as much as possible. Once more robust data on the effect of BRDs are obtained, mitigation of the current poor exploitation pattern of DPS and HKE could be achieved by adopting a set of management measures. In particular, the Fisheries Restricted Areas where bottom trawling is prohibited, implemented by the GFCM to protect juveniles of HKE and DPS in the Strait of Sicily (Russo et al., 2019; Di Maio et al., 2022), could be coupled with the adoption of a boundary zone in which trawling is allowed only for vessels that mount a BRD that minimises the capture of undersized individuals. Another measure could be the introduction of a total allowable catch for DPS and the application of the T90 50 mm codend when the quota is reached. All these potential management rules should be carefully monitored to determine their effective application. In addition, as already shown by Vitale et al. (2018b), in the near future, to simulate the effect of mounting the tested BRDs or the adoption of the above-mentioned management rules, it would be worthwhile to incorporate the selectivity results in an ecosystem model (e.g., Ecopath With Ecosim) to assess the effects not only on commercial target species but also on the other components of the trophic web in the area (Agnetta et al., 2022).

In conclusion, although further studies should be carried out in the future to test different fishing arrangements, the investigated gear appears to be promising tools to contribute to reducing the overexploitation of DPS and HKE at the same time to ensure long-term socio-economic sustainability of the fishing process in-line with the goals of the EU Common Fisheries Policy (reg. EC 1380/2013).

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

SV and FFi: conceptualization. MG: formal analysis. MG, FFa, DS, VG, and GS: data curation. MG, FFa, FM, DS, VG, GS, PC, and DM: data collection and figures. SV and FFi: validation. MG: writing – original draft. MG, VG, FM, FFa, DS, FFi, GS, PC, DM, and SV: writing – review and editing. All authors contributed to the article and approved the submitted version.

Funding

This work was conducted under the consultancy service provided by the WWF Mediterranean (project number: 9E204550).

Acknowledgments

The research leading to these results has been conceived under the International PhD Program “Innovative Technologies and Sustainable Use of Mediterranean Sea Fishery and Biological Resources (www.FishMed-PhD.org).” This study represents partial fulfilment of the requirements for the Ph.D. thesis of MG. We would like to thank Dr Marco Costantini for his genuine collaboration, Dr Giandomenico Cassano and Editage (www.editage.com) for the English language editing. In addition, we would like to thank the reviewers who substantially improved the quality of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2023.1011605/full#supplementary-material>

SUPPLEMENTARY FIGURE 1

Scheme of the control net used in the campaign, with details of the length and mesh number by net portion.

SUPPLEMENTARY FIGURE 2

Scheme of the test net with sorting grid (T45 40 mm) used in the campaign, with details of its insertion, the length, and mesh number by net portion.

SUPPLEMENTARY FIGURE 3

Scheme of the test net with T90 50 mm codend used in the campaign, with details of the length, and mesh number by net portion.

SUPPLEMENTARY FIGURE 4

Distance of among vessels, in nautical miles, during the initial, intermediate, and final haul position over the days (columns), and hauls (rows).

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