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BYCATCH AND DISCARD ISSUES IN THE ADRIATIC DEMERSAL FISHERIES

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Abstract

Commercial fisheries exploiting the fishing grounds of the Northern-Central Adriatic Sea (Italian side) are faced with many sustainability issues, such as stocks overfishing and high discard rates produced. The demersal resources of the area are mainly exploited by bottom trawls, hydraulic dredges and passive set nets. These fisheries are the subject of study of the present thesis, which identifies challenges and investigates the potential of specific technical solutions to promote more sustainable exploitation. The five research papers presented here can contribute to the mitigation of fishery-specific issues.

Papers I, II, III focused on the bottom trawl fishery, which is the main fishing sector of the area, in terms of tonnage. Paper I compared the catch performance and selectivity of the two codends allowed in this fishery, made of 40 mm square meshes and 50 mm diamond meshes, respectively. A new analysis, which accounts for the entire species community in trawl catches, was applied. Results showed that 50 and 80% of the catch in weight and count numbers, respectively, consisted of species without commercial value, highlighting the severe impact of this fishing activity on the benthic community. Further, the 40 mm square mesh codend was found to be less suitable for the sustainability of many commercial species than the 50 mm diamond mesh codend. Paper II estimated the selectivity of an experimental codend made of meshes turned by 90° (T90) and compared it to a traditional diamond mesh codend with the same mesh size. The results demonstrated that this simple modification can effectively improve the codend size selection for all the main target species and thus reduce discards. Given the promising results obtained with this practical and inexpensive solution, Paper III investigated the use of T90 meshes in the extension piece in front of the codend, together with a reduction in the number of meshes at the extension circumference. The results obtained for the main target species revealed that both these design changes did not improve the size selectivity of European hake (*Merluccius merluccius*) and monkfish (*Lophius* spp.), while for red mullet (*Mullus barbatus*) the outcomes were even opposite to expected since the reduced number of meshes in the circumference of the extension piece jeopardized the size selection obtained in the trawl with a standard extension piece. As a result, the extension piece, contrary to the codend, seemed not to be the main part of the trawl where fish were attempting to escape, and the technical measures that are usually successful when applied at the codend level did not work for the extension piece.

Paper IV is related to the hydraulic dredge fishery targeting the striped venus clam (*Chamelea gallina*), an important fishing sector of the area in terms of income and landings, for which there was no information on the gear selectivity under commercial conditions. The study aimed to fill this gap by assessing the clams’ size selection process carried out by the dredge at different haul durations. A

clogging phenomenon was observed in the gear since 25% of the clams caught did not come into contact with the metal bars of the cage, thus not being size selected. The resulting average clam length with a 50% retention probability was 18.9 mm, which did not significantly change in different tow durations (3, 6, 9 minutes). Therefore, to land only the legal sizes of clams (>22 mm in length), the additional size selection process carried out on board the fishing vessels by the sorting sieves is necessary.

Finally, Paper V focused on the small-scale fishery by comparing the catch performance of innovative fish pots with that of a trammel net traditionally used in the Italian Adriatic Sea. The data analysis revealed a similar catch efficiency between the two gears concerning the commercial portion, while the trammel net produced significantly more discards, both in terms of species number and weight. The innovative pots could therefore provide a valuable and more sustainable alternative to the local trammel nets since they do not markedly change the fishing operations and they can achieve the objectives of reducing discards and bycatch without penalizing the revenues.

Paper I is published in *PLoS One*; Paper II in *Mediterranean Marine Science*; Paper III in *Frontiers of Marine Science*; Paper IV in *Fisheries Research*; Paper V in *PeerJ*.

The review work conducted to examine the current status of the selected fisheries, allowed to publish three review papers addressing the selectivity and impact of the following fishing gears in the whole Mediterranean region: bottom trawl (Review I), passive nets (Review II) and pots (Review III).

Review I is published in *Mediterranean Marine Science*; Review II in *Fisheries Research*; Review III in *Reviews in Fish Biology and Fisheries;* they are all listed in a specific Annex.

Abbreviations and acronyms

AIC:	Akaike information criterion
C:	Contact parameter
CC:	Catch comparison
CFP:	Common fisheries policy
CIs:	Confidence intervals
CL:	Carapace length
CPUE:	Catch per unit effort
CR:	Catch ratio
DM:	Diamond mesh
DM50:	50 mm diamond mesh codend
DOF:	Degrees of freedom
EC:	European Commission
EU:	European Union
FAO:	Food and agriculture organization of the United Nations
F/V:	Fishing vessel
GFCM:	General fisheries commission for the Mediterranean
GLMM:	Generalized linear mixed model
GSA:	Geographical sub area of the GFCM
GT:	Gross tonnage
GTR:	Trammel net
ICES:	International council for the exploration of the sea
IUCN:	International union for conservation of nature
L50:	50% retention length
LFD:	Length frequency distribution

LFM:	Length at first maturity
LIFE:	Low-impact and fuel-efficient
LO:	Landing obligation
LOA:	Length overall
LPs:	Large pots
MCRS:	Minimum conservation reference size
ML:	Mantle length
MLE:	Maximum likelihood estimation
MMS:	Minimum mesh size
PA:	Polyamide
PE:	Polyethylene
R/V:	Research vessel
SM:	Square mesh
SM40:	40 mm square mesh codend
SP:	Split parameter
SPs:	Small pots
SR:	Selection range
SSFs:	Small-scale fisheries
STECF:	Scientific, technical and economic committee for fisheries
T0:	Diamond mesh
T90:	90° turned meshes
TED:	Turtle excluder device
TL:	Total length
WGFIT:	Working group on fishing technology of the GFCM
WGFTFB:	ICES working group on fishing technology and fish behaviour

1 Introduction

The fishing activities in the Mediterranean region are thousands of years old. During the Roman Empire, the alieutic resources were already exploited through a wide variety of fishing gears (e.g. beach seines, pots, harpoons, hand-lines; Osio, 2012). Given the key role of fishing in the society of Mediterranean populations throughout history, fishers have progressively developed their skills to catch fish, crustaceans, molluscs and other marine organisms in any environment: along the water column, on the bottom, or even by burrowing to the bottom. However, the highest degree of innovation in fisheries has been reached in the last hundred years, especially from World War II onwards, when the fishing sector made giant leaps in the use of technology (Graham, 2006; Ferretti, 2011). Together with an improved understanding of the habits and behaviours of the target species, fishing technology has allowed the development of more sophisticated fishing systems capable of exploiting further grounds (e.g. deeper areas) and catching the most desirable species. Technological innovation is still in progress, although with temporal differences in the evolution of fishing effort in different Mediterranean areas (Osio, 2012).

The technical advances in fishing gears have generally led to more economically efficient fishing operations and improved access to resources. By contrast, they have led to increased exploitation of living marine resources, as well as impacts on the marine environment and vulnerable species.

According to the latest information (FAO, 2022) around 74 200 fishing vessels operate in the Mediterranean Sea, of which 82% are small-scale vessels, 8% are bottom trawlers and 5% are purse seiners and pelagic trawlers. The total production for the Mediterranean Sea in 2020 was 743 100 tonnes with a revenue of USD 2.7 billion and an estimated half a million jobs along the value chain. The three most important commercial species, in terms of value, in the Mediterranean are European anchovy (*Engraulis encrasicolus*), sardine (*Sardina pilchardus*) and European hake (*Merluccius merluccius*) (FAO, 2022).

Today, more than 90% of the stocks assessed in the Mediterranean Sea (Colloca et al., 2017; GFCM, 2018) are subjected to fisheries' overexploitation (Colloca et al., 2013). High rates of discards, i.e. fish and other benthic organisms that are not retained for a variety of reasons – too small, damaged, inedible, of little or no commercial value, under the legal size or exceeding the allowed quotas – are reported throughout the basin (Tsagarakis et al., 2014). The catch of unwanted species, called 'bycatch', also poses a significant threat, especially to large marine vertebrates such as sea turtles (Casale, 2011; Lucchetti et al., 2017b, 2017c), sharks (Ferretti et al., 2008; Bradai et al., 2018) and mammals (Bearzi, 2002; Notarbartolo di Sciara, 2016). Additional impacts involve a physical alteration of the seabed (Lucchetti and Sala, 2012; Palanques et al., 2014; Lucchetti et al., 2017a), a disturbance of benthic habitats and communities (De Juan et al., 2007; Farriols et al., 2017) and greenhouse gas emissions (Guijarro et al., 2017).

Discarding is considered a major issue for fisheries management (Tsagarakis et al., 2014). The main problem is that most of the discards might not survive because they are damaged in the capture process, sometimes hauled up from the bottom too quickly, or thrown back too late. Since these fish, crustaceans, shellfish, etc. are part of an ecosystem, their removal affects the food chain (Innes and Pascoe, 2010). In addition, these rejecting practices of dead or dying organisms determine that fishing mortality does not result in any economic advantage, as catches cannot be sold for human consumption and will not benefit fishing activities in future years (Bellido et al., 2011). For this reason, the latest European Regulations aim to reduce all the impacts of fisheries with priority given to discard reduction. In the Mediterranean, the Common Fisheries Policy introduced, in 2013, the Landing Obligation (LO, also called 'discard ban') of all the catches of species subjected to the minimum conservation reference size (MCRS; EU Regulation, 1380/2013). In this way, the LO emphasizes the need to reduce discards by encouraging fishers to avoid areas or seasons characterized by large amounts of undersized/unwanted fish and to employ more selective gear (Damalas, 2015). At present, the discard ban is a matter of concern among enforcement authorities due to the almost impossible task of detecting if these rules are respected (Damalas et al., 2018) and among fishers, which are facing difficulties related to storing and bringing to land the former discard, due to limited hold space, increased sorting time or personnel (Maynou et al., 2018).

The research studies conducted in this thesis fall within the general effort of the scientific community of finding solutions to reduce the discards produced by professional fishing gears, and thus the impact on marine resources. The biggest challenge is to identify one technical measure that, in a fishing gear, allows to avoid the unintended catch while simultaneously ensuring that the retained catch is enough for the economic viability of the fishery. The two approaches here investigated are: i) the modifications to traditional fishing gears to improve the size and species selectivity; ii) the tests of potential alternative and more sustainable fishing gears.

For this thesis, only the professional fishing activities exploiting organisms living in close contact with the sea bottom (i.e. demersal resources) have been taken into account. Bottom otter trawl, hydraulic dredge and set net fisheries are the most widespread gears targeting demersal stocks in the western Adriatic Sea (i.e. the study area, described in Chapter 2), thus being the focus of the activities carried out within the thesis.

2 Study area

The study area of the present thesis is the Western FAO-GFCM geographical sub-area (GSA) 17 i.e. the Northern-Central Adriatic Sea, Italian Side, which includes the coastal regions of Friuli Venezia Giulia, Veneto, Emilia Romagna, Marche, Abruzzo and Molise. This basin is a large shallow continental shelf area mostly characterized by sandy-mud bottoms of sedimentary origin, with the depth gradually increasing from north to south, but generally not exceeding 100 meters.

The oceanographic and biological characteristics of the study area are largely determined by strong river runoff, especially the Po river (Marini et al., 2008). The shallow depths and rivers' discharges contribute to the strong thermal (5-28°C) and salinity (30.0-38.5 ‰) gradients throughout the year (Russo et al., 2012), and the considerable inflow of nutrients related to rivers makes the basin eutrophic, in contrast to the general conditions of oligotrophy that characterize the Mediterranean (Fortibuoni, 2010). The consequent high primary and secondary production are reflected in remarkable fishery production.

A wide variety of fishing activities and gears operate on these grounds, which can be divided into an inshore area, included within the 3 nautical miles of the Italian coastline, and an offshore area, from 3 nautical miles offshore (Figure 1).

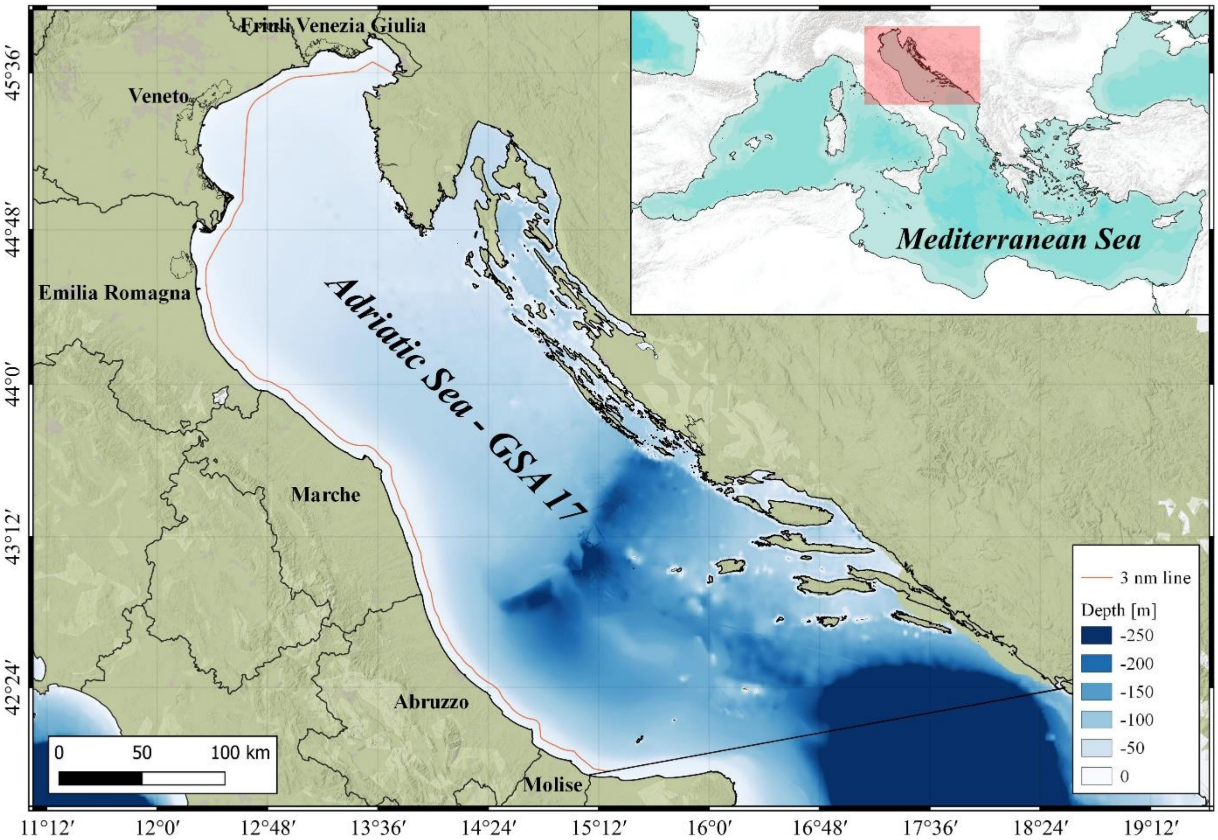

Figure 1. Map of the study area. The red line represents the 3 nautical miles from the Italian coastline, which divides the inshore area from the offshore area. The black line represents the southern limit of the FAO-GFCM geographical sub-area (GSA) 17.

The inshore area (or coastal area) is mainly exploited by small-scale fisheries (SSFs, hereafter), which are defined as fishing activities carried out by fishing vessels of an overall length of less than 12 m and not using towed gear (Grati et al., 2018). These small boats usually exploit areas that can be reached in a few hours from the home harbor (Bastardie et al., 2017). Also, the hydraulic dredges operate in this area at depths between 2 and 12 m, to harvest the striped venus clam (*Chamelea gallina;* Morello et al., 2006).

The offshore area is intensively exploited by bottom trawlers (Colloca et al., 2017). The most common fishing grounds range from 20 to 70 meters deep. Also, the hydraulic dredge fishery targeting the smooth venus clam (*Callista chione*) operates in this area (Malvarosa and Cozzolino, 2016), as well as SSFs, especially through the use of gillnets (Virgili et al., 2018). The fishing gears and fisheries above mentioned are described in Chapter 3.

3 Selected fisheries and related challenges

3.1 Bottom otter trawl fishery

In general, trawl nets are defined as active gears, since they are pulled by the vessel through the sea to catch marine organisms. A bottom otter trawl is a cone-shaped net towed on the seabed and designed to harvest marine resources in the proximity of the seabed. The otter boards assist in keeping the net in contact with the seabed and guarantee the horizontal net opening. The opposite buoyancy of the headrope (rigged with floats) and the groundrope (rigged with leads) maintain the vertical opening of the trawl net. The main components of an otter trawl are represented in Figure 2. In the Mediterranean, bottom trawling is capable of operating over many types of seabed and at depths ranging from 10 to 800 m. Fishers have always found ingenious ways to adapt their trawls to the local fishing conditions so that in each area and country there are several different net designs and characteristics.

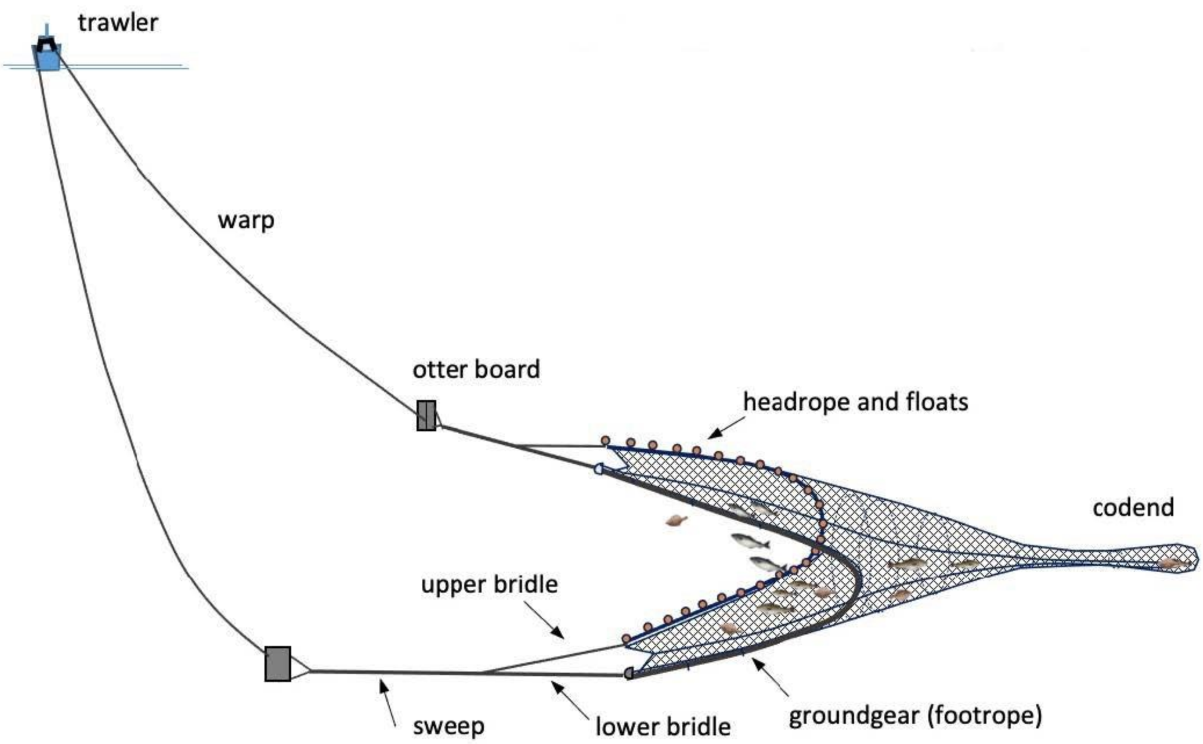

Figure 2. Drawing of the main components of a single boat otter trawl. Adapted from He et al. (2021).

In the Italian GSA 17, the bottom trawl fleet represents the main fishing sector in terms of tonnage; the number of bottom trawlers decreased from around 700 in 2013 (Mannini and Sabatella, 2015) to 625, according to the latest reports (NISEA, 2020). These vessels are located in the different regions as follows: 16 (Friuli Venezia Giulia), 132 (Veneto), 127 (Emilia Romagna), 216 (Marche), 99

(Abruzzo), 35 (Molise). The most important fishing harbors are Chioggia, Rimini, Ancona, Civitanova Marche, San Benedetto del Tronto and Pescara. The mean vessel gross tonnage is 42 tons, the main engine power is 208 kW and the average overall length is around 17 meters (PRIZEFISH, 2019).

Nowadays, the majority of bottom trawlers in the area use four faces trawls (also called ‘box trawls’), which in the last years have gradually replaced the more traditional two faces trawls (also called ‘flat trawls’; Lucchetti and Sala, 2012).

The traditional two faces trawl (called ‘Volantina’, in Italian) is commonly entirely made up of knotless polyamide (PA) netting. This trawl net is a typical asymmetric two-faces net (Figure 3 A) because the upper panel is shorter than the lower panel, allowing the towing to be mainly exercised on the headrope, thus maintaining the net opened. It has a vertical opening of about 1.5 m, long sweeps (100-200 m) and bridles (15-30 m) and a horizontal opening of about 10-25 m.

The four faces trawl (called ‘Americana’, in Italian) is manufactured with both knotless-PA and knotted-polyethylene (PE) netting (Figure 3 B), and it is usually characterized by having two very short bridles (10–15 m) directly connected to the otter boards, while the sweeps are not used. The attack angles of the otter boards (40-45°) are higher compared to those of the Volantina (19-20°) to increase the vertical opening, which can be around 2 m. Moreover, for the same vessel size, the horizontal net opening of the Americana trawl, ranging from 15 to 22 m, is generally higher than the typical of other Volantina trawls (Lucchetti and Sala, 2012).

The Americana net can be towed as a single net (Figure 4 A) or as two nets simultaneously (namely twin trawls; Figure 4 B). The twin trawl technique is possible thanks to one central clump used to maintain the horizontal opening of the two nets; this technique is employed in certain periods and fishing grounds within the area (Lucchetti et al., 2012).

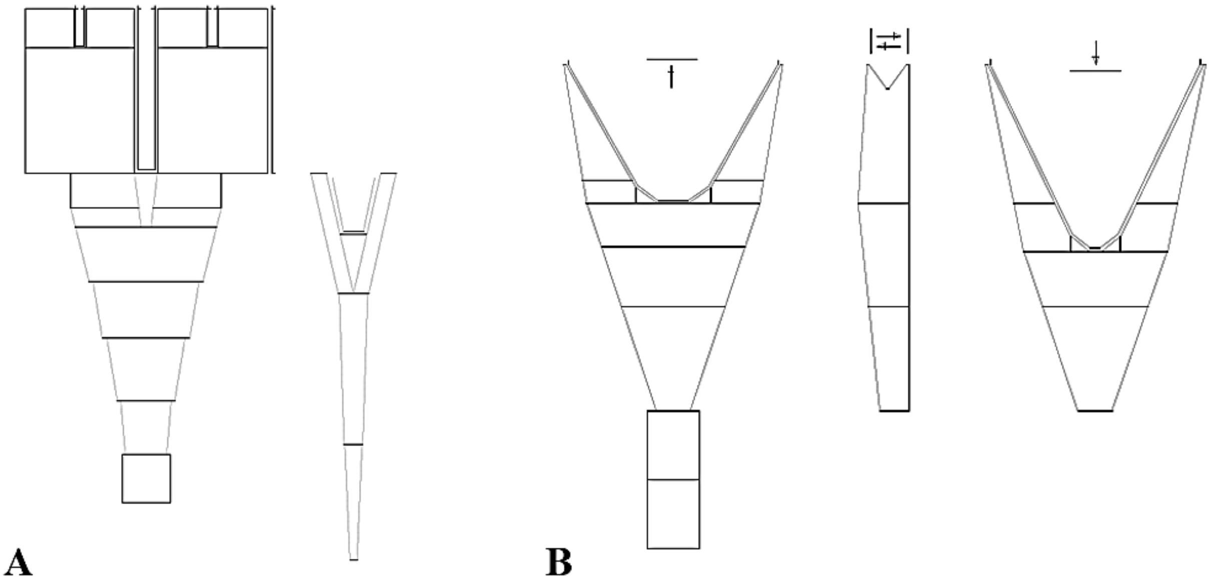

Figure 3. Schematic of the most used bottom otter trawl nets in the Italian GSA 17. A: the traditional flat trawl called 'Volantina'. B: the box trawl called 'Americana'. Source: MyGears, final report (Sala, 2013).

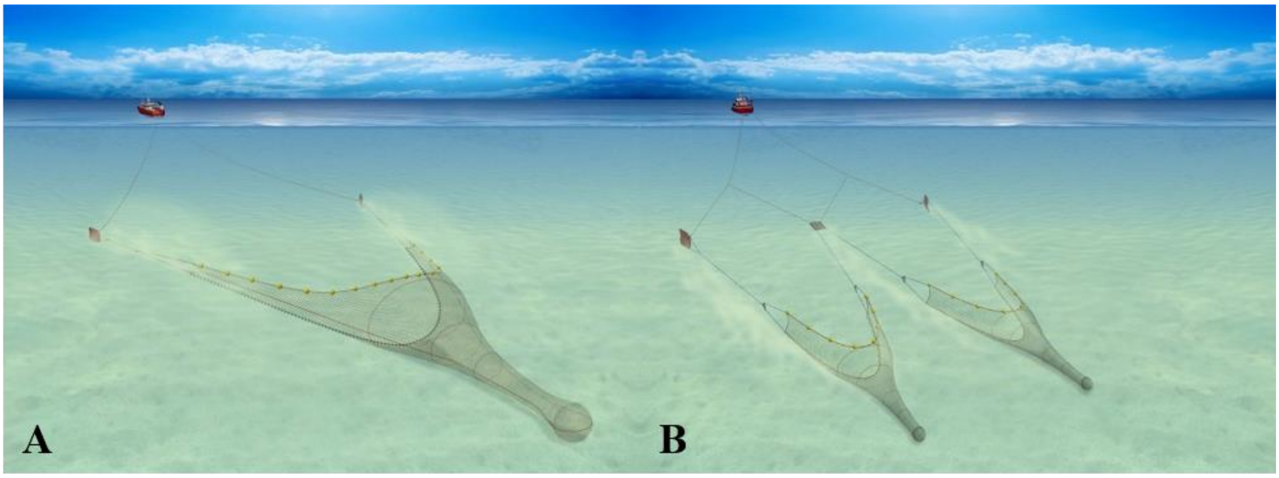

Figure 4. A: Drawing of a single-boat bottom otter trawl rigging. The trawl is towed behind one boat and is spread horizontally by a pair of otter boards. B: Drawing of a twin trawl rigging. Besides the pair of otter boards, there is an additional central clump used to maintain the horizontal opening of the two nets simultaneously towed. Source: Seafish (www.seafish.org).

The Western Adriatic bottom trawl fishery is multi-species. The European hake (*Merluccius merluccius*) and the red mullet (*Mullus barbatus*) represent the most landed demersal species in Italian GSA 17 (GFCM, 2021). Other commercially important species are mantis shrimp (*Squilla mantis*), Norway lobster (*Nephrops norvegicus*), monkfish (*Lophius* spp.), common sole (*Solea solea*), cuttlefish (*Sepia officinalis*), deep-water rose shrimp (*Parapenaeus longirostris*), caramote prawn (*Paeneus kerathurus*), broadtail shortfin squid (*Illex coindetii*), musky octopus (*Eledone* spp.) and tub gurnard (*Chelidonychthys lucerna*) (Lucchetti, 2008; Sala et al., 2008).
Currently, the intense trawl fishing effort in this area has led to a general overexploitation status for most of the demersal commercial stocks (Colloca et al., 2017).

3.1.1 Basic principles of trawl selectivity

A basic definition of selectivity is the ability of a fishing practice to target and capture organisms of a certain size and species, allowing non-targets to be released unharmed (Pope, 1975). Notably, all fishing gears are able to catch only a certain portion of the total fish community. A range of species and sizes normally exist together in a fishing area and are captured by a fishing gear at different rates depending on several factors related to the gear design and mode of operation, fish body characteristics and behaviour (Garcia, 2010), but also to the environmental variables (Brooks et al., 2022). Therefore, no gear is 100% selective for any given species or size range.

In bottom trawls, a fish contacting the gear can avoid getting caught before entering the trawl mouth, or, once inside the net, can escape through the meshes of different trawl sections. Therefore, there are several technical parameters affecting selectivity. The overall trawl net configuration (e.g. two or four faces trawl), size and rigging (e.g. angle of attacks of sweeps or groundrope modifications; Fakıoğlu et al., 2022) are known to influence the trawl catch patterns. Selection processes can occur throughout the trawl body (Dremière et al., 1999), thus modifications at this level could affect selectivity (e.g. modifications in the trawl extension piece; Bonanomi et al., 2020). However, most organisms attempt to escape through the codend meshes (Beverton, 1963; Clark, 1963). The codend is the rearmost part of the trawl net, having either a cylindrical shape or a tapered shape, where the catch accumulates. For this reason, the majority of selectivity studies carried out on bottom trawls have focused on the codend.

The most important codend technical parameters are the following:

i) Codend mesh opening. All other net parameters being equal, a larger mesh clearly improves size selectivity (e.g. Sala and Lucchetti, 2011; Dereli and Aydin, 2016).

ii) Codend mesh configuration. Diamond and square meshes are the most commonly used in Mediterranean fisheries. Currently, the codend allowed for the EU countries operating in the Mediterranean has to be constructed with 40 mm square meshes (SM40, hereafter), or with 50 mm diamond meshes (DM50, hereafter) only with a duly justified request from the shipowner (EU Regulation, 1241/2019). Alternative mesh configurations, such as hexagonal or T90 meshes, which is the traditional diamond mesh turned by 90 degrees (described below), have only been used at experimental level (e.g. Tosunoğlu et al., 2009; Tokaç et al., 2014).

iii) Codend netting properties. Differences in twine thickness, stiffness, elasticity, colour and breaking force could determine a different selectivity. For instance, an increase in twine diameter usually decreases selectivity (e.g. Sala et al., 2007).

iv) Codend circumference. Usually, increasing the codend circumference relative to the circumference of the extension piece (i.e. the rearmost part of the trawl body before the codend) decreases selectivity (e.g. Sala and Lucchetti, 2011). In this regard, the EU Council Regulation, 1967/2006 establishes that, in Mediterranean trawls equipped with SM40 codends, the circumference of the posterior end of the extension piece must be between two and four times the circumference of the anterior part of the codend.

v) Additional devices like a strengthening bag and a bottom-side chafer can mask the codend meshes, change the water flow, change the net behaviour and thus reduce the escape possibilities from the codend (e.g. Aydin et al., 2014).

Besides the technical parameters, an important role is played by parameters related to the fish. These include: i) fish size; ii) fish shape and presence of appendices (spines, teeth, etc.); iii) fish abundance; iv) fish availability to the net. The latter point is mainly related to fish behaviour. In fact, some fish can avoid the catch because i) they swim far from the bottom so that they can avoid the trawl mouth; ii) they are able to swim out of the trawl mouth; iii) they are able to escape under the groundrope; iv) they are willing to pass through the meshes of the trawl body; v) they are willing to pass through the meshes of the codend (Winger et al., 2010).

Further, the trawl selectivity is influenced by environmental parameters, such as:

i) Water temperature. A higher temperature is likely to enhance the fish swimming speed, hence its escape performances (e.g. Özbilgin et al., 2005).

ii) Sea conditions. A sea state-induced pulsing movement of the codend at the end of tow, when the net is hauled, has been shown to affect fish escapement ahead of the catch (O’Neill et al., 2003).

iii) Bottom type and depth. It can affect both the gear performance and the visual stimuli of a fish (e.g. due to turbidity or low light), consequently affecting its reaction toward the trawl (Winger et al., 2010).

Finally, the following haul variables have to be addressed:

i) Catch size. An increased catch size usually reduces selectivity, due to progressive mesh masking and closing under the weight of the catch (e.g. Brčić et al., 2018).

ii) Tow duration. Although a progressive increase of the catch inside the codend is likely to mask the codend meshes and thus reduce selectivity, no clear trends are observed in studies assessing the effect of tow duration (Godø et al., 1990; Sala, 2018).

iii) Towing speed. An increase in the towing speed can reduce selectivity by stretching the codend meshes, although no clear trends are observed in the literature (Dahm et al., 2002).

3.1.2 Estimating trawl selectivity

In trawl selectivity studies, the comparison of the length-frequency distribution of the individuals of a certain species caught in the codend and of those living in the area being investigated allows estimating selectivity curves. These absolute size-selection data are usually collected through the covered-codend technique, which includes placing a mesh cover over the codend (the cover can be also applied to any other selective gear such as grids, mesh panels, etc.). The small meshes of the cover allow collecting all the fish escaping from the codend meshes. Stewart and Robertson (1985) recommended that the cover is 1.5 times larger and longer than the codend and it is supported by circular hoops, to keep it clear off the codend and minimize the masking effects, which hinder fish from escaping (Figure 5). Covers can also be kept open over the codend by means of kites.

Figure 5. Mesh cover employed in the covered-codend sampling technique. On the left, the circular hoops used to keep the cover off the codend, which is visible on the right.

The simplest mathematical model that can be applied to estimate the specimens caught by the net (i.e. those found in the codend) out of the total specimens living in the area (i.e. those found in the codend plus the escapees found in the cover) is the 'logistic curve' (Pope, 1975). This is a non-decreasing S-shaped curve asymptotically restricted to values between 0 and 1 (an example is given in Figure 6). The codend retention probability *r(l)* for a specimen of a given length is thus modelled by the following *Logit* function (Wileman et al., 1996):

$$r(l, L50, SR) = \frac{exp\left(\frac{ln(9)}{SR} \times (l - L50)\right)}{1.0 + exp\left(\frac{ln(9)}{SR} \times (l - L50)\right)}$$

where the 50% retention length (*L50*) represents the fish length at which 50% of the fish are likely to be retained in the codend, whereas *L25* and *L75* are the lengths at which respectively 25% and 75% of the fish are likely to be retained. The length range between *L25* and *L75* is the selection range (*SR*), which is symmetrical around *L50* and determines the slope and shape of the curve (Figure 6). The *SR* expresses the efficiency of selection: the smaller the *SR* the more efficient the selection process, since it approaches the 'knife edge process'.

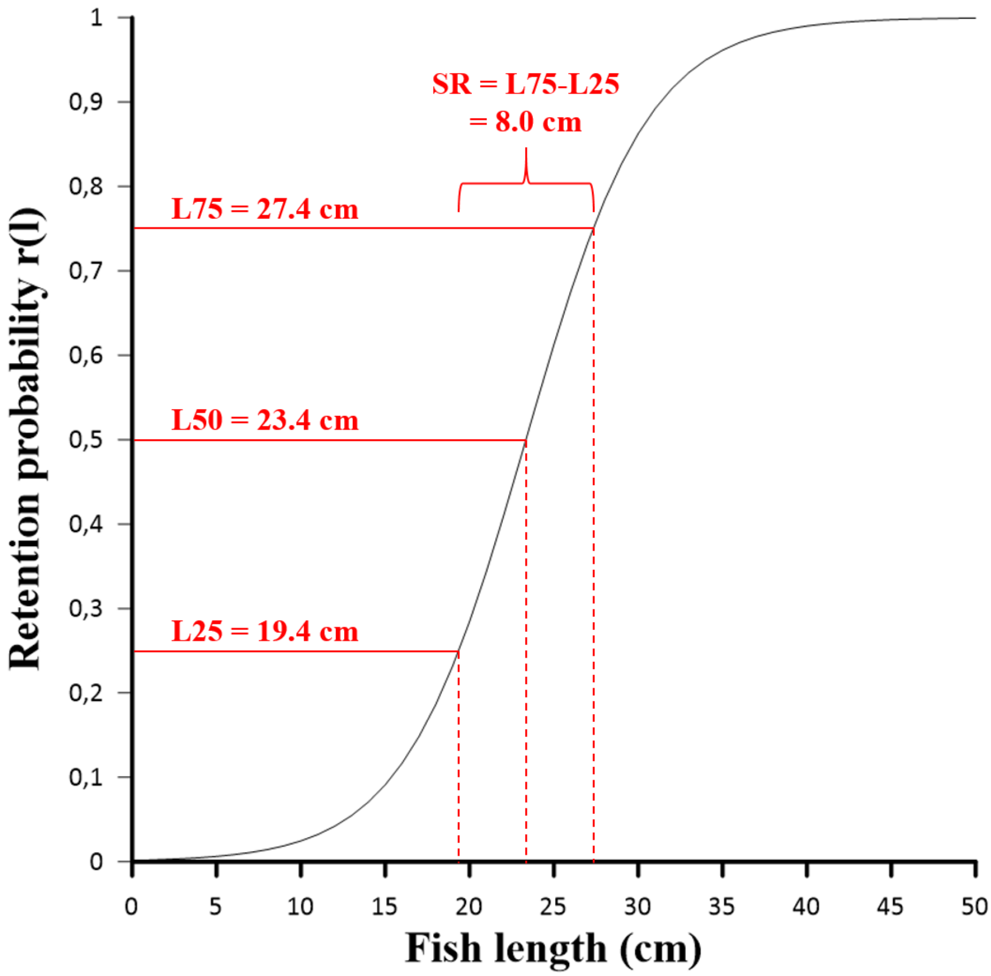

Figure 6. Example of a logistic curve describing the codend retention probability r(l), with the associated parameters L25, L50, L75 and SR.

Besides the *Logit* curve, other simple *S*-shaped size-selection models are also used (*Probit*, *Gompertz*, *Richard's* and *DLogit* curves); the functional forms for each of these parametric models are specified through equations described in the selectivity manual of Wileman et al. (1996) and listed in Paper II. The parameters of each model are estimated using a maximum likelihood estimation (MLE) approach to the data. Usually, the estimation of the size selection is averaged over hauls by pooling data from the different hauls (Herrmann et al., 2012). By including a vector $\boldsymbol{v}$ consisting of the parameters of the model, where the simplest case is $\boldsymbol{v} = (L50, SR)$, the following MLE approach is used:

$$-\sum_{j=1}^{m}\sum_{l}\left\{\frac{nc_{jl}}{qc_j} \times ln\big(r_{av}(l,\boldsymbol{v})\big) + \frac{ncc_{jl}}{qcc_j} \times ln\big(1.0 - r(l,\boldsymbol{v})\big)\right\} \qquad (1)$$

The outer summation is over *m* hauls conducted and the inner summation is over length classes *l*. Parameters nc_{jl} and ncc_{jl} are respectively the number of fish in length class *l* measured in the haul *j* for the codend and cover; qc_j and qcc_j are the related subsampling factors. The MLE approach aims to estimate the values of the parameter $\boldsymbol{v}$ that make the experimental data (averaged over hauls) most likely to be observed. By simply adding a minus sign in front of the equation, the maximization problem becomes a minimization problem.

When applying these models to describe size selectivity data, there is the need to inspect their ability to describe the experimental data sufficiently well. This ability can be evaluated by calculating the corresponding *p*-value, which expresses the likelihood of obtaining at least as large a discrepancy between the fitted model and the experimental data by coincidence. The lower limit for the selection model for an adequate description of the experimental data is 0.05 i.e. 5% probability that the observed deviation between experimental data and fitted model is a coincidence (Wileman et al., 1996). If the fit statistics are p-value < 0.05, further inspection of the residuals is needed to determine whether it is due to structural problems when modelling the experimental data or to overdispersion in the data (Wileman et al., 1996). Finally, among the models considered with acceptable fit statistics, the model with the lowest Akaike information criterion (AIC; Akaike, 1974) value is selected.

The five simple selection models listed above do not always describe the size selectivity data sufficiently well, especially in particular cases (e.g. where only a fraction of the fish contact the device to be size selected; see Paper IV). Thus, more complex models, often based on the *Logit* model, have been recently developed (Lomeli, 2019; Santos, 2021). All the size-selection models employed in the present thesis are described and discussed in Papers II and IV.

The covered-codend method allows, for each haul, to directly estimate the absolute selectivity of a test gear. Its main strengths are the precision of the resulting estimates and the low amount of data/hauls required (Herrmann et al., 2016). However, applying this method complicates fishing operations and can alter the species behaviour inside the gear. This method is employed in Paper II.

There are other methods, called ‘paired-gear methods’, used to estimate the trawl selectivity by comparing the length-dependent catches between two compartments, which can be two trawls or two codends within a trawl, with one compartment serving as the test and the other compartment as the control. To estimate the absolute selectivity, the control compartment has to be non-selective, having a codend with very small meshes that retain all fish entering it, while the fish entering the test compartment may or may not be retained depending on the retention probability of that codend (e.g. Lomeli, 2019).

The paired-gear methods include (Wileman et al., 1996; Millar and Fryer, 1999; Holst and Revill, 2009):

i) Twin trawl method. The same vessel simultaneously tows two identical trawls, with one serving as the test trawl and the other as the control trawl. This method is employed in Paper III.
ii) Trouser trawl method. A single trawl is modified so that it has two codends: one serves as the test trawl and the other as the control trawl. This method is employed in Paper IV.
iii) Parallel haul method. Two vessels are employed in parallel: one tows the test trawl and the other tows the control trawl.
iv) Alternate haul method. A single vessel separately tows test and control trawls/compartments in an alternate haul order. This method is employed in Paper II.

Contrary to the covered-codend method, in the paired gear methods there is an extra parameter to consider, i.e. the probability for an individual to enter either the test or control compartment. This is called the ‘split parameter’ (*SP*): in a situation of two identical compartments, it is ideally 0.5.

The main advantages of the paired gear methods are that they are suitable for commercial fishing conditions and they do not affect the species behaviour. However, there is an additional uncertainty deriving from the *SP* and unaccounted differences between the gears (Herrmann et al., 2016).

The methods i), ii), iii) always generate ‘paired data’, i.e. they provide, for each haul, both information on fish retained by the test and on the total population encountered (through the control). By contrast, method iv) does not always generate paired data. For instance, when the alternation between the test and control compartments could not be performed after each haul (e.g. due to time constraints) and not in the exact same fishing area, the data have to be treated as ‘unpaired’. In this case, the data from one group of hauls (test) and another group of hauls (control) are randomly picked.

The paired gear methods listed above can be also applied, especially under commercial conditions, to answer another type of research question: ‘is there a significant difference in selectivity between two gears for a given species at a given size?’ This technique, called ‘catch comparison’, is aimed to directly compare the length distribution of catches between two different fishing gears, with one serving as the control gear (e.g. a commercial unmodified trawl) and the other serving as the test gear (e.g. a modified trawl). The data obtained in this way allow estimating only the relative selectivity of the fishing gear tested, since the control trawl employed is already selective and thus the size structure of all the population fished is not measured. The catch comparison can be applied not only to bottom trawls (Papers I, III) but to any type of fishing gear. This method is described more in-depth in Section 3.3.3.

3.1.3 Improving trawl selectivity through technical modifications

Bottom trawl fisheries worldwide are mainly managed through closed areas and seasons, limitations of the fishing effort and technical restrictions. Technological modifications to conventional trawl nets are seen as one of the best solutions to improve trawl selectivity. Several measures have been tested at different zones of a trawl net to seek for successful results in reducing discards (Kennelly and Broadhurst, 2021). The catch of unwanted sizes and species can be avoided or limited through simple modifications such as larger diamond-shaped meshes in the codend or in strategic windows in the posterior trawl, or turning meshes 45° (SM) or 90° (T90; described in Section 3.1.4). The use of shortened lastridge ropes or selection grids has improved size or species selection in some fisheries, while fewer attempts have been made to modify the anterior trawl e.g. by varying sweep/bridle lengths or by using horizontal separator panels, LED lights, longer headropes; the benefits of these technical modifications depend on species-specific behavioural responses (Kennelly and Broadhurst, 2021).

In the multi-species bottom trawl fisheries of the Mediterranean, technical restrictions concern mesh geometry and size at the codend level. Clearly, it is difficult to define a minimum mesh size (MMS) in the codend, because a size that is appropriate for one species will be unsuitable for several others (Stewart, 2001). Also, since in most of the Mediterranean countries small and undersized specimens are in strong demand, an increase in codend mesh size can severely affect fishery profitability (Kelleher, 2005). The objective for such fisheries is therefore to find a MMS that minimizes the retention of undersized fish and does not significantly penalize revenues.

The two current legal codends adopted in the Mediterranean, i.e. the SM40 and the alternative DM50, are unable to avoid the catch of undersized and immature individuals of several species (Tsagarakis et al., 2017). Therefore, they contribute to producing high discard rates, approximately 20-65% of the total trawl catch, according to Tsagarakis et al. (2014). A comparison between the selectivity and the catch performance of SM40 and DM50 has been carried out in several areas: Western Mediterranean (Sala et al., 2015; Gorelli et al., 2017; Brčić et al., 2018); Eastern Mediterranean (Aydin et al., 2011; Dereli and Aydin, 2016; Dereli et al., 2016; Demirci and Akyurt, 2017; Eryaşar, 2017; Mytilineou et al., 2018, 2021a, 2021b); Black Sea (Ceylan and Sahin, 2019). Overall, the results provided indicate that the size selectivity between the two codends is similar, with differences, found locally for some species, which are usually related to their morphology. In fact, the species with a round cross-sectional body shape (e.g. red mullet) fit better to the square-shaped meshes than to the diamond-shaped meshes, and the contrary occurs for flatfish species.

In the Italian Adriatic Sea (GSA 17), a direct comparison between the two current legal codends, in terms of both size selectivity and discard reduction, has not been carried out prior to the present thesis. In this area, most selectivity studies have investigated technical measures at the codend level to enhance selectivity. Such modifications involved the size, configuration, number and twine thickness of the codend meshes (Sala et al., 2006, 2007, 2008, 2015, 2016; Lucchetti, 2008; Sala and Lucchetti, 2010, 2011). An increase in mesh size improved size selectivity (Sala and Lucchetti, 2011) while, within the same mesh size, a SM codend reduced the catch of juveniles if compared with a DM codend (Lucchetti, 2008; Sala et al., 2008). A reduction in the twine thickness (Sala et al., 2007) or in the number of meshes at codend circumference (Sala and Lucchetti, 2010; Sala et al., 2016) were also found to be able to reduce discards.

Fewer scientific works have addressed, in this area, the effect of technical modifications at the extension piece on trawl catch patterns. Studies carried out at this level mostly concerned the tests of sorting grids, in particular ‘turtle excluder devices’ (TEDs), which were found to be effective at reducing the bycatch of loggerhead sea turtles (*Caretta caretta*) without significantly penalizing the commercial catch (Sala et al., 2011; Lucchetti et al., 2016b, 2019; Vasapollo et al., 2019). Only one recent study investigated, at the extension piece level, the potential of lateral square mesh panels to reduce the capture of juveniles of red mullet, but data is too limited to draw conclusions (Bonanomi et al., 2020).

Although some promising results have been obtained at both codend and extension piece levels, there is still an urgent need for further investigations on technical measures that are able to ensure a greater size and species selection and thus reduce the discards produced by trawls.

3.1.4 The potential of T90 mesh configuration

'T90' is the name given to a typical diamond mesh that has been turned by 90 degrees (Figure 7 B). As a result, its meshes do not close as tightly under the weight of the catch, enabling smaller specimens to escape (Madsen et al., 2012). A codend made of T90 meshes is also easier to mount on a net than a SM codend (Figure 7 C), and there is no loss of net in the construction of T90 panels, whereas SM panels involve cutting the corners of a standard panel (ICES, 2009b, 2010, 2011).

The T90 mesh configuration has been mainly tested at the codend level and compared to conventional DM codends (Figure 7 A). It has been observed that the size selection properties of a T90 codend are between those of a SM codend and a DM codend. Within a given mesh size, the T90 codend, like the SM codend, generally provides an improved size selectivity compared with the DM codend (Tokaç et al., 2014; Deval et al., 2016) even though its size selection properties vary according to the cross-sectional morphology of target species (Herrmann et al., 2013; Tokaç et al., 2014; Bayse et al., 2016).

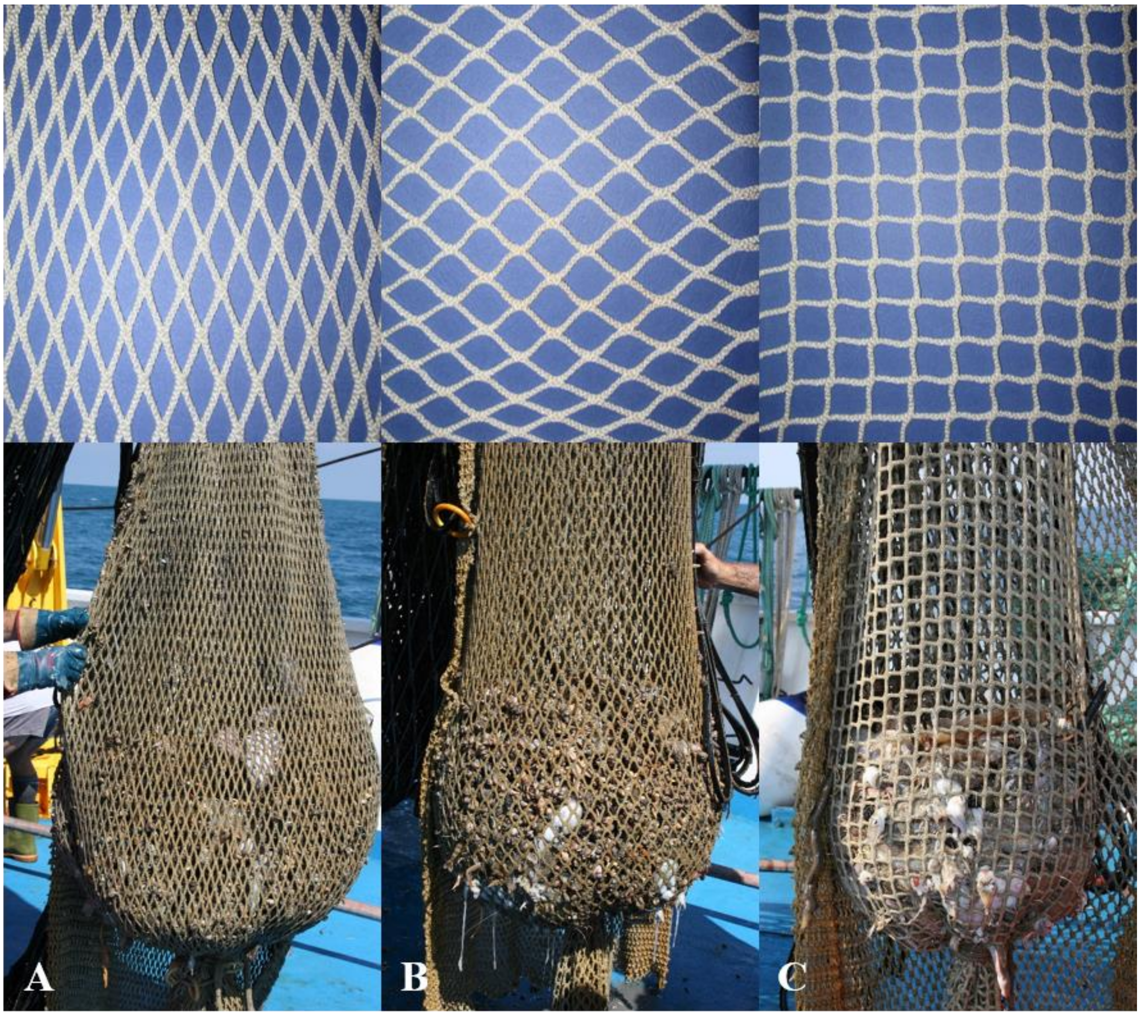

Figure 7. Different codend mesh configurations. A: Diamond mesh codend. B: T90 mesh codend. C: Square mesh codend.

Fewer studies have addressed the effect of T90 netting at the extension piece level (Kopp et al., 2018; Sola and Maynou, 2018; Maynou et al., 2021), with promising results (even if not conclusive) in terms of juveniles' exclusion from the trawl catch.

The T90 configuration is therefore considered, by the scientific community, a realistic and effective solution for reducing discards in the Mediterranean bottom trawl fisheries, as it is easy to implement and not expensive. An investigation of the viability of this technical measure in the Italian Adriatic Sea has not been carried out prior to the present thesis.

3.2 Hydraulic dredge fishery

Dredge fisheries are widely distributed throughout the Mediterranean Sea to harvest commercially important burrowing bivalve shellfish, which represent an important seafood product across the whole region (FAO, 2018). In Italy, the striped venus clam (*Chamelea gallina*) is the most important bivalve species exploited by dredgers, with great socio-economic importance especially in the Northern and Central Adriatic Sea (Scarcella and Cabanelas, 2016). In this area, mainly in soft bottoms at depths of 2-12 meters, the design of the dredge employed to harvest *C. gallina* has evolved over the past decades (Froglia, 1989) from rakes operated by hands until the advent of the modern hydraulic dredges, which enabled the development of a very profitable fishery for a large number of vessels (over 700 in Adriatic; DGPEMAC, 2019). They have average LOA of 15.5 m, tonnage of 9.98 GT and engine power of 150 kW, and the fleet shows a general evenness in terms of technology and dimensions. Also, the crew per vessel is usually composed of two fishers (MiPAAF, 2019). Although this sector accounts for less than 6% of the Italian fleet (in number of vessels), the quantities yearly landed (around 20000 tons) reach 15% of all fisheries production at national level, making *C. gallina* the second most landed species after the anchovy (*Engraulis encrasicolus)* (MiPAAF, 2020).

The typical hydraulic dredge consists of a sort of parallelepiped-shaped metal cage, towed by means of vessel propeller, whose functioning relies on pressurized water jets that remove the target species from the sediment and allow their capture (Figure 8). The cage is commonly made of metal bars in its lower, upper and rear parts, and rests on two skid-sledge runners that facilitate the sliding motion on the seabed during towing (Figure 9 A; Lucchetti and Sala, 2012). The adjective 'hydraulic' derives from the pressurized water that is injected from a centrifugal water pump into different types of nozzles mounted on the dredge. These nozzles are arranged in parallel rows and placed both at the dredge mouth and inside the dredge (Sala et al., 2017). The former spray pressurized water downwards to penetrate the sea bottom and suspend the sediment, to make the bivalves emerge and at the same time to assist the movement of the dredge in the substrate. The latter are positioned backwards to help clearing the cage from materials such as sand, mud and debris that often clog it.

Once the suitable fishing grounds are reached, the vessel releases the dredge from its bow and lets it sink to the bottom. Then, the vessel starts moving in reverse at low speed (around 1 knot), towing the dredge through the warp for a variable distance (Figure 8). At the end of the tow, the cage is hauled and its contents are tipped into a collecting box (Lucchetti and Sala, 2012). The catch is then conveyed to a vibrating sieve placed onboard and composed of multiple grids, which allow to mechanically sort the clams into different size classes (Figure 9 B). The unwanted organisms and undersized clams are directly thrown back into the sea.

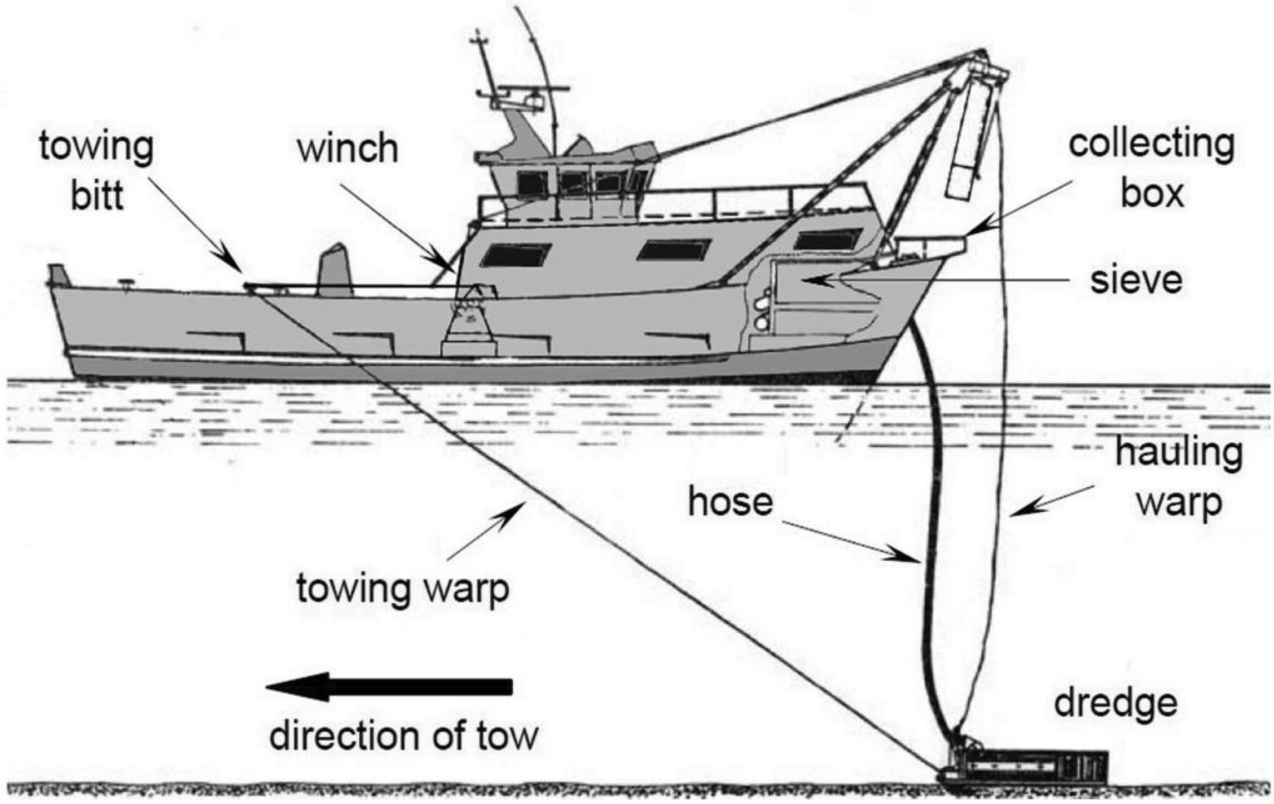

Figure 8. Drawing of a hydraulic dredge, its main components and fishing method. Source: Lucchetti and Sala (2012).

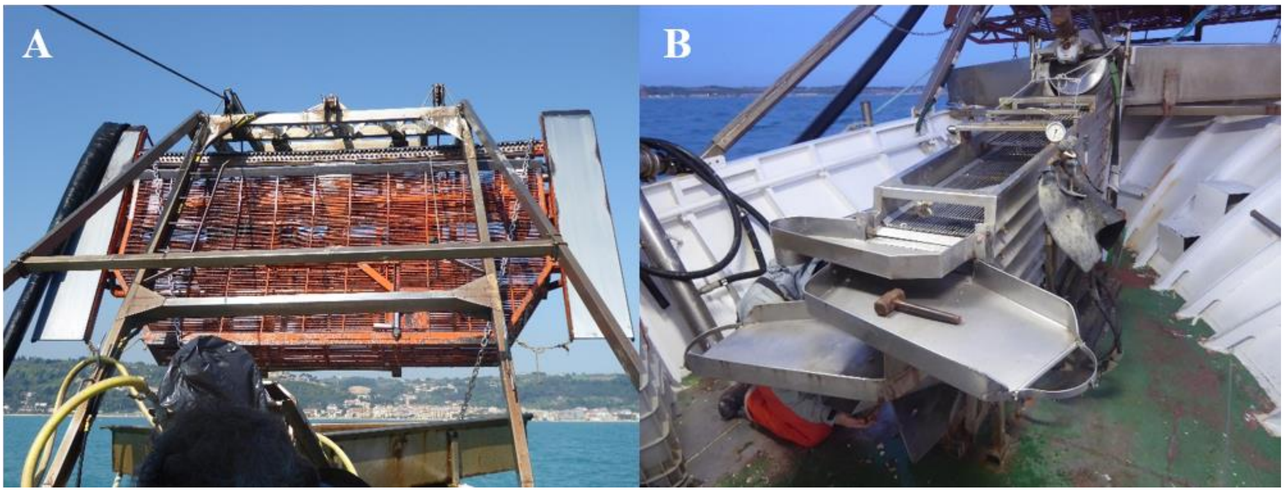

Figure 9. Photographs of the hydraulic dredge used to harvest the striped venus clam. A: the metal cage made of metal bars and the two lateral skid-sledge runners. B: the vibrating sieve onboard the vessel.

Major challenges related to this fishery concern the high discard rates produced and the associated impact on the benthic community.

The proportion of discards produced by this fishery is estimated to reach almost 50-55% of the total catch, 30-40% of which is composed of undersized individuals of *C. gallina* (Morello et al., 2005a;

Bargione et al., 2023). The remaining 15-20% of the discarded portion include benthic invertebrates typical of the shallow waters of the area, such as gastropods (e.g. *Nassarius* spp.), other bivalve species (e.g. *Donax semistriatus*, *Polititapes aureus*), crustaceans (e.g. *Diogenes pugilator*) and echinoderms (e.g. *Astropecten* spp.) (Morello et al., 2005a). Some further bycaught species have a commercial value, such as common sole (*Solea solea*), cuttlefish (*Sepia officinalis*) and caramote prawn (*Penaeus kerathurus*); however, they are generally landed for home consumption, since their abundance in the catch is too low for the sale.

The impact on the benthic community is well discernible (Vasapollo et al., 2020) although the species belonging to these soft bottoms are already naturally adapted to constant environmental stress and exceptional phenomena (in particular, significant wave movements and strong currents). Nevertheless, both clams and other benthic organisms can be injured at different degrees during the towing of the dredge on the seabed, as specimens hit against the bars of the gear or because of abrasion inside the dredge, or during the sieving and discarding processes (Veale et al., 2001). The damages and injuries induced by fishing operations may cause, in addition to direct fishing mortality, also indirect fishing mortality, for instance due to higher predation risk. Bargione et al. (2023) estimated that dredging (harvesting + sorting processes) has a physical impact on *C. gallina*, since more than 19% of the clams caught can suffer different types of shell damage. However, the authors demonstrated their high survival probability (>90% independently of the damage type) when released at sea.

3.2.1 Hydraulic dredge selectivity

Two consecutive *C. gallina* size selection processes occur: the first at the seabed by the dredge itself and the second onboard by the vibrating sieve.

The size selectivity of the dredge under fishing is primarily dependent on the spacing of metal bars that compose the cage, which can be compared to the codend mesh size of a bottom trawl net (Sala et al., 2017), and therefore follow most of the principles of otter trawl selectivity (already described in Sections 3.1.1 and 3.1.2). Accordingly, the selectivity studies on hydraulic dredges can be carried out with the same sampling techniques employed for bottom trawls. The main differences are:

i) Both the metal bars of the cage and the shell of clams are not deformable, contrary to the codend mesh sizes and the fish body, respectively.
ii) The striped venus clams have limited motility and are not able to promptly react to the gear approaching.

iii) The escapement of a clam through the metal bars is a completely passive process and strongly depends on the probability that it both contacts the bar spacing and is well-oriented for a size selection process to occur.

Besides the bar spacing, there are other factors affecting the size selectivity under fishing, such as:

i) Tow duration. As suggested by Carlucci et al. (2015), the selectivity of the hydraulic dredge may decrease with the increasing of tow duration, as clams larger than the bar spacing accumulate in the bottom of the cage and block the escapement of smaller clams.
ii) Type of sediment. It may influence the dredge catch efficiency by affecting the ability of the cage to penetrate the seabed and of the pressurized water to dissolve the sediment.
iii) Presence of other organisms at the seabed caught by the dredge (i.e. other invertebrates). They may reduce the contact probability between the clams and the bars.
iv) Other technical properties of the dredge (i.e. blade length and angle, dredge weight, water pressure level on the nozzles), operational factors (e.g. towing speed) and environmental conditions (e.g. sea state).

The *C. gallina* size selection process carried out by the dredge at the seabed is practically unknown in the Adriatic fishery, contrary to the second size selection process occurring onboard through the vibrating sieve (Sala et al., 2017). Although it has been demonstrated that the adjustment of the hole diameter of the sieve allows obtaining a satisfactory selection ability and retaining only commercial-sized clams (Sala et al., 2017), a better understanding of the impact exerted by this gear on the target species is needed.

3.3 Small-scale fishery

The SSFs play a major socioeconomic role in the Mediterranean fishing sector, accounting for 84% of the total fishing fleet (around 70 000 vessels; FAO, 2018, 2022) and providing a large fraction of landings and revenues (Lucchetti et al., 2014).

The Adriatic SSFs are active full- or part-time throughout the year and use a wide range of fishing strategies that can be described in terms of target species, fishing gear, fishing grounds, and métiers (Grati et al., 2018).

3.3.1 Passive set nets

The passive bottom-set nets are the most important gear used in Adriatic SSFs (Grati et al., 2018, 2022). They are fixed nets i.e. walls of netting that are held open vertically in the water column by a headrope, usually with floats, and by a footrope weighted with sinkers; their function is to intercept fish, crustaceans and cephalopods as they swim (Figure 10; Hameed and Boopendranath, 2000). The nets are usually deployed in the afternoon, remaining on a fishing ground for a few hours or more (usually 12 hours at night) before being hauled in the morning. The prey can be caught in several ways:

i) Gilling. A fish is caught by the mesh surrounding the body behind the operculum.
ii) Enmeshing. A fish is caught by the mesh surrounding the largest part of the body as far as the dorsal fin.
iii) Snagging. A fish is caught through the mouth, teeth, maxillaries or other parts of the head region, without necessarily penetrating the mesh.
iv) Entangling. A fish is caught through the spines, fins or other parts of the body, without necessarily penetrating the mesh.
v) Entrapping. A fish is entrapped in bags or pockets of netting.

There are two main types of passive set nets: gillnets and trammel nets.

The gillnet consists of a single netting wall generally made of mono-filament or multi-filament twisted nylon twine (Figure 11 A). It caches fish through gilling, enmeshing, snagging and entangling.

The trammel net is made of three panels of nets with the inner panel being made either of twisted or mono-filament nylon with small meshes, while the outer panels have a larger mesh size and are generally made of twisted nylon filament (Figure 11 B). The three panels allow catching fish not only through gilling, enmeshing, snagging or entangling, but also through entrapping. This capture process implies that a fish, in attempting to pass through the larger mesh, entangles itself in a pocket of small mesh webbing between the two outer panels.

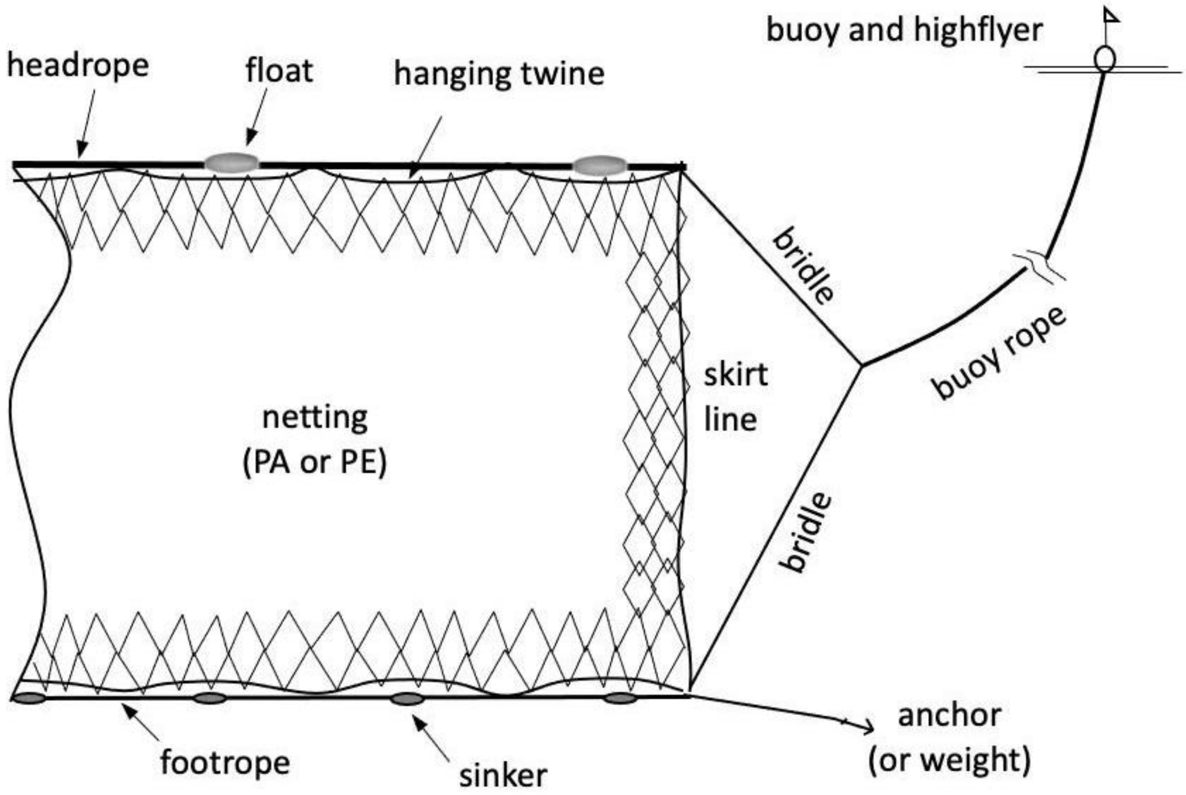

Figure 10. Drawing of a bottom set net and its main components. Source: He et al. (2021).

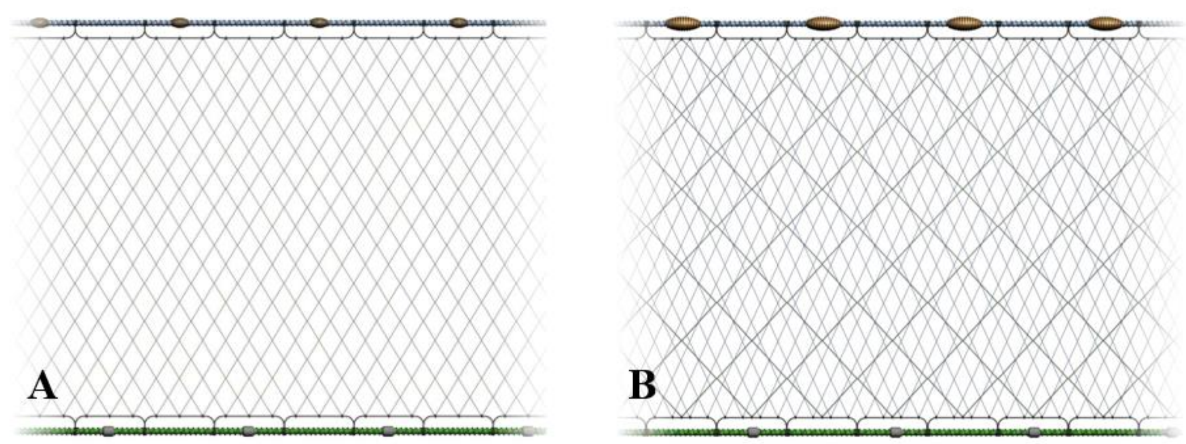

Figure 11. Schematic of a passive set net. A: Gillnet. B: Trammel net. Source: Seafish (www.seafish.org).

A third type of set net, sometimes employed in the study area, is the combined net gillnet-trammel net which is usually composed of two parts; a trammel net in the lower part, and a gillnet in the upper part (Figure 12). This type of net combines the catching methods of a trammel net with those of a gillnet.

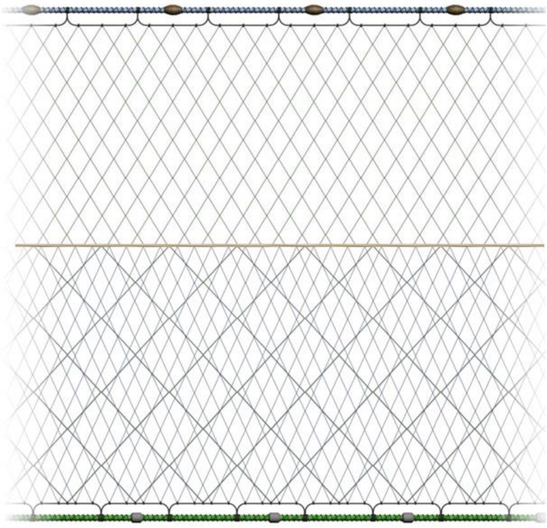

Figure 12. Schematic of a combined gillnet-trammel net. Adapted from Seafish (www.seafish.org).

The length of the passive set nets commercially employed commonly ranges from 1 000 to 6 000 m (Lucchetti et al., 2015) and mainly depends on vessel size and manpower availability for gear cleaning. In the Italian GSA 17, gillnets and trammel nets are used on a seasonal basis to target a range of demersal species (Grati et al., 2018).

Gillnets are used in coastal waters from April to January to target the common sole (*Solea solea*) and from July to December to target the mantis shrimp (*Squilla mantis*; Grati et al., 2018). Other gillnets are deployed in offshore waters (40-70 m of depth) to mainly target rays (*Raja clavata* and *Raja asterias*) and turbots (*Scophthalmus maximus* and *Scophthalmus rhombus;* Lucchetti et al., 2017c; Virgili et al., 2018). The smooth-hound shark, *Mustelus* sp., is targeted by specific gillnets in the north Adriatic Sea during spring (Costantini et al., 2000).

Trammel nets target a wider range of species than gillnets, which includes cuttlefish (*Sepia officinalis*), various fish species (e.g., *Solea solea*, *Lithognathus mormyrus*, *Diplodus* spp., *S. aurata*, *Sciaena umbra*, *Umbrina cirrhosa*, *Dicentrarchus labrax*) and crustaceans (*S. mantis*, *Paeneus kerathurus*) (Fabi and Grati, 2005).

Combined nets are mainly used to catch cuttlefish, common squid (*Loligo vulgaris*), tub gurnard (*Chelidonichthys lucerna*), common sole and striped sea bream (*Lithognathus mormyrus*) (Lucchetti, 2012).

3.3.2 Factors affecting passive nets selectivity and efforts to improve it

The selectivity of passive nets strongly depends on several gear properties. The most important technical parameters to be addressed are (Holst et al., 1998):

i) Mesh size. It is the most studied technical parameter. The modal lengths of the fish caught always increase with an increase in the mesh size used. Therefore, a specific mesh size is adapted to a target species and size.

ii) Netting twine. A different twine determines a different selectivity, based on its thickness, material (PA, PE, polypropylene), yarn type (monofilament, multifilament, mono-multifilament) and colour (transparent, green, etc.).

iii) Horizontal hanging ratio. It is a ratio between the length of the rope on which a net panel is mounted (i.e. hanging twine; Figure 10), and the length of the stretched netting hung on the rope. Changing this parameter will affect how much the net is stretched in the water and therefore its catching modalities (Lucchetti et al., 2016a).

iv) Vertical slackness. In gillnets, it is defined as the ratio between the real net height during fishing and the stretched net height. The more slackness, the more frequent the entanglement capture method. This slackness can be modified in different ways, such as by reducing the floatability of the headrope (e.g. reducing the number of floats) or by reducing the hanging ratio (i.e. reducing the horizontal tension on the net). In trammel nets, the vertical slack is the ratio between the height of the internal panel and that of the external panels. This slack, usually above 1, allows the inner panel to form pockets that entrap fish.

Additional operational factors can affect the passive net selectivity, such as the number of panels constituting the gear hence the overall net dimensions, the soaking time and the net handling techniques. Also, the catch efficiency is dependent on fish morphological and behavioural patterns and environmental parameters i.e. turbidity, sea state, seabed type and depth (Holst et al., 1998).

Although passive nets are considered as more selective gears than bottom trawl, they nonetheless produce, in the study area, a large amount of discards (e.g. 20-30% in biomass of *S. solea*, caught by gillnets, is below the MCRS of 20 cm set for this species; Grati et al., 2002). Moreover, they are responsible for the bycatch of protected species such as *C. caretta* (Lucchetti et al., 2017c, 2017b).

Some studies have evaluated the effect of different mesh sizes (Fabi et al., 2002; Fabi and Grati, 2008) and netting twines (Grati et al., 2015). It has been demonstrated that, especially in gillnets, a given mesh size catches a specific size of the targeted species; therefore, an increase in mesh size allowed to protect juveniles (Fabi et al., 2002; Fabi and Grati, 2008). On the contrary, an increased twine thickness was found to reduce the catch efficiency (Grati et al., 2015). To mitigate the sea turtle interactions with passive nets, Virgili et al. (2018) and Lucchetti et al. (2019) mounted ultraviolet LED lamps to the gillnets; these devices eliminated the sea turtle bycatch without affecting the catch efficiency for the commercial portion.

No other studies have been carried out, in the study area, to improve the passive net selectivity through technical modifications, also because there are few technical solutions that can help reduce the impact of these gears on the benthic community while maintaining the catch efficiency for the commercial species. Concerning trammel nets, one technical solution could be the ‘guarding net’ i.e. a strip of monofilament net with large meshes placed in the lower part of the net, just above the footrope. The guarding net helps the species living close to the bottom, mostly composed of non-commercial benthic invertebrates, to avoid being caught; the use of this modification showed some potential at reducing discards in other Mediterranean areas (Martínez-Baños and Maynou, 2018; Sartor et al., 2018).

3.3.3 Pots as alternative and more sustainable gears

Besides applying technical modifications on passive nets to minimize discards and bycatch, one appealing solution resides in the shift towards more sustainable fishing gears, such as pots (Amengual-Ramis et al., 2016).

Pots are passive gears consisting of small enclosures with one or more entrances that allow easy entry but make exit difficult (Pol et al., 2010). They attract and retain fish, crustaceans and molluscs with bait or simply act as a shelter or a hollow space in which to lay eggs (e.g. for cephalopods; Sobrino et al., 2011). Pots come in several different shapes and commonly consist of a rigid or semi-rigid frame in natural or artificial materials. The entrance(s) may have funnel(s), usually with a larger external opening that allows access to one or more inner chambers and a narrower internal opening preventing escape. Pots may be set on the bottom or allowed to float, according to the species being targeted, and may be single or stringed along branch lines that connect to a mainline (longline system;

Figure 13). They are movable gears that after a variable soak time (hours to days) are hauled on deck, by hand or by mechanized haulers, and emptied.

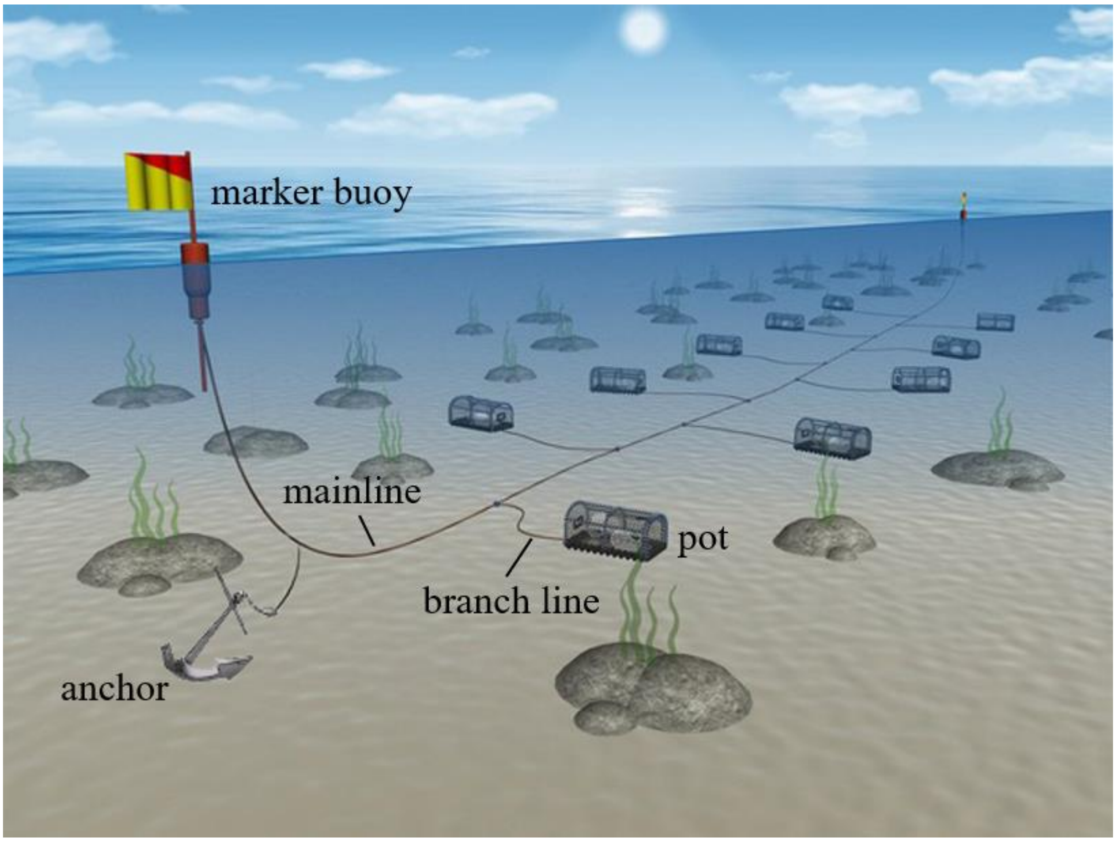

Figure 13. Drawing of pots set in a longline system. Adapted from Seafish (www.seafish.org).

As in passive nets, there are several factors affecting the catch efficiency and selectivity of a pot. The most important technical parameters are:

i) Pot structure. A pot may differ from another in shape, colour, frame material (e.g. reeds, metal, plastic) and dimensions.

ii) Netting. The netting covering a pot (when present) may be of different materials, and the meshes may have a different shape (e.g. diamond, square) and size.

iii) Entrance(s). A pot may have one or more entrances, which may have a different shape and dimension, and may be placed in different positions (e.g. on the short, long or upper side of the pot).

iv) Bait. Different types of bait may be used, such as fish, molluscs or mixed. Also, bait may be fresh, frozen or fermented. Some pots do not require bait (e.g. for cephalopods).

Besides pot technical parameters, the operational (e.g. number of pots used, distance between pots, soaking time) and environmental factors (e.g. fishing ground, seasonality) have to be addressed when evaluating the efficiency of a pot. Also, the parameters related to the fish behaviour, such as hunger, ability to detect the bait, ability to enter and escape from a pot, etc. play a key role in the capture process (Thomsen et al., 2010; Winger et al., 2016).

The current interest in pots (ICES, 2007, 2008, 2009a; Pol et al., 2010) is underpinned by their high potential to reduce the habitat impacts, fuel consumption, gear costs, discards and bycatch associated with passive nets and bottom trawls (‘Low Impact and Fuel Efficient’, LIFE; Suuronen et al. 2012). Moreover, any discards removed from pots on board have considerable survival probability if they are not too stressed by factors such as barotrauma, air exposure and thermal shock (Suuronen et al., 2012). Notably, pots also provide greater catch quality (Olsen, 2014) and are less subject to depredation (e.g. from seals and dolphins; Königson 2011; Pusch 2011) than passive nets. The research works conducted in the Mediterranean to test experimental pots have yielded good results in terms of catch efficiency, although further effort is needed to improve their economic viability (Addis et al., 1998; Colloca, 2002; Sartor et al., 2006; Sbrana et al., 2008; Morello et al., 2009; Amengual-Ramis et al., 2016). Currently, the weight and value of landings generated by Mediterranean pot fisheries account for a small fraction of the fishing sector (approximately 3 800 tonnes and EUR 25.5 million), representing respectively 0.8% of fisheries landings and 1.5% of their revenues (STECF, 2020).

In the Italian GSA 17, traditional pot fisheries targeting changeable nassa (*Nassarius mutabilis*) are by far the most important small-scale fishing activity, in terms of both fishing effort and landings each year (Grati et al., 2010). On the contrary, pots targeting cuttlefish (*Sepia officinalis*) are intensively used in the Spring-summer period (Fabi et al., 2001; Melli et al., 2014). Moreover, the pots targeting mantis shrimp (*Squilla mantis*) and gobies (mainly *Gobius niger*) are being increasingly used instead of the traditional gillnet (Bon et al., 2006).

In this area, funding has recently been provided through research projects (e.g. TartaLife, LIFE12NAT/IT/000937; Life Delfi, LIFE18 NAT/IT/000942), to investigate and promote innovative pots as potential alternative gears. A wider use of this low-impact gear is therefore encouraged by the scientific community to stimulate fishing fleet conversion and increasingly attract fishers’ interest.

3.3.4 Comparing the catch efficiency between pots and set nets

The pots can be considered valid alternatives to the set nets only if they yield good results in terms of catch efficiency, to sustain the economic viability of the fishery. One statistical approach to directly compare the catch efficiency between these two gears for the target species is the catch comparison, already introduced in Section 3.1.2.

This method can provide a length-dependent catch comparison and catch ratio between two different fishing gears, can quantify the magnitude of difference and can be easily applied under commercial fishing conditions. Moreover, the catch comparison method can be applied to paired (i.e. in each haul the two gears are simultaneously deployed) and unpaired (the two gears are not simultaneously deployed) data sets. However, this method cannot estimate a size-selection curve, as the size selectivity of the gear tested can only be measured relative to the compared gear (Lomeli, 2019).

For a given species included in a study, the following equation assesses the relative length-dependent catch comparison rate (*CCl*) of changing from one gear to another:

$$CC_l = \frac{\sum_{j=1}^{ht}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{i=1}^{hb}\left\{\frac{nb_{li}}{qb_i}\right\} + \sum_{j=1}^{ht}\left\{\frac{nt_{lj}}{qt_j}\right\}}$$

where nb_{li} and nt_{lj} are the number of fish of length *l* of a given species retained by one gear (called 'baseline'; *b*) in haul *i* and by the other gear (called 'test'; *t*) in haul *j*, respectively. Parameters qb_i and qt_j are the subsampling ratios, in case only a subsample of all individuals caught by the baseline or the test gears is measured (i.e. the ratio of the measured to the total number). Parameters *hb* and *ht* represent the total number of hauls conducted with baseline and test gear, respectively. If the hauls are paired, there will be only one *i* and *h* parameters.

CC(l,v) quantifies the probability that a fish of length *l* is retained by the test gear, provided that it is retained in one of the two gears compared. For instance, a *CC(l)* of 0.5 indicates that a fish of length *l* has the same probability of being retained by either gear. Therefore, *CC(l,v)* cannot be used to provide a direct relative value of the catch efficiency between the test and the baseline gears. The following catch ratio *CR(l,v)* equation is then usually applied:

$$CR(l,\boldsymbol{v}) = \frac{hb \times CC(l,\boldsymbol{v})}{ht \times [1 - CC(l,\boldsymbol{v})]}$$

In this case, *CR(l,v)* = 1.0 means that the catch efficiency of both gears is equal, while *CR(l,v)* = 0.25 indicates that the test gear is catching only 25% of the fish of length *l* compared to the baseline gear.

4 Objective of the thesis

Based on the current challenges addressed for the selected fisheries in the Northern-Central Adriatic Sea (Italian side), the objectives of this thesis are multiple:

i) to improve the knowledge on the size and species selectivity of the two legal codends (40 mm square mesh and 50 mm diamond mesh codends) employed in the bottom otter trawl fishery.

ii) to increase the size and species selectivity of the bottom otter trawl fishery by testing technical modifications that have the potential to reduce discards and bycatch.

iii) to improve the knowledge on the size selectivity of the hydraulic dredge targeting *C. gallina*.

iv) to investigate the potential of pots as alternative and more sustainable fishing gears to the traditional passive set nets, both in terms of catch efficiency and of discards and bycatch reduction.

The experimental work carried out within the thesis ultimately aims at reducing the amount of discards generated by the selected fisheries by testing the efficacy of more selective fishing gears/practices. If a solution is proven to be successful at reducing unwanted catches while not significantly penalizing commercial catches, it can be adopted in the regulation as a management measure to help face the landing obligation (LO).

Paper I evaluates and compares the catch performance of the two legal codends (SM40 and DM50) by accounting, through a holistic approach, for the full species community in the catches. In particular, it takes into account all the animals being caught intentionally or unintentionally and being both landed or discarded, and determines if there are changes in the catch profiles, in terms of species composition and dominance, when shifting from one codend to another.

Paper II estimates the selectivity of an experimental codend made of T90 meshes compared to a traditional diamond mesh codend with the same mesh size. The size selectivity of both codends is provided for seven commercially important species of the Adriatic bottom trawl fishery: European hake, red mullet, mantis shrimp, whiting (*Merlangius merlangus*), common squid, mackerel (*Scomber scombrus*), Mediterranean horse mackerel (*Trachurus mediterraneus*).

Paper III describes the effect, at the extension piece level, of two technical modifications (T90 meshes and reduction in the number of meshes at circumference), on the trawl catch patterns for three commercially important species of the Adriatic bottom trawl fishery (European hake, red mullet, monkfish).

Paper IV assesses the size selectivity of the hydraulic dredge targeting the venus clam in the Italian Adriatic Sea, under commercial conditions and at different haul durations.

Paper V compares the catch performance of innovative fish pots with that of the local traditional trammel net used in Adriatic SSFs, by analysing differences in terms of catch composition and by assessing the pots' effectiveness in terms of their use and handling, discard and bycatch reduction.

Moreover, the information collected on the selected fisheries to gain an overview of their current status, in terms of impact and selectivity at Mediterranean level, has significantly contributed to publishing three review papers, which, for completeness, are listed in Annex I.

Review I and II give an overview on the selectivity respectively of bottom trawls and passive set nets currently in use in the Mediterranean Sea, evaluating their sustainability within the current regulatory framework.

Review III gives an overview of the main pot designs, their spatial distribution and their main target species in the Mediterranean and evaluates the main technical parameters affecting the catch efficiency of pots targeting different target species.

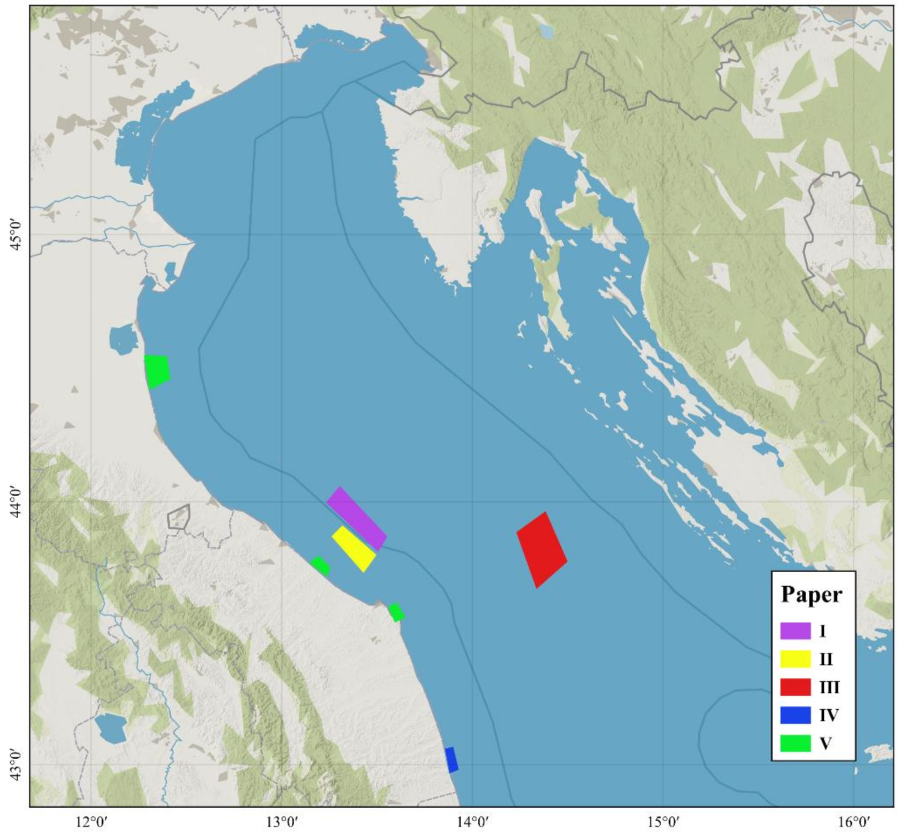

Figure 14. Spatial distribution of the sea trials related to the research of this thesis.

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5 List of papers

Paper I: Petetta, A., Herrmann, B., Li Veli, D., Virgili, M., De Marco, R., Lucchetti, A. (2023). Every animal matters! Evaluating the selectivity of a Mediterranean bottom trawl fishery from a species community perspective. *PLoS One*, 18(3), e0283362. https://doi.org/10.1371/journal.pone.0283362.

Paper II: Petetta, A., Herrmann, B., Virgili, M., De Marco, R., Canduci, G., Li Veli, D., Bargione, G., Vasapollo, C., Lucchetti, A. (2020). Estimating selectivity of experimental diamond (T0) and turned mesh (T90) codends in multi-species Mediterranean bottom trawl. *Mediterranean Marine Science* 21, 545–557. https://doi.org/10.12681/mms.22789.

Paper III: Petetta, A., Herrmann, B., Virgili, M., Li Veli, D., Brinkhof, J., Lucchetti, A. (2022). Effect of extension piece design on catch patterns in a Mediterranean bottom trawl fishery. *Frontiers in Marine Science*, 9:876569. https://doi.org/10.3389/fmars.2022.876569.

Paper IV: Petetta, A., Herrmann, B., Virgili, M., Bargione, G., Vasapollo, C., Lucchetti, A. (2021). Dredge selectivity in a Mediterranean striped venus clam (*Chamelea gallina*) fishery. *Fisheries Research*, 238, 105895. https://doi.org/10.1016/j.fishres.2021.105895

Paper V: Petetta, A., Vasapollo, C., Virgili, M., Bargione, G., Lucchetti, A. (2020). Pots vs trammel nets: a catch comparison study in a Mediterranean small-scale fishery. *PeerJ* 8, e9287. https://doi.org/10.7717/peerj.9287.

Paper I

Every animal matters! Evaluating the selectivity of a Mediterranean bottom trawl fishery from a species community perspective

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RESEARCH ARTICLE

Every animal matters! Evaluating the selectivity of a Mediterranean bottom trawl fishery from a species community perspective

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Abstract

Bottom trawl fisheries often catch several species simultaneously. However, most studies addressing the catch performance and selectivity of a specific trawl focus on a few commercially important or most vulnerable species requiring management measures. By contrast, the present study considers the multispecies nature of Mediterranean bottom trawl fisheries through a holistic approach that accounts for the full species community in the catches. Specifically, we evaluated and compared the catch performance of the two codends allowed for this fishery, made of 40 mm square (SM40) and 50 mm diamond (DM50) meshes. Results showed that 50 and 80% of the catch in weight and count numbers, respectively, consisted of species without commercial value, demonstrating that large proportions of the catch are not considered when using the existing approach to evaluate the ecological impact of the fishing activity. Significant differences in catch profiles between the two codends were observed, especially for two commercial flatfish species, *Arnoglossus laterna* and *Citharus linguatula*, with larger contributions in the SM40. Further, the SM40 codend had a significantly higher retention, compared to DM50 codend, for specific sizes of *Merluccius merluccius* and *Mullus barbatus*. The outcomes of the study can be useful for the Mediterranean bottom trawl fisheries management.

Keywords

Bottom trawling, species and size selectivity, Mediterranean demersal fisheries, discards, catch comparison, fishing performance

Introduction

Most of the demersal trawl fisheries operating in the Mediterranean Sea simultaneously target different species sharing the same grounds at the same time (Lucchetti et al., 2021). Besides them, there are several other species caught more or less frequently which can both provide additional income to fishers, or be discarded because of little or no commercial value.

The catch of unwanted species is one of the main issues in bottom trawl fisheries' management, since it contributes, together with the catch of undersized or damaged specimens of commercial species, to the high discard rates reported throughout the basin (20-65% of the total catch, according to Tsagarakis et al. (2014)). Most of the discards might not survive because they are damaged in the capture process, sometimes hauled up from the fishing depth too quickly, or thrown back too late. Since these fish, crustaceans, shellfish etc. are part of an ecosystem, their removal affects the entire food chain (Innes and Pascoe, 2010). In addition, the rejecting practises of dead or dying organisms does not result in any economic advantage, as catches cannot be sold for human consumption and will not benefit fishing activities in future years (Bellido et al., 2011).

The minimization of this wasteful practice of discarding is one of the pillars of the Common Fisheries Policy (CFP), which, in the Mediterranean basin, enforced several specific frameworks of fisheries management (EU Regulation 1241, 2019; EU Regulation 1380, 2013). First, the CFP established the landing obligation (LO) of all the catches of species subjected to the minimum conservation reference size (MCRS; EU Regulation 1380, 2013). Other measures concern the establishment of fisheries restricted areas (FAO, 2020), initiatives to facilitate control by authorities and to provide incentives to fishers to improve compliance (EC, 2021), and the enforcement of technical limitations on fishing gears. In bottom trawl fisheries, these limitations concern the mesh size and geometry at the trawl codend level. In fact, the codend is considered to be the main part of the net where the fish escapement process takes place (Beverton, 1963; Clark, 1963). Currently, the codend allowed for the Mediterranean has to be constructed with 40 mm (full mesh) square meshes (SM40, hereafter); an alternative legal codend, only with a duly justified request from the shipowner, is the 50 mm (full mesh) diamond mesh (DM50, hereafter) codend (EU Regulation 1241, 2019). However, both these codends are unable to avoid a considerable capture of unwanted species and immature and undersized fish, thus being inefficient at ensuring a sustainable harvest for the majority of the fish stocks (Lucchetti et al., 2021).

Most of the scientific studies investigating the catch patterns, size and species selectivity of trawls usually focus on a few species. These are often the most economically important species (Petetta et al., 2022) or most vulnerable species requiring urgent management measures (Fakıoğlu et al., 2022).

On the contrary, the multispecies nature of Mediterranean bottom trawl fisheries is rarely addressed, despite the growing need for ecosystem-based fishery management for conserving biodiversity (Mytilineou et al., 2022). However, the overall ecological impact of using a specific gear or technical modification cannot be determined if significantly important fractions of the catch are neglected, which may cause an underestimation of the unaccounted fishing mortality (Gilman et al., 2013). Accordingly, there is a need for a more holistic approach that considers the whole species community in the bottom trawl catches. The present study, therefore, aims at using a methodology that takes into account all the animals being caught intentionally or unintentionally and being both landed or discarded. This methodology was applied to sea trials carried out in the North-western Adriatic Sea (FAO Geographical Sub Area 17). The objective was to assess the selectivity of the two codends (SM40 and DM50) from a species community perspective, and evaluate if there were changes in the catch profiles, in terms of species composition and dominance, when shifting from one codend to another. Moreover, a comparison of the catch efficiency at size between SM40 and DM50 was performed on the most abundant commercial species.

Materials and Methods

Sea trials and data collection

The sea trials were conducted 13-16 nautical miles off the coast of Senigallia (central Italy; Figure 1) from 16th to 25th February 2022 on board R/V ‘G. Dallaporta’ (810 kW at 1650 rpm, Length Over All 35.30 m, Gross Tonnage 285 GT).

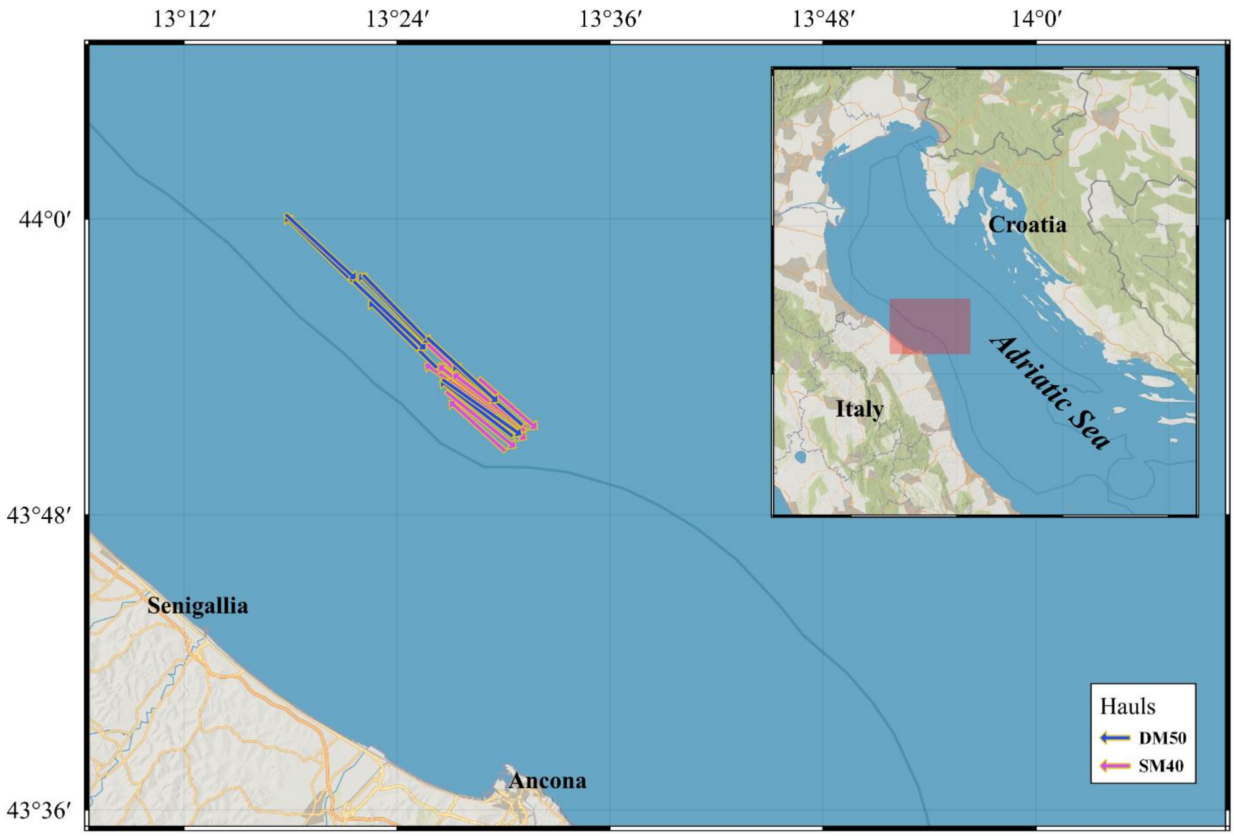

Figure 1: Map of the hauls carried out during the sea trials, distinguished by codend type (SM40: 40 mm square mesh codend; DM50: 50 mm diamond mesh codend). The light blue line represents the 12 nautical miles from Italian coastline, which divides the national from the international waters. The arrows indicate the towing direction.

The gear used in the experiments was a 'Volantina' net often employed by commercial trawlers of the area. It is an asymmetric 2-panels net (with the upper panel shorter than the lower panel) entirely made of knotless polyamide (PA) netting (see Sala and Lucchetti (2011) for trawl design). The length from the wing tips to the codend was approximately 60 m, with 600 meshes in the top panel at the footrope level. The sweeps and bridles were 80 and 50 meters long, respectively. A single pair of otter boards (163x100 cm, 270 kg each) was used to maintain the horizontal net opening.

Both codends tested (SM40 and DM50) were made of the same netting twine and twine thickness (knotless PA, 3880 RTEX). Their mean measured mesh size, obtained with an OMEGA gauge (Fonteyne et al., 2007) at 50 N while the netting was wet, was 38.1 mm for SM40 and 50.3 mm for DM50. The number of meshes at codend circumference was 140 for SM40 and 220 for DM50 (Table 1), to obtain a similar circumference between codends during fishing, thus avoiding different effects on selectivity. In fact, following the considerations and calculations made by Sala et al. (2015) on the expected mesh openness during fishing in square and diamond configurations, respectively, the expected circumference of both codends were around 2.7 meters.

Table 1: Technical features of the two codends tested. SM40: 40 mm square mesh codend; DM50: 50 mm diamond mesh codend.

	SM40	**DM50**
Codend length (m)	4.8	4.8
Nr. Meshes in codend circumference	140	220
Mesh configuration	Square	Diamond
Nominal mesh size (mm)	40	50
Measured mesh size (mm ± SD)	38.11 ± 0.94	50.26 ± 0.81
Netting twine	PA (Knotless)	PA (Knotless)
Twine thickness (RTEX)	3880	3880

Each of the two codends was mounted on the same trawl. 19 valid hauls were performed: the first 9 hauls with SM40 and the last 10 with DM50. All hauls were carried out in daylight at a mean depth (SD) of 55.5 meters (1.2), with a standardized towing duration of around 60 minutes (59.2 ± 1.9). The average towing speed was 3.0 knots (range 2.8-3.2 knots). The horizontal net opening (19.5 ± 0.2 meters) was monitored using acoustic sensors (SIMRAD, Norway).

After each haul, the catch was sorted following the commercial procedures. The fishers on deck divided the total catch into a discarded and a landed fraction. Then the researchers on board divided the catch of each fraction by species, by identifying all taxa to the lowest possible level. For each species within each fraction, the total weight was recorded and the individuals were counted. The counts were performed without sub-sampling except for the large catches of swimming crab (*Liocarcinus depurator*) obtained in each haul, for which the count was conducted on a randomly selected subsample, and the subsample coefficient was determined. Furthermore, individual length measurements (total length for fish and mantle length for cephalopods) were taken to the lowest 0.5 cm for the most abundant commercial species caught in the sea trials. These were: European hake (*Merluccius merluccius*), red mullet (*Mullus barbatus*), Atlantic mackerel (*Scomber scombrus*), Mediterranean scaldfish (*Arnoglossus laterna*), spotted flounder (*Citharus linguatula*), broadtail shortfin squid (*Illex coindetii*) and tub gurnard (*Chelidonichthys lucerna*). The measurements were recorded without sub-sampling except for a large catch obtained for *A. laterna* in one haul, where measurements were conducted on a randomly selected subsample.

Data analysis

The statistical software SELNET (Herrmann et al., 2012) was used to analyse the catch data. Data were treated as unpaired (Herrmann et al., 2017) since the shift from one codend to another was not done after each haul and therefore we could not treat them as paired hauls.

Catch dominance analysis

Catch dominance curves are often used to quantify information about the relative species abundances for a given sample. The catch dominance analysis was here performed to evaluate, for each species, its relative abundance in both the total catch, the discarded catch and the landed catch. The aim was to assess if the proportion of each species in each fraction was significantly different between the two codends tested.

Usually, the dominance curves are based on the ranking of species in a sample in decreasing order of their abundance (Clarke, 1990). In the present study, a fixed rank was assigned to each single species caught in the sea trials, by including it into one of the following 4 categories: 1) ‘Target species’, i.e. the main commercial species targeted by the Italian Adriatic bottom trawl fishery in 20-100 meters of depth (Lucchetti, 2008); 2) ‘Bycatch species of commercial value’, i.e. additional species with a commercial value, that are landed; 3) ‘Species of no commercial value’, i.e. those species usually discarded by the fishers; 4) ‘Protected species’, i.e. those species included in EU regulations and International lists (e.g. EU Habitat directive, IUCN red list).

Since our intent was to estimate, on average, the performance of the two codends in the fishery, the catch dominance curves were averaged over hauls. They were then estimated, in both number of individuals (dn_i) and weight (dw_i), for each codend and each fraction of the catch (total, discarded, landed) by using the following equations (Warwick et al., 2008; Petetta et al., 2022):

$$dn_i = \sum_{j=1}^{h} \left\{ \frac{\frac{n_{ij}}{q_{ij}}}{\sum_{i=1}^{S} \left\{ \frac{n_{ij}}{q_{ij}} \right\}} \right\} \qquad (1)$$

$$dw_i = \sum_{j=1}^{h} \left\{ \frac{\rho_{ij} \times \frac{n_{ij}}{q_{ij}}}{\sum_{i=1}^{S} \left\{ \rho_{ij} \times \frac{n_{ij}}{q_{ij}} \right\}} \right\} \qquad (2)$$

where j represents the haul and i is the species rank previously defined. n_{ij} is the number of individuals of the species i being counted in the subsample in haul j. q_{ij} represents the subsampling ratio, i.e. the counted subsample of species i in haul j. Parameter ρ is the average weight of species i in haul j in a given fraction of the catch, and it is obtained from the total weight and number of individuals. S is the total number of species considered, whereas h is the total number of hauls conducted with the specific codend.

The cumulative dominance curves were then estimated, in both number of individuals (Dn_I) and weight (Dw_I), to better represent species dominance patterns, as follows:

$$Dn_I = \sum_{j=1}^{h} \left\{ \frac{\sum_{i=1}^{I} \frac{n_{ij}}{q_{ij}}}{\sum_{i=1}^{S} \left\{ \frac{n_{ij}}{q_{ij}} \right\}} \right\} \text{ with } 1 \leq I \leq S \qquad (3)$$

$$Dw_I = \sum_{j=1}^{h} \left\{ \frac{\sum_{i=1}^{I} \rho_{ij} \times \frac{n_{ij}}{q_{ij}}}{\sum_{i=1}^{S} \left\{ \rho_{ij} \times \frac{n_{ij}}{q_{ij}} \right\}} \right\} \text{ with } 1 \leq I \leq S \qquad (4)$$

where I is the species rank summed up in the nominator.

The Efron percentile 95% confidence intervals (*CIs*; Efron, 1982) were used to provide the uncertainty of the values of dominance patterns obtained following the procedure described in Herrmann et al. (2022). This procedure enables estimation of the uncertainty around the dominance values at species level induced by the limited sample sizes at a single haul without having to make any prior assumptions regarding the distributions in the hauls (Herrmann et al., 2022).

Furthermore, the difference Δd in species dominance d in the SM40 (x) and DM50 (y) codends was estimated by:

$$\Delta d = d_y - d_x \qquad (5)$$

By applying the technique described in Herrmann et al. (2022), the *CIs* for Equation 5 were obtained based on separate bootstrap populations for d_x and d_y. The significance was detected by inspecting if the *CIs* contained the value 0.0. If the 0.0 value was within the *CIs*, no significant difference was detected.

Catch comparison and catch ratio analysis

The length-frequency distributions, obtained from the most abundant commercial species mentioned above, were used to perform a catch comparison and catch ratio analysis. The aim was to investigate the size-dependent effect on the catch efficiency of each species by changing the codend.

For each species independently, we assessed the relative length-dependent catch comparison rate (CC_l) of shifting from one codend to another, by using Equation 6 (Herrmann et al., 2017):

$$CC_l = \frac{\sum_{j=1}^{ht} \left\{ \frac{nt_{lj}}{qt_j} \right\}}{\sum_{j=1}^{hb} \left\{ \frac{nb_{lj}}{qb_j} \right\} + \sum_{j=1}^{ht} \left\{ \frac{nt_{lj}}{qt_j} \right\}} \qquad (6)$$

where nb_{lj} and nt_{lj} are the number of fish of length l of a given species retained in haul j by the baseline codend (b, i.e. SM40 codend) and test codend (t, i.e. DM50 codend), respectively. Parameters qb_j and qt_j are the subsampling ratios, i.e. the ratios of the measured to the total number of individuals retained by the baseline and the test codend, respectively. Parameters *hb* and *ht* represent the total number of hauls conducted with baseline and test codend, respectively.

We estimated the catch comparison rate *CC(l,v)* experimentally expressed by Equation 6, by minimizing the Expression 7 (maximum likelihood estimation):

$$-\sum_{l}\left\{\sum_{j=1}^{hb}\left\{\frac{nb_{lj}}{qb_j}\times ln[CC(l,\boldsymbol{v})]\right\}+\sum_{j=1}^{ht}\left\{\frac{nt_{lj}}{qt_j}\times ln[1.0-CC(l,\boldsymbol{v})]\right\}\right\} \quad (7)$$

where the outer summation is over the length classes *l* and the inner summation is over the hauls *ht* and *hb* in the experimental dataset. The *v* parameter describes the catch comparison curve defined by *CC(l,v)*. The experimental CC_l was modelled by the function *CC(l,v)*:

$$CC(l,\boldsymbol{v})=\frac{exp[f(l,v_0,\ldots,v_k)]}{1+exp[f(l,v_0,\ldots,v_k)]} \quad (8)$$

where *f* is a polynomial of order *k* with coefficients v_0 to v_k, such that $v = (v_0, \ldots, v_k)$. *f* was considered up to an order of 4. Leaving out one or more of the parameters $v_0 \ldots v_4$ yielded 31 additional candidate models for the catch comparison function *CC(l,v).* We estimated the catch comparison rate, among these models, by using the multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017). We based the ability of the combined model to describe the experimental data on the *p*-value, calculated based on the ratio between the model deviance and the degrees of freedom (DOF; Wileman et al., 1996; Herrmann et al., 2017). A *p*-value > 0.05 indicates suitable fit statistics for the combined model to describe the experimental data sufficiently well. With poor fit statistics (*p*-value < 0.05 and deviance/DOF >> 1), the residuals were inspected to determine whether the results were due to structural problems when modelling the experimental data, or to overdispersion in the data (Wileman et al., 1996).

CC(l,v) quantifies the probability that a fish of length *l* is retained by the DM50 codend, provided that it is retained in one of the two codends (DM50 or SM40). Since the number of valid hauls conducted with the two codends was different (10 hauls with DM50, 9 hauls with SM40), the same probability, for a fish with a given length *l*, of being retained by either gear will be at *CC(l)* = 0.526 (i.e. the ratio 10 to 19).

The results of *CC(l,v)* do not provide a direct relative value of the catch efficiency between the test and the baseline codends. Therefore, we used the catch ratio *CR(l,v),* since it provides such a direct comparison and can be easily derived from *CC(l,v)* following the equation:

$$CR(l,\boldsymbol{v})=\frac{hb\times CC(l,\boldsymbol{v})}{ht\times[1-CC(l,\boldsymbol{v})]} \quad (9)$$

In this case, *CR(l,v)* = 1.0 means that the catch efficiency of both codends is equal, while *CR(l,v)* = 0.25 indicates that the test net is catching only 25% of the fish of length *l* compared to the baseline net.
We then estimated the 95% *CIs* for both the catch comparison and catch ratio curves by using a double bootstrapping method with 1000 bootstrap repetitions. By using this approach, following the description given by Lomeli (2019), both within and between haul variations were taken into account.

Exploitation pattern indicator analysis

We applied the exploitation pattern indicators for catch comparison to summarize the relative performance of the two codends tested. The indicators were adopted from Bonanomi et al. (2020) and Veiga-Malta et al. (2019) on the seven species previously selected for the catch comparison and catch ratio analysis. Among them, only *M. merluccius*, *M. barbatus* and *S. scombrus* are subjected to a minimum conservation reference size (MCRS of 20, 11 and 15 cm, respectively; Council Regulation 1967, 2006); therefore, individuals below this size were considered as discards. Regarding *A. laterna*, the 12 cm length class was considered as a reference size between the individuals discarded (<12 cm) and landed (≥12 cm), according to common fishers' practises. All the individuals of *C. linguatula*, *I. coindetii* and *C. lucerna* caught were landed, thus no reference sizes were available for those species.

For the species with a reference size, the average percentage of individuals below and above this size retained by the test codend (DM50) compared to the baseline codend (SM40), in terms of number of individuals (*nP*-, *nP+*) were estimated as follows:

$$nP- = \frac{hb \times \sum_{j=1}^{ht} \sum_{l < MCRS} \left\{ \frac{nT_{jl}}{qT_j} \right\}}{ht \times \sum_{j=1}^{hb} \sum_{l < MCRS} \left\{ \frac{nB_{jl}}{qB_j} \right\}} \qquad (10)$$

$$nP+ = \frac{hb \times \sum_{j=1}^{ht} \sum_{l \geq MCRS} \left\{ \frac{nT_{jl}}{qT_j} \right\}}{ht \times \sum_{j=1}^{hb} \sum_{l \geq MCRS} \left\{ \frac{nB_{jl}}{qB_j} \right\}} \qquad (11)$$

where nT_{jl} and qT_j represent the estimation made for the test codend, and nB_{jl} and qB_j the estimation made for the baseline codend. The summations of *j* and *l* in (10) and (11) are over the hauls *ht* and *hb*, and length classes *l*, respectively. An indicator value of 100% means that the test codend caught an equal number of individuals below (*nP*-) and above (*nP+*) the MCRS, respectively, compared to the baseline codend. Indicator values of 50% and 150% mean that the test codend caught 50% less and 50% more individuals (below or above MCRS) than the baseline codend, respectively.

For those species not subject to a MCRS or without a reference size, the mean percentage of all individuals retained by the test codend compared to the baseline codend was estimated, in number of individuals (*nP*), as follows:

$$nP = \frac{hb \times \sum_{j=1}^{ht}\left\{\sum_{l}\frac{nT_{jl}}{qT_{j}}\right\}}{ht \times \sum_{j=1}^{hb}\left\{\sum_{l}\frac{nB_{jl}}{qB_{j}}\right\}} \qquad (12)$$

A value of 100% means that the test codend catches the same total number (*nP*) of the species analysed as the standard codend.

Discard ratios were then estimated for each gear in terms of number for both the test (*nDRatioT*) and baseline (*nDRatioB*) codends, as follows:

$$nDRatioT = 100 \times \frac{\sum_{j=1}^{ht}\left\{\sum_{l< MCRS}\frac{nT_{jl}}{qT_{j}}\right\}}{\sum_{j=1}^{ht}\left\{\sum_{l}\frac{nT_{jl}}{qT_{j}}\right\}} \qquad (13)$$

$$nDRatioB = 100 \times \frac{\sum_{j=1}^{hb}\left\{\sum_{l< MCRS}\frac{nB_{jl}}{qB_{j}}\right\}}{\sum_{j=1}^{hb}\left\{\sum_{l}\frac{nB_{jl}}{qB_{j}}\right\}} \qquad (14)$$

A discard ratio of 0% would imply that no discard was produced. Again, the 95% *CIs* for each indicator were estimated using the double bootstrap method described above.

Results

Catch dominance analysis

A total of 68 species belonging to 9 higher taxa (Osteichthyes and Condrichthyes; Crustacea Decapoda; Mollusca Cephalopoda, Bivalvia and Gastropoda; Echinodermata; Polychaeta; Ascidiacea) were caught during the sea trials (Table 2). Only 4 fish species were included in the 'Target species' category: European hake, red mullet, monkfish and tub gurnard. 27 species were classified as 'Bycatch species of commercial value'; they included 16 fish species (13 bony fishes and 3 elasmobranches), 7 cephalopod species and 4 crustacean species. 37 species were classified as 'Species of no commercial value'. Most of them were fish (21 species), followed by crustaceans (6 species), echinoderms (5 species), molluscs (3 species), polychaetes (1 species) and ascidian (1 species). Only 1 protected species (the twait shad, *Alosa fallax,* listed in Annexes II and V of the Habitats Directive as requiring close protection; Council Directive 92, 1992) was caught during the cruise. This classification was specifically related to the fishers' choice in a precise spatiotemporal context. Therefore, it does not fully represent neither all the Mediterranean bottom trawl fisheries, where some species, here classified as commercial, could be always discarded elsewhere and vice versa due to local consumers' preferences, nor the Adriatic fishery, where some species can have a market value only in a specific season.

Table 2: Assigned ranking (S) of the animal species, divided by category, caught during the sea trials.

Target species	**Bycatch species of commercial value**	**Species of no commercial value**	**Protected species**
S1 *Merluccius merluccius*	S5 *Trisopterus minutus capelanus*	S32 *Liocarcinus depurator*	S68 *Alosa fallax*
S2 *Mullus barbatus*	S6 *Scomber scombrus*	S33 *Medorippe lanata*	
S3 *Lophius* spp	S7 *Trachurus mediterraneus*	S34 *Goneplax rhomboides*	
S4 *Chelidonichthys lucerna*	S8 *Alloteuthis media*	S35 *Dardanus arrosor*	
	S9 *Loligo vulgaris*	S36 *Maja squinado*	
	S10 *Sepia officinalis*	S37 *Solenocera membranacea*	
	S11 *Eledone* spp.	S38 *Sardina pilchardus*	
	S12 *Illex coindetii*	S39 *Engraulis encrasicolus*	
	S13 *Octopus vulgaris*	S40 *Sardinella aurita*	
	S14 *Sepia elegans*	S41 *Spicara maena*	
	S15 *Raja asterias*	S42 *Boops boops*	
	S16 *Raja clavata*	S43 *Blennius ocellaris*	
	S17 *Squalus acanthias*	S44 *Conger conger*	
	S18 *Citharus linguatula*	S45 *Eutrigla gurnardus*	
	S19 *Arnoglossus laterna*	S46 *Gobius niger*	
	S20 *Solea solea*	S47 *Lepidotrigla cavillone*	
	S21 *Scophthalmus rhombus*	S48 *Lesuerigobius friesii*	
	S22 *Nephrops norvegicus*	S49 *Microchirus variegatus*	
	S23 *Melicertus kerathurus*	S50 *Pagellus acarne*	
	S24 *Squilla mantis*	S51 *Pagellus bogaraveo*	
	S25 *Parapenaeus longirostris*	S52 *Pagellus erythrinus*	
	S26 *Sparus aurata*	S53 *Pagrus pagrus*	
	S27 *Uranoscopus scaber*	S54 *Callionymus* spp.	
	S28 *Trachinus draco*	S55 *Cepola macrophthalma*	
	S29 *Merlangius merlangus*	S56 *Scorpaena notata*	
	S30 *Pomatomus saltator*	S57 *Serranus hepatus*	
	S31 *Zeus faber*	S58 *Sphyraena sphyraena*	
		S59 *Phallusia mamillata*	
		S60 *Ocnus planci*	
		S61 *Marthasterias glacialis*	
		S62 *Astropecten irregularis*	
		S63 *Aphrodite aculeata*	
		S64 *Armina tigrina*	
		S65 *Ostrea edulis*	
		S66 *Mytilus galloprovincialis*	
		S67 *Stichopus regalis*	

Table S1 shows the catch dominance percentages, in both number of individuals and weight, of each species in each codend tested (SM40 and DM50). The first 31 species often had both a landed and a discarded fraction, since some animals were rejected because they were too few or too small, damaged, with little commercial value in that specific area and season or below the MCRS. The latter 37 species were always discarded.

Figure 2 represents, for each codend, the cumulative species dominance (in percentages), in both number of individuals and weight, of the three catch fractions: total catch, discarded catch and landed catch. The cumulative curve of the total catch shows that, in the DM50 codend, the targeted species (S1-S4) and the species with a commercial value (S5-S31) cover, on average, less than 15% in number of individuals and less than 50% in weight of all the species caught. This means that the species with no commercial value represent the largest proportion of the total catch. The results are slightly different for the SM40, where the proportions of the first 31 species reach, on average, the 20% (in number of individuals) and the 50% (in weight) of all the catches. In both codends, there is a dramatic curve increase at species 32, corresponding to the swimming crab (*Liocarcinus depurator*), which brings the curve up to almost 90% considering both individuals and weight (Figure 2; see also Table S1 for the proportion of each species in the catch).

Regarding the discarded fraction of the catch, the proportion of the first 17 species (S1-S17) is low in both codends, but there is a clear increase in S18 and S19 (corresponding to two flatfish species, *C. linguatula* and *A. laterna*). This increase is more marked in SM40 than in DM50, in both number of individuals and weight. Again, in both codends *L. depurator* makes the curve rise from less than 10% to almost 90% when considering individuals and to around 80% when considering weight (Figure 2, Table S1). Regarding the landed fraction of the catch, the cumulative curve reaches 100% within the first 31 species. A significant curve increase is observed, in SM40 (number of individuals), for S18 and S19 (i.e. the flatfish species above mentioned). This increase is not discernible in the corresponding curve of DM50 (Figure 2).

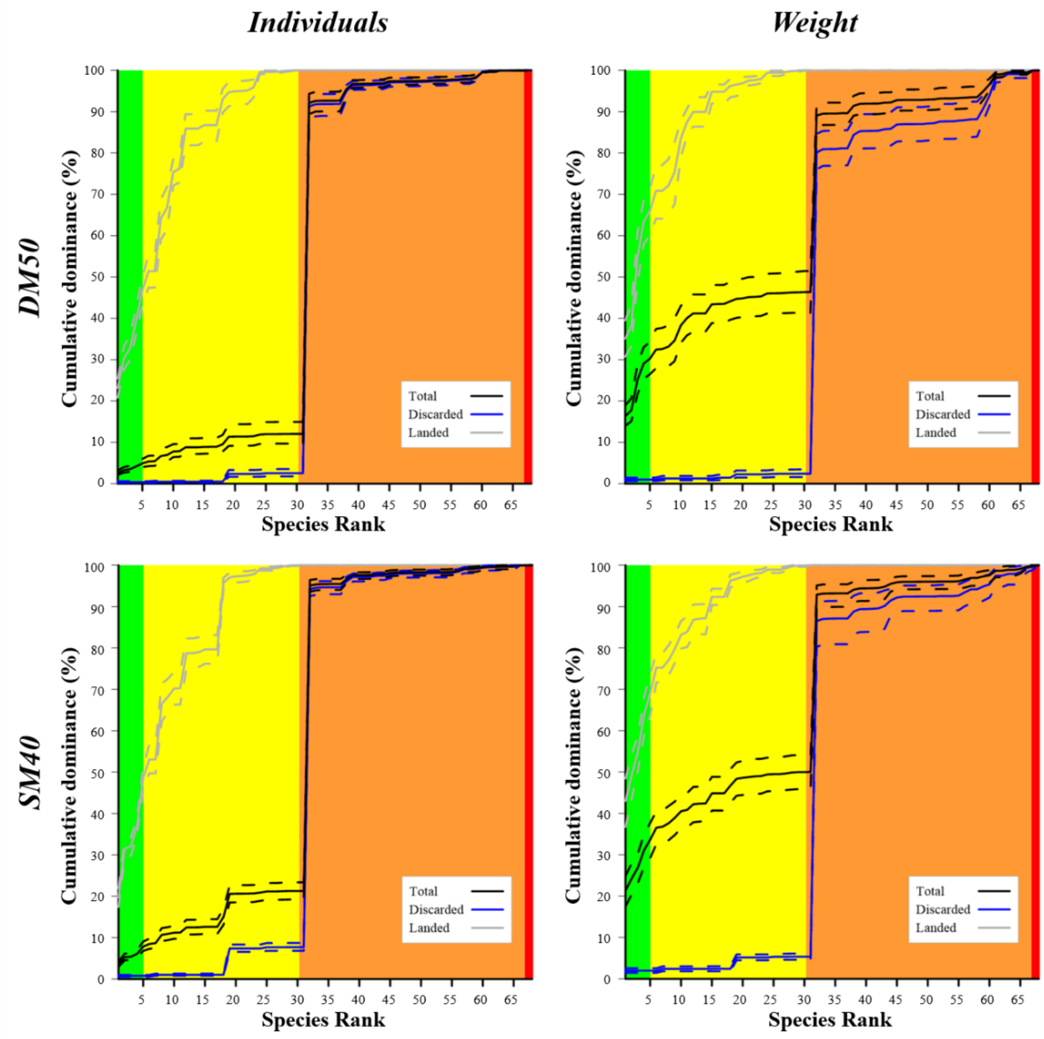

Figure 2: Cumulative species dominance in the catch of the 50 mm diamond mesh codend (DM50, above) and 40 mm square mesh codend (SM40, below). The curves (solid lines) with 95% CIs (dotted lines) represent the cumulative species dominance for the catches in both number of individuals (left) and weight (right). The green, yellow, orange and red areas represent the target species, the bycatch species of commercial value, the species of no commercial value and the protected species, respectively.

Figure 3 shows the delta plots resulting from the comparisons between the cumulative dominance curves obtained with the two codends for both the total, discarded and landed fractions of the catch.

The left column takes into account the number of individuals. The delta plot reveals a significant difference, in the total catch, from species S1 to S31 i.e. all the species of commercial interest, since both the upper and lower *CIs* are always below the 0.0 line which expresses an equal proportion between SM40 and DM50. A larger proportion, for these species, was in fact captured by the SM40. The same trend is observed in the discarded catch, meaning that SM40 also produced a larger proportion of discards for these species than the DM50, especially for the two flatfish species (S18, S19). Regarding the landed fraction of the catch, the DM50 produced a significantly larger proportion of the species from S10 to S17, which include commercial cephalopods and elasmobranches. No significant differences are observed in the proportion of the other species.

The right column takes into account the weight. In the total catch, a significant difference between the two codends is observed for the species S2 (*M. barbatus*), where the upper *CI* is below the 0.0 line, highlighting a lower proportion of this species in DM50 compared to SM40 catches. The same trend is observed, in the discarded catch, for species S1 to S31 i.e. all the species of a commercial value, especially from S18 to S31. Other barely significant differences (the upper *CI* almost reaches the 0.0 line) are observed in the left end of the curves of both total and discarded fractions from species S45 to S58 i.e. 'Species of no commercial value', whose proportion in the DM50 codend is slightly less than in the SM40 codend. Concerning the landed catch, the only significant difference concerns S2, whose proportion in DM50 is significantly less than in the SM40 (Fig. 3, bottom left).

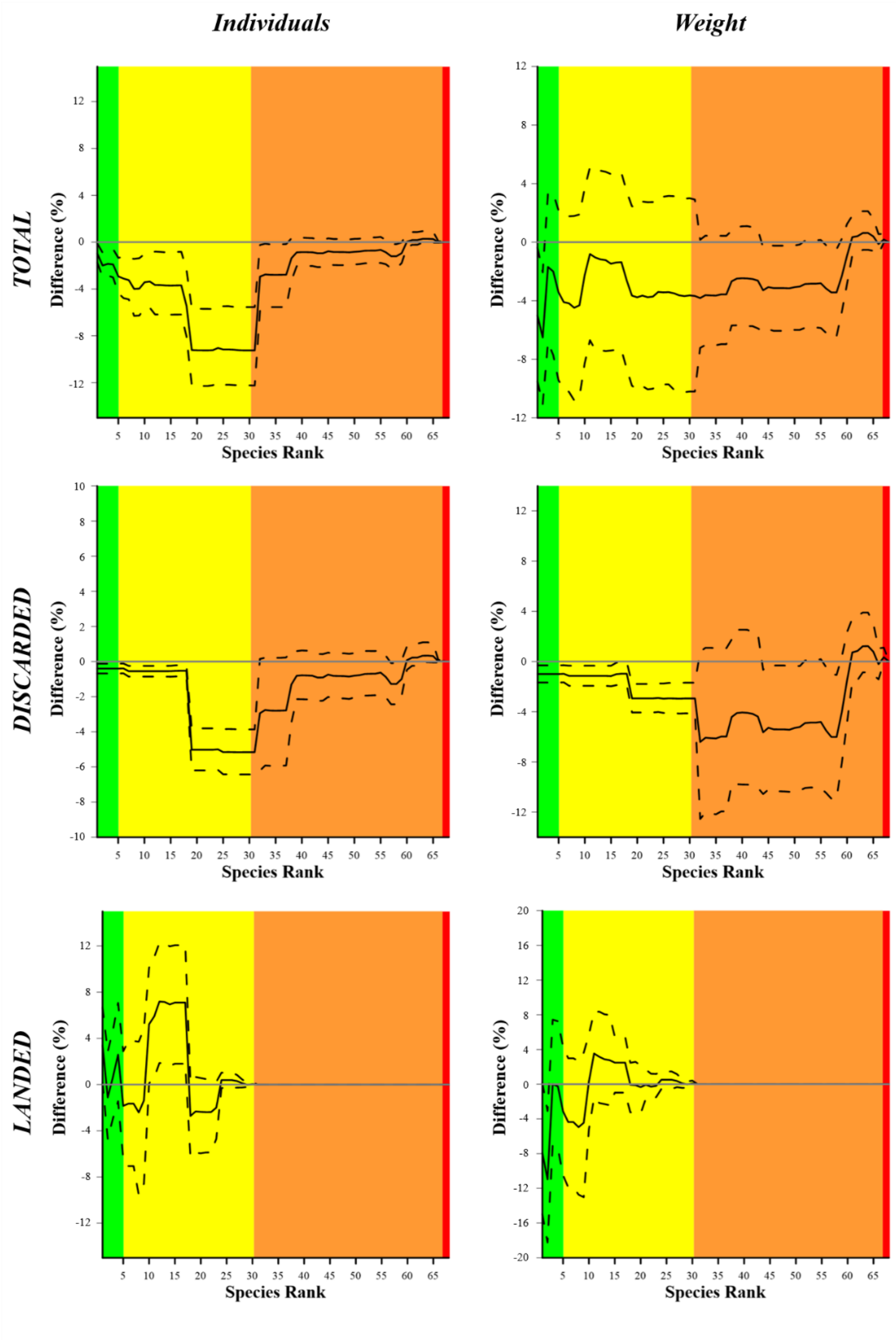

Figure 3: Delta plots resulting from the comparison of the cumulative dominance curves between the two codends tested (DM50, SM40) in both number of individuals (left column) and weight (right column). The curves (solid lines) with 95% CIs (dotted lines) are relative to the Total (top), discarded (middle) and landed (bottom) fractions. The 0 grey horizontal line represents an equal proportion between the two codends. The green, yellow, orange and red areas represent the target species, the bycatch species of commercial value, the species of no commercial value and the protected species, respectively.

Figure 4 shows the delta plots resulting from the comparison of the catch dominance curves, for the total, discarded and landed fractions of the catch. This figure provides a detailed insight at each single species level.

The plots of total and discarded fractions show, in particular, a significant difference between codends for the European hake (S1) and the two flatfish species (S18, S19), indicating a larger proportion of their dominance in the SM40 catches than in the DM50 catches in both number of individuals (Fig. 4, left column) and weight (Fig. 4, right column). The delta plot of the total catch also shows a significantly larger proportion of red mullet (S2) in SM40 than in DM50 catches, only in weight; on the contrary, a significantly larger proportion of monkfish (S3) is present in DM50 catches, in both number of individuals and weight. Also, *L. depurator* (S32) had a significantly larger proportion in the total catch of DM50 compared to SM40, only in number of individuals. Other differences detected at species level for these two fractions are barely significant. The delta plot of the landed fraction, in both number of individuals and weight, shows in particular that a larger proportion of the target species *M. merluccius* (S1), *Lophius* spp. (S3), the cephalopods *S. officinalis* (S10) and *Eledone* spp. (S11), is present in the DM50 catches than in the SM40 catches. On the contrary, a larger proportion of *M. barbatus* (S2), *T. minutus capelanus* (S5) and *C. linguatula* (S18) is present in SM40 catches than in DM50 catches.

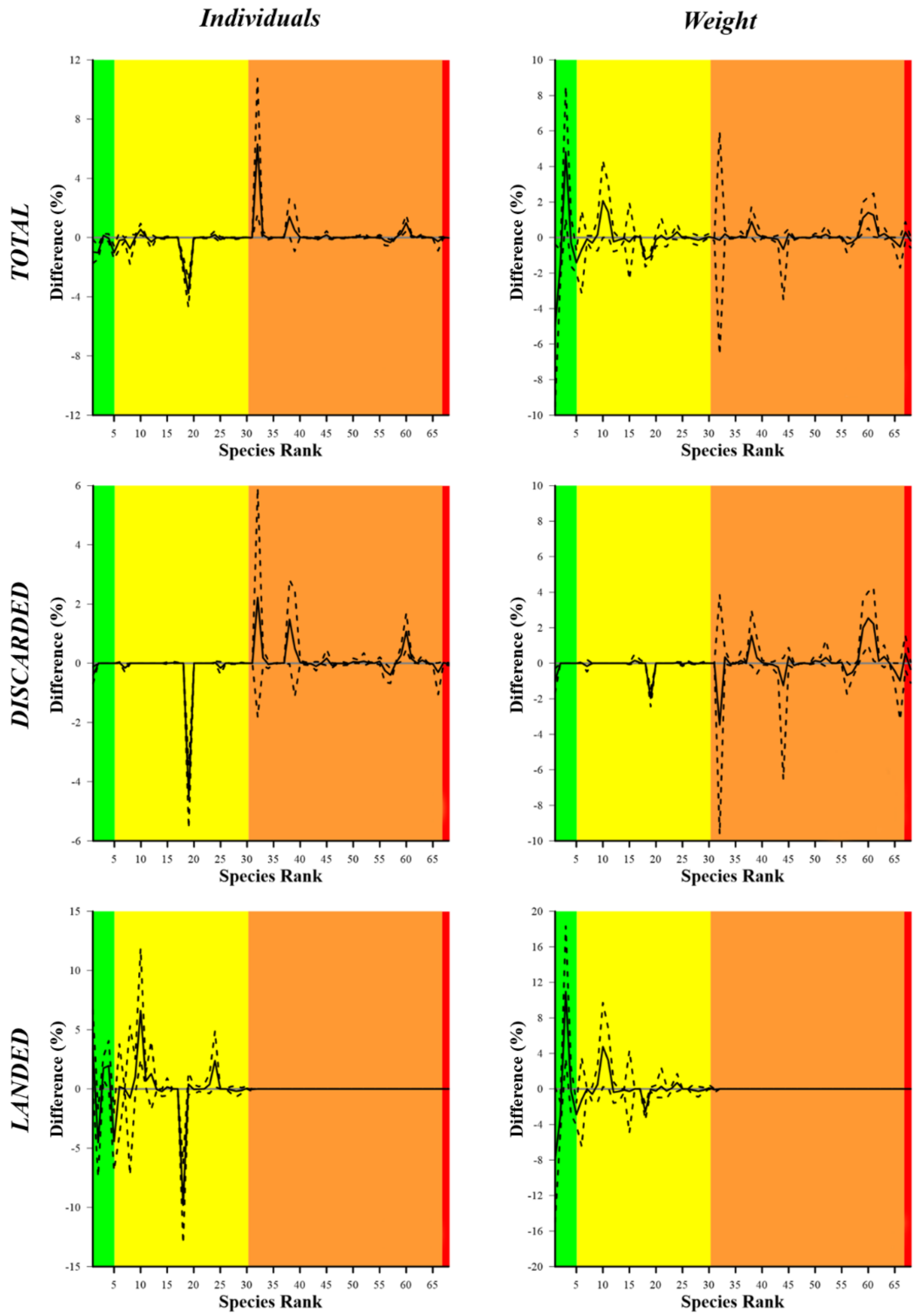

Figure 4: Delta plots resulting from the comparison of the species catch dominance between the DM50 and the SM40, in both number of individuals (left column) and weight (right column). The curves (solid lines) with 95% CIs (dotted lines) are relative to the Total (top), discarded (middle) and landed (bottom) fractions. The 0 grey horizontal line represents an equal proportion between the two codends. The green, yellow, orange and red areas represent the target species, the bycatch species of commercial value, the species of no commercial value and the protected species, respectively.

Catch comparison analysis

Table 3 reports the number of individuals measured in each haul for the 7 species selected for the catch comparison analysis (*M. merluccius, M. barbatus, S. scombrus, A. laterna, C. linguatula, I. coindetii, C. lucerna*).

Table 4 reports the fit statistics of the combined model. The *p*-value were < 0.05 for *A. laterna* (*p*=0.0071), *I. coindetii* (*p*=0.0179) and *C. lucerna* (*p*=0.026). These low *p*-values were assumed to be due to overdispersion in the experimental rates rather than a lack of fit, since the visual inspection of the modelled catch comparison curves against the experimental rates for these species did not indicate any length-dependent patterns in the deviations (see Figures 6, 7).

Table 3. Number of individuals of the most abundant commercial species measured in each haul, selected for the catch comparison analyses. No sub-samplings were performed except in one case, where the value of the subsampling coefficient is in brackets. SM40: 40 mm square mesh codend; DM50: 50 mm diamond mesh codend.

	Haul	*Merluccius merluccius*	*Mullus barbatus*	*Scomber scombrus*	*Arnoglossus laterna*	*Citharus linguatula*	*Illex coindetii*	*Chelidonichthys lucerna*
SM40	1	97	60	4	133	49	28	22
	2	90	29	9	122	60	38	18
	3	95	40	15	143	61	33	19
	4	53	37	23	133	37	14	14
	5	55	31	10	79	37	6	8
	6	65	20	2	72 (0.43)	68	28	12
	7	85	27	1	107	52	23	15
	8	50	47	44	108	28	34	11
	9	93	40	14	86	62	34	17
DM50	10	41	6	19	44	10	15	12
	11	57	13	6	35	22	10	14
	12	47	18	21	51	14	25	8
	13	67	23	6	43	23	31	12
	14	75	22	13	41	13	22	19
	15	55	9	0	22	11	8	19
	16	61	18	18	42	9	32	26
	17	48	10	1	28	8	23	13
	18	43	11	5	31	12	11	9
	19	48	17	5	45	6	21	6

Table 4. Fit statistics of the combined model used in the catch comparison between the 40 mm square mesh codend and 50 mm diamond mesh codend. DOF: degrees of freedom.

	Merluccius merluccius	*Mullus barbatus*	*Scomber scombrus*	*Arnoglossus laterna*	*Citharus linguatula*	*Illex coindetii*	*Chelidonichthys lucerna*
***p*-value**	0.1408	0.0846	0.0739	0.0071	0.1741	0.0179	0.026
Deviance	59.7	22.98	17.02	34.54	21.12	40.72	36.62
DOF	49	15	10	17	16	24	22

Figures 5-7 show the catch comparison and catch ratio results obtained by comparing the two codends (DM50 VS SM40) for the species selected. Regarding the European hake (Figure 5, top) a difference is observed from the 12 cm to the 26.5 cm length class, for which both the catch comparison and catch ratio curves display a significantly lower catch efficiency of the DM50 codend compared to the SM40 codend. A significantly lower retention of DM50 compared to SM40 is also observed for red mullet (Figure 5, middle) from 11 to 14.5 cm. This difference is well discernible not only from the catch comparison and catch ratio curves, but also from the length frequency distributions obtained. No individuals below 11 cm, which represents the MCRS of the species, were caught in the sea trials. Regarding the Atlantic mackerel (Figure 5, bottom), there are no significant differences between the catch efficiency of the two codends, since the *CI*s of both the catch ratio and catch comparison curves overlapped, for the full length range measured, the horizontal 0.526 line representing equal catch rates. The low number of individuals caught during the sea trials are reflected in the wide *CI*s of the curves. Also, very few individuals below 15 cm (i.e. the MCRS of the species) were caught in the sea trials.

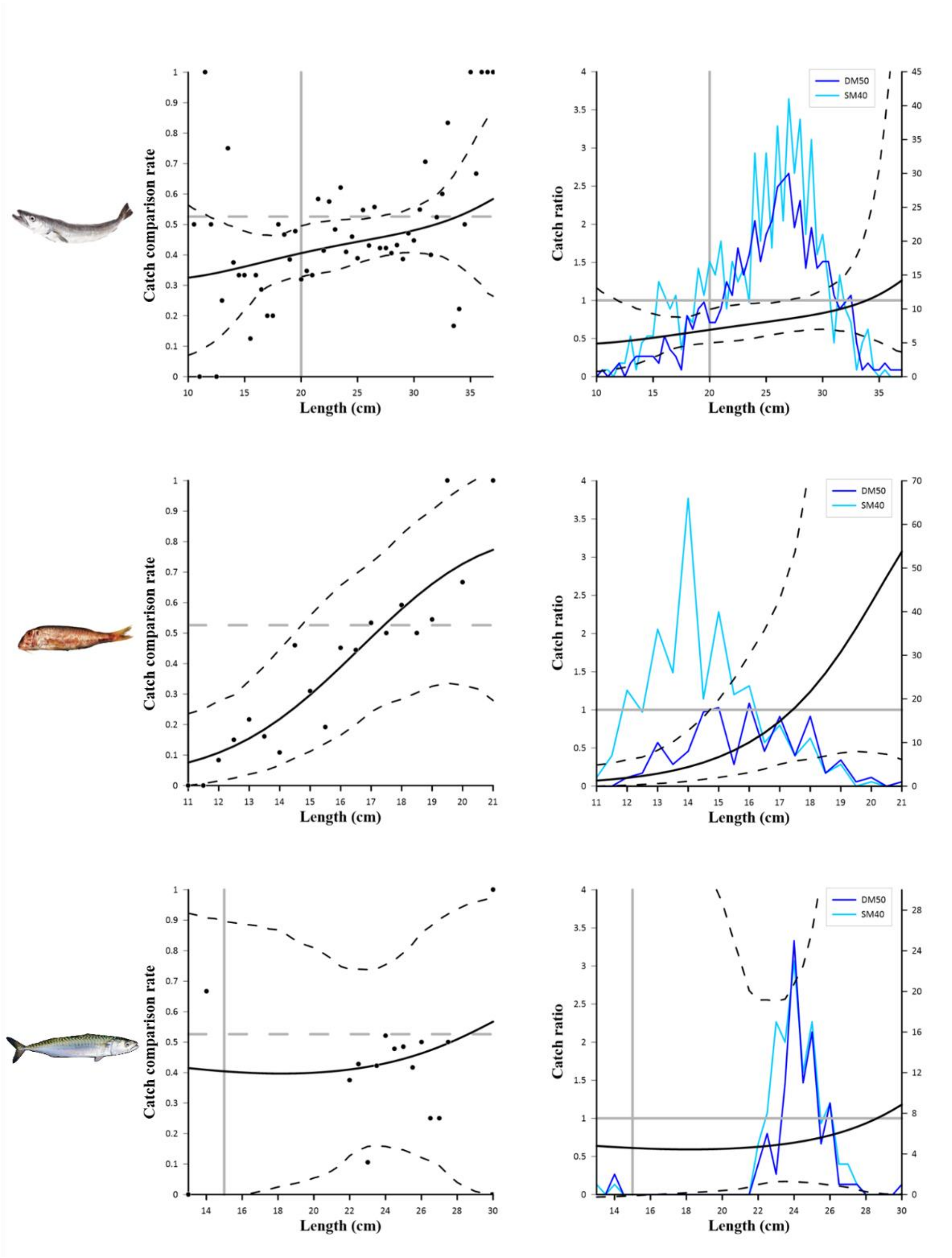

Figure 5: Results of the catch comparison analyses obtained for Merluccius merluccius (top), Mullus barbatus (middle) and Scomber scombrus (bottom). The graphs on the left show the modelled catch comparison rate (black line) with 95% CI (black stippled curves); the black circles represent the experimental rate; the grey horizontal line at 0.526 represents the point at which both configurations have equal catch rates; the grey vertical lines represent the MCRS of the species. The graphs on the right show the catch ratio (black line) with 95% CI (black stippled curves); the blue lines represent the length frequency distributions obtained with the two codends tested (DM50 and SM40); the grey horizontal line at 1.0 represents the point at which both configurations have equal catch rates; the grey vertical line represents the MCRS of the species.

Figure 6 shows the catch comparison results for the two flatfish species. The curves obtained for *A. laterna* clearly indicate a significantly lower catch efficiency of DM50, compared to SM40, in the 6.5 to 13.5 cm length range. In fact, the length frequency distributions show a clear decrease, in DM50, of the catch of individuals within this length range, when compared to SM40. The same trend is observed for *C. linguatula*, for which the DM50 codend display a significantly lower retention than the SM40 codend in the 9 -16 cm length range. Again, the difference between the catches of the two codends is evident not only from the catch comparison and catch ratio curves, but also from the length frequency distributions.

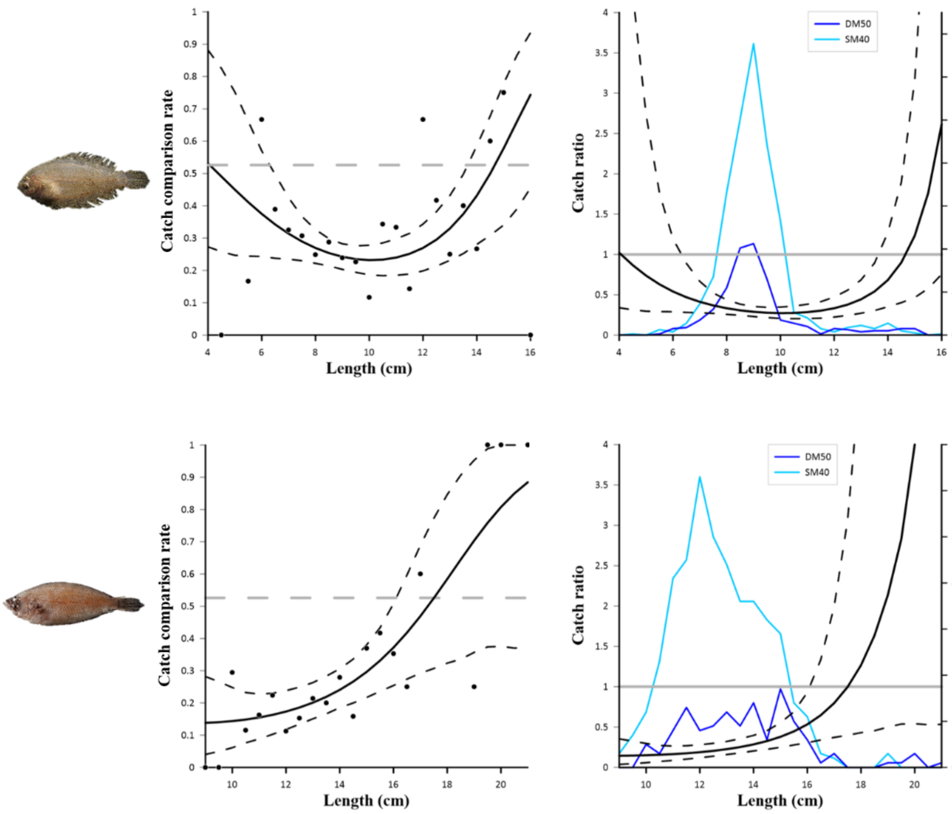

Figure 6: Results of the catch comparison analyses obtained for Arnoglossus laterna (top) and Citharus linguatula (bottom). The graphs on the left show the modelled catch comparison rate (black line) with 95% CI (black stippled curves); the black circles represent the experimental rate; the grey horizontal line at 0.526 represents the point at which both configurations have equal catch rates. The graphs on the right show the catch ratio (black line) with 95% CI (black stippled curves); the blue lines represent the length frequency distributions obtained with the two codends tested (DM50 and SM40); the grey horizontal line at 1.0 represents the point at which both configurations have equal catch rates.

Figure 7 shows the results obtained for two important commercial species, the squid *I. coindetii* and the fish *C. lucerna*. In both cases, no significant differences in the catch efficiency of the two codends were detected. The wide *CI*s of both catch comparison and catch ratio curves and the high dispersion in the experimental rates are probably due to a relatively low number of individuals caught during the sea trials.

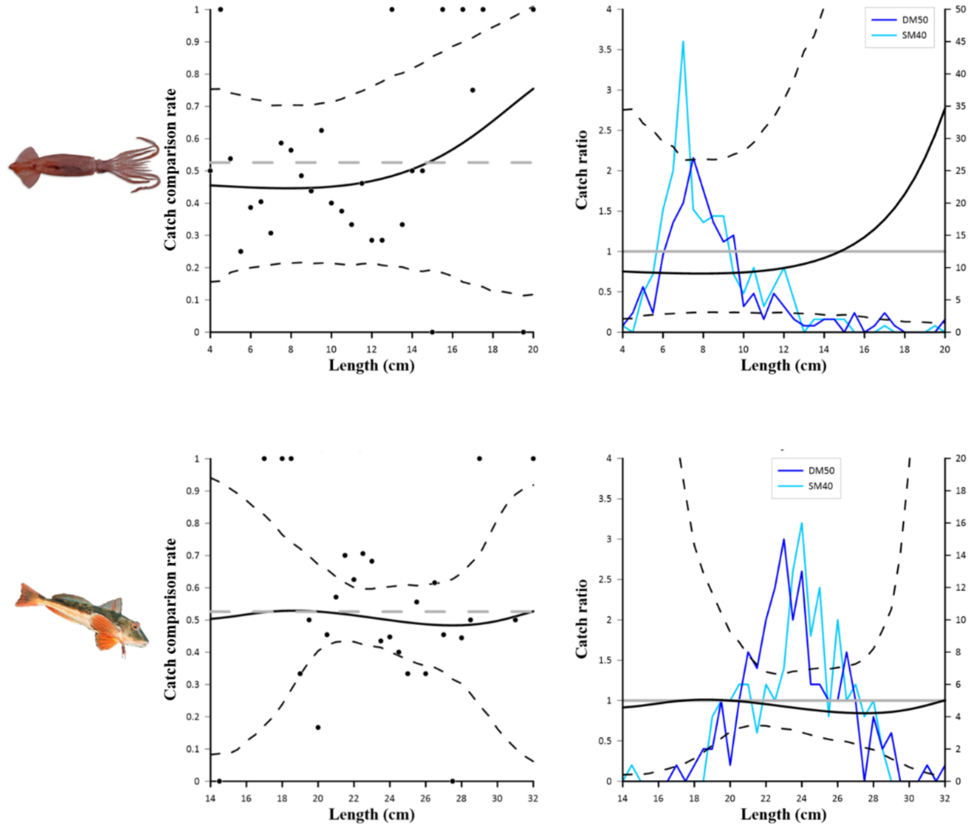

Figure 7. Results of the catch comparison analyses obtained for Illex coindetii (top) and Chelidonichthys lucerna (bottom). The graphs on the left show the modelled catch comparison rate (black line) with 95% CI (black stippled curves); the black circles represent the experimental rate; the grey horizontal line at 0.526 represents the point at which both configurations have equal catch rates. The graphs on the right show the catch ratio (black line) with 95% CI (black stippled curves); the blue lines represent the length frequency distributions obtained with the two codends tested (DM50 and SM40); the grey horizontal line at 1.0 represents the point at which both configurations have equal catch rates.

Exploitation pattern indicator analysis

Table 5 shows the results obtained from the exploitation pattern indicator analysis. Regarding the European hake, the test codend (DM50) caught on average, in number of individuals, 50% (*nP-*; *CIs* 32.4-73.0%) less undersized individuals (< 20 cm) than the baseline codend (SM40). A slight but significant difference was found also for the individuals above the 20 cm MCRS (*nP+*) since the average percentage retained by DM50 was 76% (*CIs*: 60.0-97.9%) compared to SM40. The mean discard ratio, in number of individuals, obtained with DM50 (13.1%) was less than the mean discard ratio obtained with SM40 (18.6%), although the difference was not statistically significant (the *CIs* of the two values overlapped; Table 5).

The *nP+* estimated for red mullet revealed that DM50 caught, on average, 44.4% of individuals above the 11 cm MCRS compared with SM40. However, the *CIs* of this indicator contained 100 (*CIs*: 7.8-118.3%), reflecting a lack of significant differences between the two codends. No individuals below the MCRS of the species were caught by the two codends, therefore neither the *nP-* nor the discard ratios were estimated (Table 5). Regarding the Atlantic mackerel, no significant differences between codends were found concerning the number of individuals above the 15 cm MCRS retained (*nP+*; *CIs*: 22.8-152.2%). The few number of individuals below the MCRS caught by both codends did not allow to estimate both the *nP-* and the discard ratio indicators (Table 5).

A significant difference was found, for the Mediterranean scaldfish, concerning the number of individuals below the 12 cm reference size (*nP-*), of which DM50 retained, on average, 33.7% (*CIs*: 8.1-94.0%) compared to SM40. On the contrary, we did not observe any significant difference, between codends, in both the *nP+* indicator (the *CIs* contained 100) and the discard ratios (the *CIs* of the two values overlapped; Table 5). Concerning the three species without a reference size, the percentages of all the individuals retained by DM50 compared to SM40 revealed a significant difference only for the spotted flounder. In fact, the average percentage caught by DM50 was around 26% (*CIs*: 18.7-35.2%) compared to SM40. Both the tub gurnard and the broadtail shortfin squid did not reveal any statistically significant difference in their catches between codends, since the *CIs* contained 100% indicating an equal number of individuals caught (Table 5).

Table 5: Values of the exploitation pattern indicators (in average percentages with 95% confidence intervals) for the species selected for the catch comparison analysis. They represent the number of individuals i.e. nP (total), nP- (below the reference size), nP+ (above the reference size) retained by the test codend (DM50) compared to the baseline codend (SM40), and the resulting discard ratios estimated for both the test (nDRatioT) and baseline (nDRatioB) codends.

Species	**Indicator**	**Mean % (95% CI)**
Merluccius merluccius	*nP-*	50.3 (32.4-73.0)
MCRS=20 cm	*nP+*	76.2 (60.0-97.9)
	nDRatioT	13.1 (8.9-17.9)
	nDRatioB	18.6 (14.7-23.0)
Mullus barbatus	*nP-*	*
MCRS=11 cm	*nP+*	44.4 (7.8-118.3)
Scomber scombrus	*nP-*	*
MCRS=15 cm	*nP+*	69.0 (22.8-152.2)
Arnoglossus laterna	*nP-*	33.7 (8.1-94.0)
Reference size=12 cm	*nP+*	79.1 (10.9-236.4)
	nDRatioT	91.1 (86.7-94.5)
	nDRatioB	96.0 (94.2-97.5)
Citharus linguatula	*nP*	25.8 (18.7-35.2)

Chelidonichthys lucerna	*nP*	92.0 (66.2-124.6)
Illex coindetii	*nP*	83.2 (17.4-235.3)

**Very few or no individuals below the MCRS were caught, thus nP- was not estimated.*

Discussion

Mediterranean bottom trawl fisheries exert multiple impacts on the marine environment and ecosystem. Besides the physical alteration of the seabed (Lucchetti et al., 2017a; Lucchetti and Sala, 2012; Palanques et al., 2014) and the greenhouse gas emissions (Guijarro et al., 2017), these towed gears are well-known to cause a significant disturbance on the benthic habitats and communities (De Juan et al., 2007; Farriols et al., 2017). The present study is focused on evaluating the impact of a bottom trawl fishery from a species community perspective. To this aim, we performed a catch dominance analysis, to provide information on the species composition dynamics when applying different technical modifications. This holistic approach, here investigated in the trawl selectivity field, allows to better understand and evaluate the impact of a fishery by including, in the analysis, not only those species having a commercial interest or requiring close protection or management measures, but all the species caught by the specific gear. In particular, we here compared the catches of the codends established for the Mediterranean, the SM40 codend, with those of the only alternative codend allowed after justified request, the DM50 codend (EU Regulation 1241, 2019).

The large number of species present in the catches of the two codends, which are usually not accounted for in traditional selectivity studies, demonstrate the relevance of this methodology. Most of these species contribute to the discarded fraction of the catch, which accounts for 50% (in weight) of all the catches obtained with both codends. This percentage falls within the range (20-65%) reported by Tsagarakis et al. (2014) and gives a clear insight into the high impact exerted by this fishing gear on the benthic and benthopelagic community. The fate of the species entering the trawl codend is also quantified in the recent work of Mytilineou et al. (2022), who estimated that less than 30% of the species caught were selected to be marketed. Also, in the present study, there were more species entirely discarded (37) than the ones possibly landed (31). The swimming crab *L. depurator*, which was by far the dominant animal species in the catches in both numbers and weight, is also a sign of the intense fishing effort carried out by trawlers in the Adriatic Sea, one of the most overexploited areas of Mediterranean (Colloca et al., 2017; Eigaard et al., 2017). In fact, the intense discarding practices carried out by fishers in this area let the benthic opportunistic scavengers (i.e. some fish species, crabs as *L. depurator*, echinoderms and molluscs) consume these dead animals and thus thrive (Demestre et al., 2000; Ramsay et al., 1998; Sánchez et al., 2004). Some of these species, which can have a massive presence in bottom trawl catches, are starting to be marketed by some vessels in the study area (e.g. the largest individuals of *L. depurator*; Lucchetti, personal communication). This is clear evidence of the fishing down the marine food webs (Pauly et al., 1998) as demonstrated by stock assessments in the Mediterranean, which highlight a situation of overexploitation for around 75% of the assessed commercial species (FAO, 2020).

The twaite shad, *A. fallax*, was the only protected species caught during the sea trials. In the Adriatic Sea, this species is commonly by-caught and discarded not only in demersal trawl fisheries (Sánchez et al., 2007) but also in pelagic trawl (La Mesa et al., 2015) and set net fisheries (Petetta et al., 2020b). Another protected species, commonly subject to incidental captures from the same fishing gears, is the loggerhead sea turtle, *Caretta caretta* (listed in Annex IV of the Habitat Directive; Council Directive 92, 1992). Although no individuals were caught in the present study, bottom trawlers are responsible, in the Central-Northern Adriatic, for frequent bycatch events (around 8600 individuals per year; Lucchetti et al., 2017b).

Both the legal codends currently in use in the Mediterranean (SM40 and DM50) are known to be insufficiently size selective for many commercial species targeted by bottom trawl fisheries since individuals below the MCRS and/or the length of first maturity are often retained in the catches (Lucchetti et al., 2021). Regarding the European hake, one of the most landed and overexploited demersal species in the whole region (GFCM, 2021), the two codends were unable to avoid the catch of individuals either below the length of first maturity (more than 30 cm; Candelma et al., 2021; Carbonara et al., 2019) or below the MCRS of 20 cm. This is in line with several selectivity studies conducted on SM40 and DM50, where the predicted 50% retention length (L50) was always lower than 20 cm in different areas (Adriatic Sea (Lucchetti, 2008; Sala et al., 2008; Sala and Lucchetti, 2010); Aegean Sea (Petrakis and Stergiou, 1997; Tosunoğlu et al., 2008; Aydin and Tosunoğlu, 2010; Dereli and Aydin, 2016); Alboran Sea (Baro and Muñoz de los Rejes, 2007); Balearic Islands (Guijarro and Massutí, 2006; Ordines et al., 2006); Tyrrhenian Sea (Brčić et al., 2018)). Accordingly, in the present study, a discard ratio of 9-23% of the total catch in number of hakes was estimated. Interestingly, from the catch comparison results, we observed that SM40 caught significantly more undersized European hakes than DM50, contrary to what is usually expected (i.e. a similar size selectivity of the two codends for this species; see the review of Lucchetti et al. (2021)). The exploitation pattern indicators confirm these results, stating that the DM50 was able to exclude from the catch, on average, half of the undersized hakes observed in the SM40 catches. These findings are probably due to the slightly different mesh size (38.1 mm on average) of the SM40 codend compared with the Regulation requirements.

The same hypothesis could be done for the red mullet, another key target species in several Mediterranean fisheries, since the catch efficiency for the smaller length classes (11-14.5 cm) was significantly lower in the DM50 than in the SM40. The difference in the measured mesh size (around 12 mm) between DM50 and SM40 could have exerted, in the present study, a bigger effect on selectivity than the difference in the mesh configuration and/or mesh openness (Tokaç et al., 2016). Nevertheless, the number of commercial individuals caught by the two codends was not significantly different, based on the exploitation pattern indicators analysis. However, the *CIs* for *nP+* were really wide (7.8-118.3%), reducing the power of these results. No red mullets below the 11 cm MCRS were caught in the sea trials. Although we cannot rule out that both codends avoided the catch of undersized individuals, since the experiment lacked the presence of a codend-cover to study the entire population entering the trawl net, Sala et al. (2015) already demonstrated that the current legal codends provide a predicted L50 higher than the MCRS of the species. Accordingly, very few specimens of Atlantic mackerel under the 15 cm MCRS were caught by the two codends. Although there is no information on the size selectivity of SM40 and DM50 for this commercial species, Petetta et al. (2020a) estimated an L50 of more than 21 cm by using a 55 mm diamond mesh codend.

The significantly lower catch efficiency of DM50 compared to SM40, observed in both the catch comparisons and the exploitation pattern indicators, for the two flatfish species (Mediterranean scaldfish and spotted flounder) is in accordance with what found in the literature (Demirci and Akyurt, 2017; Mytilineou et al., 2021; Sala et al., 2008). In fact, the flat morphology of these species fits better to the diamond-shaped meshes than to the square-shaped meshes (Tokaç et al., 2014). That is the reason why, in trawl fisheries specifically targeting flatfish, such as the 'Rapido' trawls in the Adriatic Sea (Pranovi et al., 2000), the advice is to only mount diamond mesh codends to increase the size selectivity (Lucchetti et al., 2021). The shift from one codend to another seemed not to influence the catch performance for tub gurnard and broadtail shortfin squid, but the wide CIs observed in both the catch comparison and exploitation pattern indicator analyses reflect a low number of individuals caught and do not allow to draw definitive conclusions.

The experimental design applied for the data collection in the present study was unpaired, with a first group of hauls carried out with one codend design and afterwards with the other design. Therefore, we cannot be 100% certain that the average populations entering the two codends were identical. However, since the hauls were carried out on the same cruise, within a relatively small geographical area and also within a limited time span, we assume that there only would be minor differences in the population size structures and species composition between the hauls conducted with SM40 and those with DM50. Therefore, we assume that the collected data can be used for a comparison between the performance of the two codends.

The avoidance of unwanted catches through improved selectivity is one of the primary goals for the implementation of the CFP in Mediterranean bottom trawl fisheries. In the last decades, several European projects (e.g. DISCATCH, DiscardLess, MINOUW, GALION, IMPLEMED) have focused on identifying measures, including technical ones related to fishing gear characteristics, to reduce discards and increase the fishers' awareness (EC, 2021). Furthermore, there is an increased interest of the scientific community towards the so-called LIFE (Low Impact and Fuel Efficient) fishing gears (Suuronen et al., 2012), which are more sustainable and could be employed as alternative gears. The methodology here described allows to evaluate more in-depth the overall impact of a fishing gear and to compare the catches obtained with two or more different gears from a species community perspective. Thus, it can definitely contribute to evaluate the economic and environmental viability of a specific fishing activity.

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Ethic statements

The fishing trials carried out on board the research vessel have been authorised by the Italian coastguard. The only protected species caught during sea trials is *Alosa fallax*, included in the list of Annexes II and V of animals requiring close protection under the Habitats Directive. No other authorization or ethics board approval was required. No information on animal welfare or on steps taken to mitigate fish suffering and methods of sacrifice is provided since the animals were not exposed to any additional stress other than that involved in commercial fishing practices. This article does not contain any studies with human participants performed by any of the authors.

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Author contribution

AP, BH and AL conceived and performed research; AP, DLV, MV and RDM collected data; AP and BH analysed the data; AP wrote the paper with support of BH, DLV, MV and AL. AL was the scientific responsible of the research. All authors contributed to the article and approved the submitted version.

Supporting information

S1 Table: Dominance percentages of each species caught with the 50 mm diamond mesh codend (DM50) and the 40 mm square mesh codend (SM40), in both number of individuals and weight, for each fraction (total, discarded and landed). The green, yellow, orange and red areas represent the target species, the bycatch species of commercial value, the species of no commercial value and the protected species, respectively.

Species Rank	DM50						SM40					
	Individuals			Weight			Individuals			Weight		
	Total	Discarded	Landed	Total	Discarded	Landed	Total	Discarded	Landed	Total	Discarded	Landed
S1	2.6 (2.1 - 3.2)	0.4 (0.2 - 0.6)	23.1 (20.8 - 25.5)	16.3 (14.0 - 18.9)	1.0 (0.6 - 1.5)	35.1 (30.7 - 39.5)	3.6 (3.0 - 4.2)	0.8 (0.6 - 1.0)	19.7 (17.4 - 21.9)	21.3 (17.5 - 24.8)	2.0 (1.5 - 2.5)	43.0 (36.7 - 48.4)
S2	0.7 (0.5- 0.9)	0.0 (0.0 - 0.0)	7.2 (5.6 - 9.0)	1.4 (1.0 - 1.9)	0.0 (0.0 - 0.0)	3.1 (2.2 - 4.2)	1.7 (1.3 - 2.1)	0.0 (0.0 - 0.0)	11.7 (9.5 - 14.0)	2.9 (2.3 - 3.6)	0.0 (0.0 - 0.0)	6.2 (5.1 - 7.5)
S3	0.22 (0.1 - 0.3)	0.0 (0.0 - 0.0)	2.4 (1.5 - 3.3)	7.5 (4.5 - 10.7)	0.0 (0.0 - 0.0)	16.6 (10.5 - 23.2)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.6 (0.3 - 1.1)	2.6 (0.9 - 4.8)	0.0 (0.0 - 0.0)	5.6 (2.0 - 10.2)
S4	0.7 (0.5 - 0.9)	0.0 (0.0 - 0.0)	6.8 (5.0 - 8.6)	3.9 (2.9 - 5.1)	0.0 (0.0 - 0.0)	8.6 (6.6 - 10.8)	0.7 (0.6 - 0.9)	0.0 (0.0 - 0.0)	4.8 (4.0 - 5.7)	4.2 (3.3 - 5.1)	0.0 (0.0 - 0.0)	8.9 (7.2 - 10.6)
S5	0.7 (0.5 - 1.0)	0.0 (0.0 - 0.0)	7.4 (5.8 - 9.3)	1.1 (0.8 - 1.5)	0.0 (0.0 - 0.0)	2.6 (1.9 - 3.4)	1.7 (1.4 - 2.2)	0.0 (0.0 - 0.0)	11.8 (10.1 - 13.9)	2.6 (2.0 - 3.1)	0.0 (0.0 - 0.0)	5.4 (4.5 - 6.3)
S6	0.5 (0.2 - 0.8)	0.0 (0.0 - 0.0)	4.5 (2.3 - 7.1)	2.2 (0.9 - 3.8)	0.0 (0.0 - 0.1)	4.9 (2.1 - 8.0)	0.6 (0.3 - 1.1)	0.0 (0.0 - 0.0)	4.3 (1.8 - 7.7)	2.9 (1.3 - 5.2)	0.0 (0.0 - 0.0)	6.1 (2.7 - 10.8)
S7	0.1 (0.0 - 0.1)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.3)	0.3 (0.0 - 0.6)	0.0 (0.0 - 0.0)	0.2 (0.1 - 0.3)	0.2 (0.1 - 0.4)	0.0 (0.0 - 0.0)	0.2 (0.1 - 0.3)	0.4 (0.2 - 0.7)	0.0 (0.0 - 0.0)
S8	1.2 (0.7 - 1.9)	0.0 (0.0 - 0.0)	12.7 (9.2 - 17.3)	0.6 (0.3 - 0.8)	0.0 (0.0 - 0.0)	1.3 (0.8 - 1.8)	2.0 (1.3 - 2.9)	0.0 (0.0 - 0.0)	13.5 (9.7 - 18.8)	0.9 (0.6 - 1.2)	0.0 (0.0 - 0.0)	1.8 (1.3 - 2.5)
S9	0.3 (0.1 - 0.4)	0.0 (0.0 - 0.0)	2.7 (1.5 - 4.1)	1.5 (0.8 - 2.2)	0.0 (0.0 - 0.0)	3.2 (1.8 - 5.0)	0.2 (0.1 - 0.4)	0.0 (0.0 - 0.0)	1.7 (0.9 - 2.6)	1.3 (0.8 - 1.8)	0.0 (0.0 - 0.0)	2.7 (1.6 - 4.0)
S10	0.8 (0.5 - 1.2)	0.0 (0.0 - 0.0)	8.6 (4.7 - 13.9)	3.7 (1.8 - 5.8)	0.0 (0.0 - 0.0)	8.1 (3.9 - 13.0)	0.3 (0.2 - 0.4)	0.0 (0.0 - 0.0)	2.0 (1.1 - 3.0)	1.6 (0.9 - 2.4)	0.0 (0.0 - 0.0)	3.4 (1.9 - 5.1)
S11	0.1 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.8 (0.3 - 1.5)	1.8 (0.6 - 3.3)	0.0 (0.0 - 0.0)	3.9 (1.3 - 7.5)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.3)	0.3 (0.0 - 0.9)	0.0 (0.0 - 0.0)	0.7 (0.0 - 1.9)
S12	0.9 (0.6 - 1.4)	0.0 (0.0 - 0.0)	9.7 (7.2 - 12.2)	1.1 (0.8 - 1.6)	0.0 (0.0 - 0.0)	2.5 (1.75 - 3.4)	1.2 (0.9 - 1.6)	0.0 (0.0 - 0.0)	8.4 (6.7 - 10.3)	1.4 (1.0 - 1.7)	0.0 (0.0 - 0.0)	2.9 (2.2 - 3.6)
S13	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.2)	0.1 (0.0 - 0.7)	0.0 (0.0 - 0.0)	0.3 (0.0 - 1.5)
S14	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.2 (0.0 - 0.6)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.4)
S15	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.8 (0.3 - 1.5)	2.2 (0.8 - 4.0)	0.0 (0.0 - 0.0)	4.9 (1.7 - 8.5)	0.1 (0.1 - 0.2)	0.0 (0.0 - 0.0)	0.7 (0.3- 1.1)	2.4 (1.2 - 3.9)	0.0 (0.0 - 0.1)	5.2 (2.5 - 8.2)
S16	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.3)	0.2 (0.0 - 0.5)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)
S17	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)
S18	0.6 (0.4 - 0.8)	0.0 (0.0 - 0.0)	6.3 (4.6 - 8.2)	0.6 (0.5 - 0.8)	0.0 (0.0 - 0.0)	1.4 (1.0 - 1.8)	2.4 (1.9 - 2.9)	0.0 (0.0 - 0.0)	16.1 (13.2 - 19.1)	1.9 (1.5 - 2.2)	0.0 (0.0 - 0.0)	4.0 (3.2 - 4.8)
S19	1.8 (1.3 - 2.5)	1.8 (1.3 - 2.6)	1.7 (0.9 - 2.5)	0.6 (0.4 - 0.8)	0.8 (0.6 - 1.1)	0.3 (0.2 - 0.5)	5.6 (5.0 - 6.4)	6.3 (5.6 - 7.3)	1.3 (0.8 - 1.9)	1.6 (1.4 - 1.9)	2.8 (2.4 - 3.2)	0.4 (0.2 - 0.5)
S20	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.2 (0.0 - 0.6)	0.1 (0.0 - 0.3)	0.0 (0.0 - 0.0)	0.3 (0.0 - 0.7)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.3 (0.1 - 0.6)	0.3 (0.0 - 0.6)	0.0 (0.0 - 0.0)	0.5 (0.1 - 1.2)
S21	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.2)	0.3 (0.0 - 1.3)	0.0 (0.0 - 0.0)	0.6 (0.1 - 2.7)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.2)	0.2 (0.0 - 0.6)	0.0 (0.0 - 0.0)	0.4 (0.0 - 1.2)
S22	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.5)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.2 (0.0 - 0.5)	0.0 (0.0- 0.1)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.4)	0.2 (0.0 - 0.6)	0.0 (0.0 - 0.0)	0.4 (0.0 - 1.2)
S23	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.7 (0.1 - 1.6)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.3 (0.1 - 0.5)	0.1 (0.0- 0.1)	0.0 (0.0 - 0.0)	0.4 (0.1 - 0.7)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.2 (0.0 - 0.4)
S24	0.4 (0.2 - 0.6)	0.0 (0.0 - 0.1)	3.7 (1.8 - 6.1)	0.7 (0.4 - 1.1)	0.0 (0.0 - 0.1)	1.5 (0.8 - 2.4)	0.2 (0.1 - 0.3)	0.0 (0.0 - 0.0)	1.3 (0.7 - 2.3)	0.4 (0.2 - 0.6)	0.0 (0.0 - 0.0)	0.8 (0.4 - 1.4)
S25	0.1 (0.0 - 0.2)	0.1 (0.0 - 0.3)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.3 (0.1 - 0.4)	0.3 (0.1 - 0.5)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.1)	0.1 (0.1 - 0.2)	0.0 (0.0 - 0.0)

S26	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)
S27	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.3)	0.1 (0.0 - 0.3)	0.0 (0.0 - 0.0)	0.2 (0.0 - 0.7)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.2 (0.0 - 0.4)	0.2 (0.0 - 0.4)	0.0 (0.0 - 0.1)	0.3 (0.0 - 0.9)
S28	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.2 (0.0 - 0.5)	0.1 (0.0 - 0.3)	0.0 (0.0 - 0.0)	0.2 (0.0 - 0.6)	0.1 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.4 (0.1 - 0.8)	0.2 (0.1 - 0.5)	0.0 (0.0 - 0.1)	0.5 (0.1 - 1.0)
S29	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.2)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.1 (0.0 - 0.3)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.2 (0.0 - 0.4)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.2 (0.0 - 0.5)
S30	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.2)	0.0 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.5)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)
S31	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.2)	0.0 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.4)
S32	80.1 (75.7 - 83.5)	88.7 (85.1 - 91.4)	0.0 (0.0 - 0.0)	42.7 (38.3 - 47.0)	77.7 (73.7 - 81.9)	0.0 (0.0 - 0.0)	73.8 (70.9 - 76.5)	86.5 (84.1 - 88.6)	0.0 (0.0 - 0.0)	42.9 (38.1 - 47.6)	81.2 (74.9 - 85.8)	0.0 (0.0 - 0.0)
S33	0.5 (0.3 - 0.7)	0.5 (0.3 - 0.7)	0.0 (0.0 - 0.0)	0.4 (0.3 - 0.6)	0.8 (0.5 - 1.2)	0.0 (0.0 - 0.0)	0.3 (0.2 - 0.5)	0.3 (0.2 - 0.5)	0.0 (0.0 - 0.0)	0.2 (0.2 - 0.4)	0.5 (0.3 - 0.7)	0.0 (0.0 - 0.0)
S34	0.1 (0.0 - 0.2)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.2)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)
S35	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)
S36	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.4)	0.2 (0.0 - 0.7)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)
S37	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)
S38	2.7 (1.7 - 3.7)	3.0 (1.9 - 4.1)	0.0 (0.0 - 0.0)	1.8 (1.1- 2.4)	3.3 (2.1 - 4.4)	0.0 (0.0 - 0.0)	1.3 (0.6 - 2.1)	1.5 (0.7 - 2.5)	0.0 (0.0 - 0.0)	0.9 (0.4 - 1.5)	1.7 (0.8 - 3.0)	0.0 (0.0 - 0.0)
S39	1.3 (0.1 - 3.0)	1.5 (0.1 - 3.4)	0.0 (0.0 - 0.0)	0.5 (0.1 - 1.0)	0.9 (0.1 - 1.9)	0.0 (0.0 - 0.0)	0.8 (0.3- 1.6)	1.0 (0.3 - 1.9)	0.0 (0.0 - 0.0)	0.3 (0.1 - 0.6)	0.6 (0.1 - 1.1)	0.0 (0.0 - 0.0)
S40	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.1 (0.0- 0.2)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)
S41	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.1 (0.0 - 0.1)	0.0 (0.0 - 0.0)
S42	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.1 (0.0- 0.2)	0.1 (0.0 - 0.3)	0.0 (0.0 - 0.0)
S43	0.1 (0.0 - 0.2)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.2 (0.1 - 0.4)	0.4 (0.1 - 0.7)	0.0 (0.0 - 0.0)	0.2 (0.1 - 0.3)	0.2 (0.1 - 0.3)	0.0 (0.0 - 0.0)	0.3 (0.1 - 0.5)	0.6 (0.3 - 0.9)	0.0 (0.0 - 0.0)
S44	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.2)	0.1 (0.0 - 0.4)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.7 (0.0- 3.5)	1.4 (0.0 - 6.5)	0.0 (0.0 - 0.0)
S45	0.46 (0.3 - 0.7)	0.5 (0.3 - 0.8)	0.0 (0.0 - 0.0)	0.6 (0.3 - 0.8)	1.0 (0.6 - 1.5)	0.0 (0.0 - 0.0)	0.3 (0.2 - 0.4)	0.3 (0.2 - 0.5)	0.0 (0.0 - 0.0)	0.4 (0.2 - 0.5)	0.7 (0.4 - 0.9)	0.0 (0.0 - 0.0)
S46	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.2)	0.1 (0.1 - 0.2)	0.0 (0.0 - 0.0)	0.1 (0.1 - 0.2)	0.2 (0.1 - 0.4)	0.0 (0.0 - 0.0)
S47	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)
S48	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)
S49	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)
S50	0.0 (0.0 - 0.1)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.2)	0.1 (0.0 - 0.5)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)
S51	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.2)	0.1 (0.0 - 0.3)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)
S52	0.1 (0.0 - 0.3)	0.1 (0.0 - 0.4)	0.0 (0.0 - 0.0)	0.2 (0.0 - 0.7)	0.4 (0.0 - 1.4)	0.0 (0.0 - 0.0)	0.0 (0.0- 0.1)	0.1 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)
S53	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)
S54	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)
S55	0.1 (0.1 - 0.3)	0.1 (0.1 - 0.3)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.2)	0.2 (0.1 - 0.3)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.1)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)
S56	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.1)	0.1 (0.0 - 0.3)	0.0 (0.0 - 0.0)	0.3 (0.0 - 0.6)	0.3 (0.0 - 0.7)	0.0 (0.0 - 0.0)	0.4 (0.0- 0.9)	0.8 (0.1 - 1.9)	0.0 (0.0 - 0.0)
S57	0.1 (0.1 - 0.3)	0.2 (0.1 - 0.3)	0.0 (0.0 - 0.0)	0.1 (0.1 - 0.2)	0.2 (0.1 - 0.3)	0.0 (0.0 - 0.0)	0.5 (0.3 - 0.7)	0.6 (0.4 - 0.8)	0.0 (0.0 - 0.0)	0.4 (0.2 - 0.5)	0.7 (0.4 - 1.1)	0.0 (0.0 - 0.0)
S58	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.2)	0.0 (0.0 - 0.0)

S59	0.4 (0.2 - 0.6)	0.4 (0.2 - 0.7)	0.0 (0.0 - 0.0)	1.5 (0.7 - 2.3)	2.7 (1.3 - 4.1)	0.0 (0.0 - 0.0)	0.1 (0.1 - 0.2)	0.1 (0.1 - 0.2)	0.0 (0.0 - 0.0)	0.4 (0.2 - 0.6)	0.7 (0.3 - 1.2)	0.0 (0.0 - 0.0)
S60	1.2 (0.7 - 1.8)	1.3 (0.7 - 1.9)	0.0 (0.0 - 0.0)	1.7 (0.9 - 2.5)	3.0 (1.6 - 4.5)	0.0 (0.0 - 0.0)	0.2 (0.1 - 0.4)	0.3 (0.1 - 0.4)	0.0 (0.0 - 0.0)	0.3 (0.1 - 0.5)	0.5 (0.2 - 1.0)	0.0 (0.0 - 0.0)
S61	0.3 (0.2 - 0.4)	0.3 (0.2 - 0.4)	0.0 (0.0 - 0.0)	2.4 (1.3 - 3.4)	4.3 (2.5 - 6.1)	0.0 (0.0 - 0.0)	0.1 (0.1 - 0.2)	0.1 (0.1 - 0.2)	0.0 (0.0 - 0.0)	1.1 (0.5 - 1.8)	2.1 (1.0 - 3.4)	0.0 (0.0 - 0.0)
S62	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.3)	0.1 (0.0 - 0.6)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)
S63	0.2 (0.1 - 0.3)	0.2 (0.1 - 0.3)	0.0 (0.0 - 0.0)	0.4 (0.2 - 0.8)	0.8 (0.3 - 1.4)	0.0 (0.0 - 0.0)	0.1 (0.0 - 0.1)	0.1 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.2 (0.1 - 0.4)	0.4 (0.1 - 0.8)	0.0 (0.0 - 0.0)
S64	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)
S65	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (-0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.2 (0.0 - 0.6)	0.4 (0.0 - 1.2)	0.0 (0.0 - 0.0)
S66	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.3 (0.0 - 0.9)	0.3 (0.0 - 1.1)	0.0 (0.0 - 0.0)	0.5 (0.0 - 1.7)	1.0 (0.0 - 3.2)	0.0 (0.0 - 0.0)
S67	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.5 (0.1 - 1.0)	0.9 (0.1 - 1.8)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.2 (0.0 - 0.5)	0.3 (0.0 - 1.0)	0.0 (0.0 - 0.0)
S68	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.2)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.1)	0.0 (0.0 - 0.0)	0.2 (0.0 - 0.6)	0.4 (0.0 - 1.2)	0.0 (0.0 - 0.0)

Supporting Information File. Data collected through the sea trials used for the analyses. The file is in 'xslx' format, and can be downloaded at: https://doi.org/10.1371/journal.pone.0283362.s002. Data is divided into: haul data; catch data; frequency distribution data.

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Paper II

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

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

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Abstract

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

Keywords

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

Introduction

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

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

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

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

Materials and Methods

Sea trials and data collection

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

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

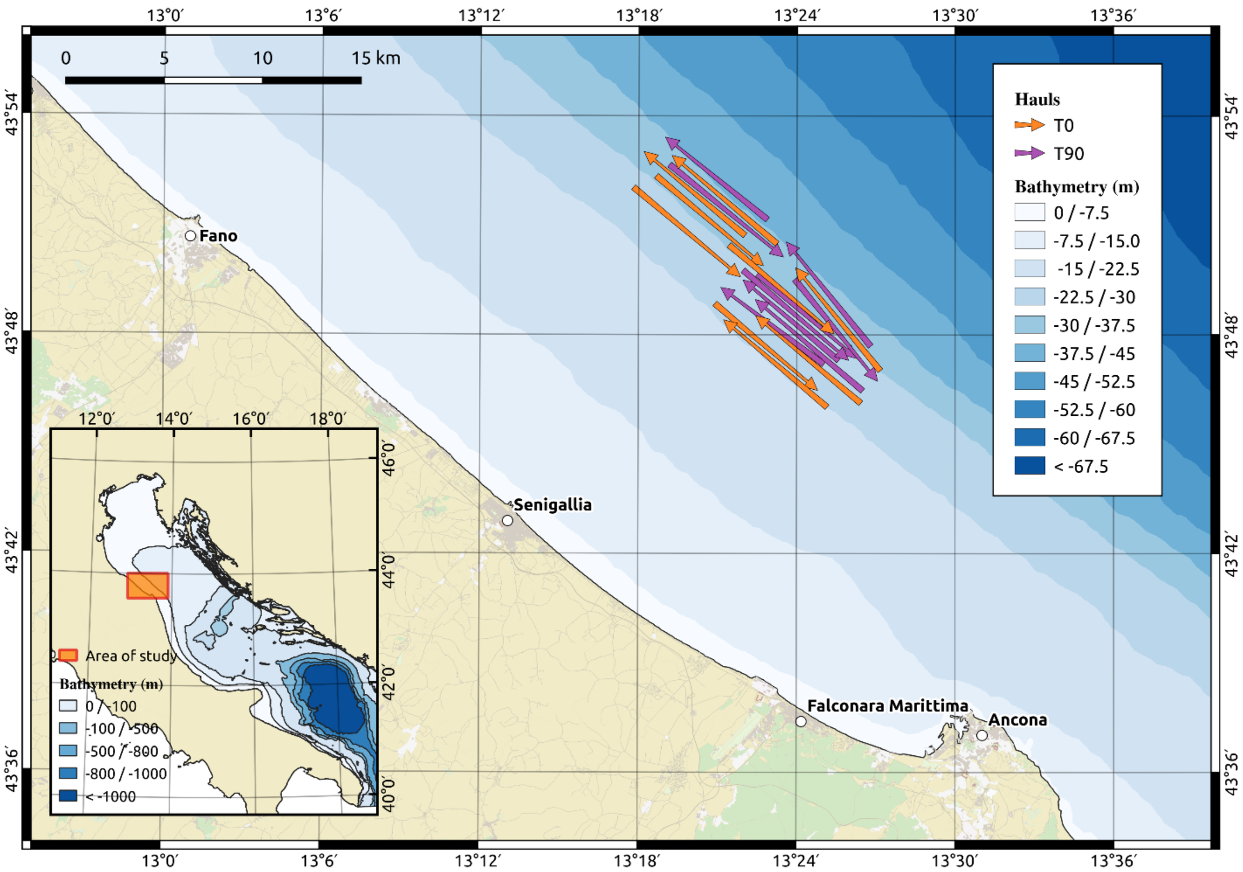

Figure 1: Map of the area where the sea trials were conducted in the Adriatic Sea in October and November 2019. All 18 hauls are represented (orange arrows, T0 codend; purple arrows, T90 codend).

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

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

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

Data analysis

Catch data

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

Size selectivity

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

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

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

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

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

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

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

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

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

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

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

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

Results

Catch data

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

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

ID haul	Codend type	Latitude		Longitude		Mean depth [m]	Mean HNO [m]	Mean VNO [m]	Mean speed [knots]	Codend catch [kg]	Cover catch [kg]
		Start	End	Start	End						
1	T90	43°47.19'	43°49.30'	13°25.02'	13°21.11'	27.3 ± 0.1	17.27 ± 0.29	1.84 ± 0.03	3.52 ± 0.04	16.10	54.80
2	T90	43°49.66'	43°47.35'	13°22.51'	13°26.29'	31.5 ± 0.4			3.59 ± 0.04	13.94	46.14

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

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

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

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

Size selectivity

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

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

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

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

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

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

The size selection parameters and fit statistics were calculated using the model selected for each species and codend type (Table 6).

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

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

The resulting selectivity curves and their *CIs* are represented in Figures 2 and 3. Inspection of the p-values revealed that the experimental data were adequately described by the selected models with the only exception of *S. scombrus* – T0 configuration (p-value = 0.02); nevertheless, the inspection of the modelled curve against the experimental rates did not indicate any length-dependent pattern in the deviation observed (Figure 2A). Therefore, the low p-value was assumed to be due to overdispersion in the experimental rates than to a poor ability to model the size selection.

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

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

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

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

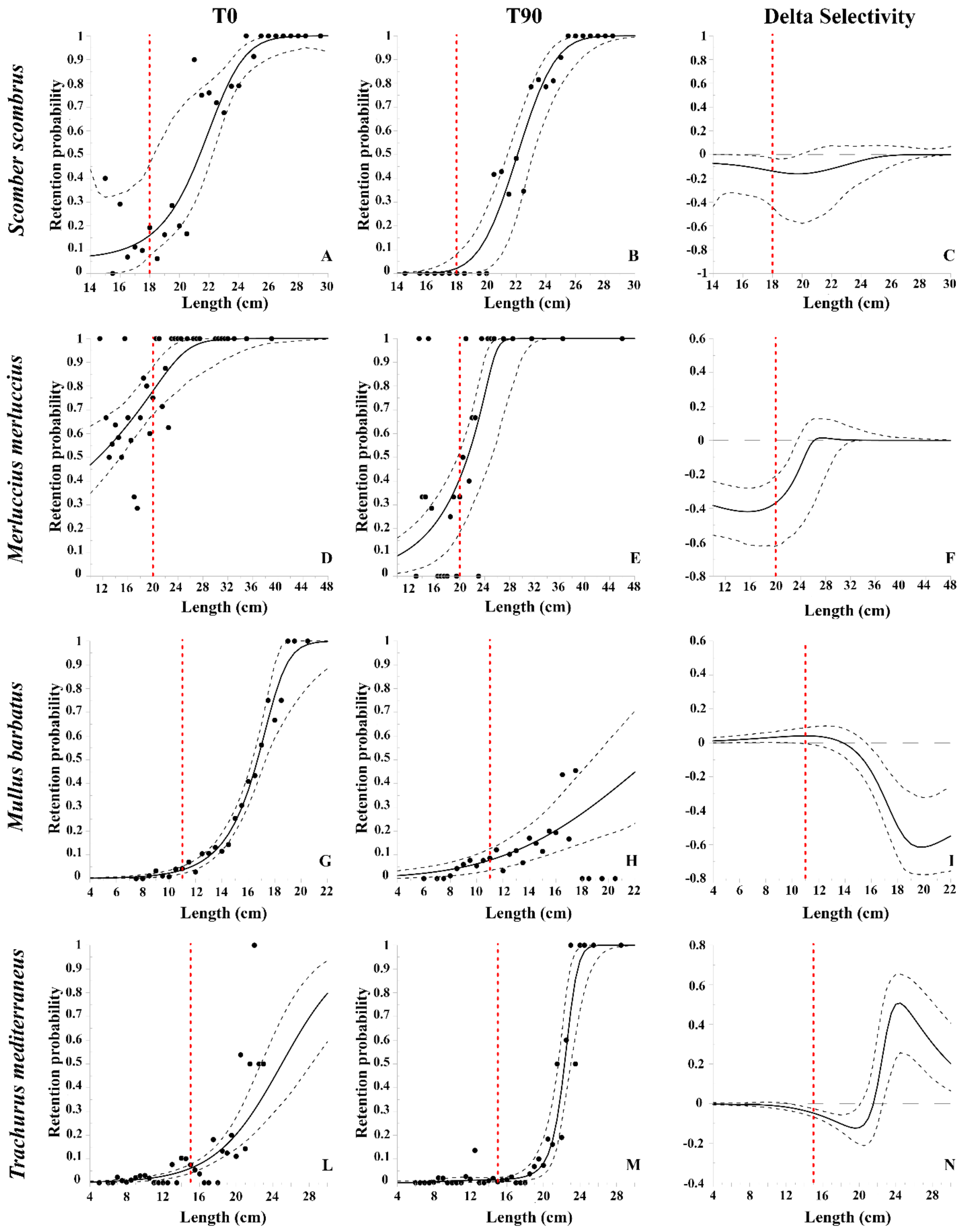

Figure 2: Selectivity diagrams for Scomber scombrus (A, B, C), Merluccius merluccius (D, E, F), Mullus barbatus (G, H, I) and Trachurus mediterraneus (L, M, N). The first two columns show the size selectivity curves (full lines) with the confidence intervals (dashed lines) together with the experimental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

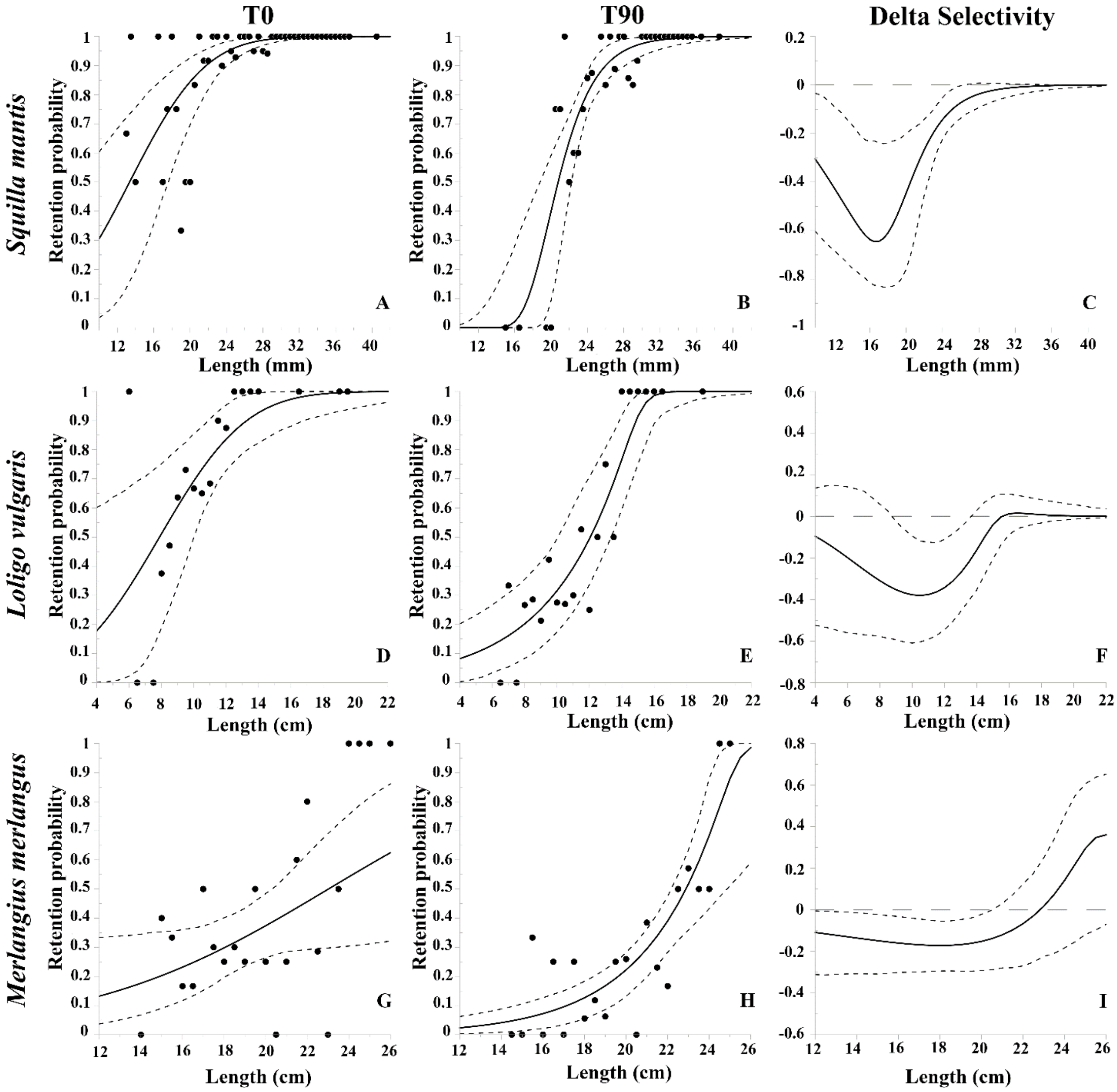

Figure 3: Selectivity diagrams for Squilla mantis (A, B, C), Loligo vulgaris (D, E, F) and Merlangius merlangus (G, H, I). The first two columns show the size selectivity curves (full lines) with confidence intervals (dashed lines) and the experimental retention data (black dots) obtained with the T0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

Discussion

The T90 mesh configuration has attracted the interest of researchers who, after the introduction of the Landing Obligation (EU, 2013), are working to identify technical solutions to reduce discards. In fact, the T90 mesh provides selectivity advantages that can be obtained in a simple way (Herrmann, 2009). Its improved size selection compared with the DM, documented in northern European fisheries (Wienbeck et al., 2011), and its ease of application and repair compared with the SM (Moderhak,

1995) have the potential to help its diffusion in the Mediterranean fishing industry. Its larger cross-section and more limited flow and turbulence may also reduce the risk of damaging the more delicate fish species (e.g. haddock), thus improving their quality (Hansen, 2004; Digre et al., 2010). This is the first study comparing the selectivity of an experimental 54 mm DM codend (T0) and a 54 mm 90° turned mesh codend (T90) for seven commercially important species in the Adriatic bottom trawl fishery.

There are no size selectivity studies for Atlantic mackerel in the Mediterranean bottom trawl fishery. We found predicted L50 values above the MCRS (18 cm) (EU, 2006) with both configurations. The significantly better selection properties of the T90 codend, at least for some length classes, may be explained by the round body shape of Atlantic mackerel, which is more likely to go through the T90 than the DM (Tokaç et al., 2014). Selectivity data for European hake are important for stock management. For the first time, we report an average L50 value above the MCRS of 20 cm (STECF, 2015), obtained with the T90 configuration, whereas the higher values reported in the literature have been obtained with a 60 mm DM (19.50 cm, Aldebert & Carries, 1991; 16.64 cm, Soldo, 2004; 18.10 cm, Belcari et al., 2007). The size selection properties of the T90 mesh described herein are much greater than those found by Genç et al. (2018), who tested a 40 mm and 44 mm mesh (average L50 values, 12 - 13 cm). To our knowledge, no other published data on the selectivity of the T90 mesh is available for this species. We found that the selectivity for European hake strongly depended on mesh configuration. The poor size selectivity of the T0 mesh, found in this study, contrasts with the data reported by Sala & Lucchetti (2011) with a 56 mm DM. The authors found that reducing the number of meshes in the codend circumference from 280 to 240 involved an increase in L50 from 11.99 ± 1.50 to 16.25 ± 0.63 cm. In theory, the even lower number of meshes (222) used in our T0 codend should have involved a higher L50 for European hake (Sala & Lucchetti, 2011). The most likely explanation is that, at the high catch rates encountered, the closing of the mesh holes occurred; as a result, our SR was much wider than those found by Sala & Lucchetti (2011) thus clearly indicating a nonselective net. In contrast, the T90 meshes may have closed less tightly under the weight of the catch, resulting in an average L50 greater than 20 cm, thus efficiently excluding hake juveniles.

The 54 mm nominal mesh size was excessively selective for red mullet and Mediterranean horse mackerel regardless of the mesh configuration, being inefficient at retaining specimens of commercial size. In fact, the size selection process with both codends often occurred at lengths greater than the MCRS of the two species. These data agree with those reported for red mullet by Sala et al. (2015), who found that even the current legal codend mesh sizes (40 mm SM and 50 mm DM) led to a predicted L50 value that was higher than the MCRS (11 cm). The same is true of Mediterranean horse mackerel, where an average L50 of 15.60 cm (MCRS, 15 cm) and an SR of 5.50 cm have been described by Tosunoğlu et al. (2008) a 50 mm DM. Moreover, Dereli & Aydin (2016) have found that L50 increased from a 50 mm DM (12.9 cm for *M. barbatus,* 14.2 cm for *T. trachurus*) to a 40 mm T90 mesh (13.6 cm for *M. barbatus,* 17.1 cm for *T. trachurus*), demonstrating how a 40 mm turned mesh already avoids catching undersized individuals. Mantis shrimp, common squid and whiting are major species targeted by the Adriatic bottom trawl fishery and have no MCRS (EU, 2006). Mantis shrimp is especially abundant in the north-western Adriatic (Sánchez et al., 2007). In our study, the T90 codend proved to be more effective than the T0 codend in avoiding smaller specimens (< 26 mm CL), which are usually discarded due to their scarce commercial value (Scarcella et al., 2007). This is in line with the findings of a Mediterranean study (Deval et al., 2016), where the comparison of a T0 and a T90 codend demonstrated a higher percentage of juvenile escapees of four crustacean species from the T90 gear. With regard to common squid, previous studies have shown how selectivity increased from a DM to a SM codend, since its body shape can be approximated to that of a round fish (Ordines et al., 2006; Tosunoğlu et al., 2009); similarly, in our study the L50 of squid was significantly higher in the T90 codend. Moreover, the average L50 value reported herein for the T90 codend is greater than the length at first maturity (LFM) of males (11 cm), but still well below the LFM of females (18.5 cm) according to Roper et al. (1984). However, since common squid caught with the current legal codend mesh size, though being mostly immature (Tosunoğlu et al., 2009), are of high commercial value, the greater size selection provided by our T90 codend would result in significant economic losses. Commercially valuable whiting were also lost with both codends, since their average L50 values predicted in the present study are more than double those reported by Sala, et al. (2007) with a 44 mm DM codend.

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

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Paper III

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Effect of Extension Piece Design on Catch Patterns in a Mediterranean Bottom Trawl Fishery

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Abstract

The catch composition of bottom trawls is commonly refined and improved through changes in codend design. Measures like reducing number of meshes in codend circumference or turning diamond netting by 90 degrees are well-known to improve the size selectivity of fish species with rounded cross-sectional shape. Based on this we speculated whether the same measures, if applied in other parts of a bottom trawl, would provide similar benefits as in the codend. Therefore, experiments were carried out by deploying these changes to the trawl extension piece in a Mediterranean bottom trawl fishery. However, for European hake and monkfish, results showed no indication of improved selectivity or catch pattern compared to the standard extension piece in the trawl. Contrary, for red mullet, one of the most important species in this fishery, reducing number of meshes in the circumference of the extension piece jeopardized the size selection obtained in the trawl with a standard extension piece. The lesson learnt from this study was that the design changes that work for

the codend do not necessarily work for other parts of the trawl, in fact they can even have negative effects.

Keywords

size selectivity, bottom trawling, T90 turned meshes, trawl extension piece, Mediterranean demersal fisheries

Introduction

The Mediterranean bottom trawl fisheries are multi-species. The variability in factors such as body size, morphology, behaviour, and minimum conservation reference size (MCRS) between the different species makes it challenging to identify one technical solution, for the trawl net, that avoids the retention of juveniles and simultaneously ensures that the retained catch is enough for the viability of the fishery. In recent decades, most of the scientific studies in the Mediterranean regarding trawl selectivity focused on experiments in the codend (see review by Lucchetti et al., 2021). The current regulatory framework requires 40 mm square meshes or, alternatively, 50 mm diamond meshes for the codend of trawl nets (EU, 2019). However, these codends still retain undersized and immature individuals of several species (Lucchetti et al., 2021) and contribute to producing high discard rates, approximately 20%-65% of the total catch, according to Tsagarakis et al. (2014). Besides increasing the mesh size, the codend size selectivity can be improved by applying design changes that increase the mesh openness. This is well established for diamond mesh codends (Herrmann et al., 2009) and also confirmed for square mesh codends (Sala et al., 2016). For example, a reduction in the number of meshes in circumference increases the mesh openness in both diamond (Sala and Lucchetti, 2010; Tokaçet al., 2016) and square mesh codends (Sala et al., 2016). Another option resides in the change to a different mesh configuration, such as rotating the mesh orientation by 90° in relation to the towing direction, so called T90 (Wienbeck et al., 2011). The rotation of the traditional diamond mesh netting by 90° allows meshes to remain more open under the drag forces action due to the catch accumulation, enabling smaller specimens to escape (Herrmann et al., 2007; Madsen et al., 2012; Cheng et al., 2022). A T90 codend, like the square mesh codend, generally provides a significantly higher size selectivity than the diamond mesh codend, especially for those species with a rounded cross-section morphology (Tokaç et al., 2014; Deval et al., 2016; Petetta et al., 2020). The combined effect of both a reduction in the number of meshes in circumference and a shift to the T90 mesh configuration gave better selection results than those determined where the two factors were applied separately (Herrmann et al., 2007; Wienbeck et al., 2011).

Given the benefits obtained in trawl selectivity by reducing codend number of meshes in circumference and turning meshes by 90 degrees, we speculated that we might improve trawl selectivity by making similar design changes in other parts of the trawl, for example, in the extension piece in front of the codend. The extension piece is the rearmost part of the trawl body (tapered or untapered section) before the codend, made of one or more panels of the same netting characteristics (mesh size, mesh configuration, twine diameter and material). In a Mediterranean bottom trawl, its length ranges from 3 to 17 meters (Sala, 2013). The selectivity processes occurring in the trawl extension pieces have been less investigated than in the codend. Further, it is unknown to what extent design changes in the extension piece might affect the codend selectivity.

Based on the above considerations, the present study investigated the effect of reducing the number of meshes in circumference and turning meshes by 90 degrees in the extension piece of bottom trawls applied in the Mediterranean fishery. The main target species were the European hake (*Merluccius merluccius*) and the red mullet (*Mullus barbatus*), which are among the most landed and overexploited demersal species in the Mediterranean Sea, and require urgent management measures (GFCM, 2021). The monkfish (*Lophius* spp.) is another commercially important species in this fishery (Lucchetti, 2008). Specifically, this study aimed to answer to the following research questions:

i) In what way does reducing the number of meshes in circumference in the extension piece affect the catch patterns in the trawl and the catch efficiency at size of European hake and red mullet compared to the standard extension pieces?

ii) In what way does turning the meshes by 90 degrees in the extension piece affect the catch patterns in the trawl and the catch efficiency at size of European hake and red mullet compared to the standard extension pieces?

iii) Is there a change in the species composition and species dominance when applying these technical modifications?

Materials and Methods

Sea trials and data collection

Fishing trials were performed in February 2021 in the Northwestern Adriatic Sea (FAO Geographical Sub-Area 17) with a commercial bottom trawler (F/V 'Braveheart'; overall length: 22.2 m; gross tonnage: 64 GT). The experiments were carried out with twin trawls, i.e., the trawler simultaneously towed two identical trawls side by side.

The gears used were the typical commercial bottom trawl nets employed in the area ('Americana' trawls). Each trawl was an asymmetrical 4-face net with an overall length of 41.6 m, a 33.2 m long headrope (Ø 16 mm, polyethylene material) and a 40 m long footrope (Ø 34 mm, polyamide-polyethylene combined material). A single pair of otter boards (186×114 cm, 390 kg each) and one central clump (190 kg) were used to maintain the horizontal opening of the two nets. The otter boards and the clump were attached to the trawls with double 20 m long sweeps and 6 m long bridles. The traditional extension piece (Standard, hereafter) was cylindrical, with a total length of 9.5 m, a 44 mm nominal diamond mesh size and 240 meshes in circumference.

Two experimental extension pieces were designed: one having 44 mm (nominal) diamond meshes and a reduced (170) number of meshes in circumference (Reduced, hereafter); the second having 44 mm (nominal) T90 meshes and 170 meshes in circumference (T90, hereafter). The three extension pieces were constructed from the same netting panel and identical 40 mm legal square mesh codends (4 m long) were attached to each of them. The mesh openings of both extension pieces and codends were measured in wet conditions with the OMEGA mesh gauge (Fonteyne et al., 2007). The resulting three trawl configurations are schematized in Figure 1, and their specifications are listed in Table 1.

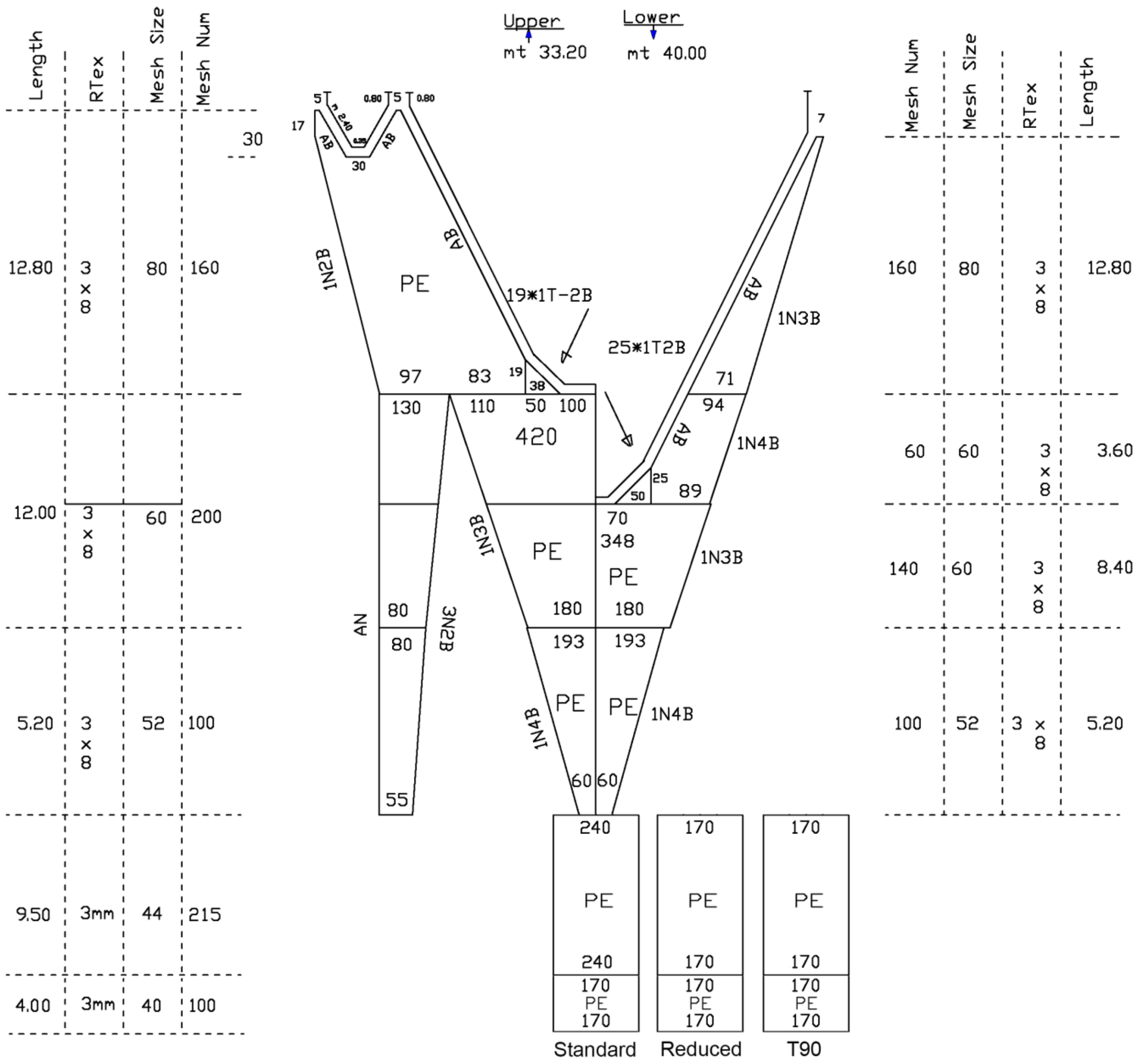

Figure 1: Scheme of the trawl net used in the survey, with details of the extension piece plus codend of the three net configurations tested in the survey (Standard, Reduced, T90).

The experiment consisted in testing two of the three net configurations at a time. Eighteen valid hauls were performed: six hauls T90 vs. Standard; six hauls Reduced vs. Standard; six hauls Reduced vs. T90. Therefore, we obtained a total of 36 samples (12 samples for each net configuration). An overview of the hauls is presented in Figure 2 and Table 2.

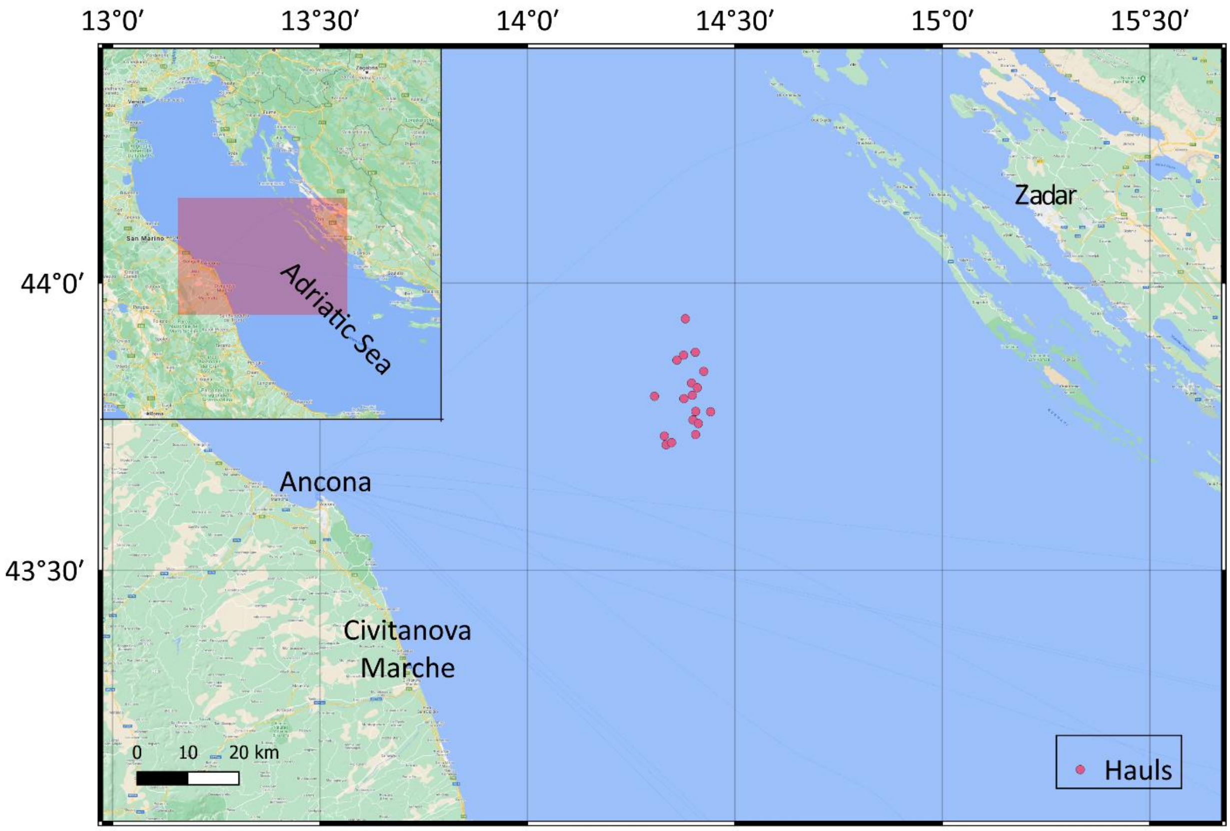

Figure 2: Map of the area where the hauls were carried out.

Table 1: Technical features of the extension piece plus codend of the three net configurations (Standard, Reduced, T90) tested in the survey.

		Standard	Reduced	T90	Codend
Extension piece	Length (m)	9.5	9.5	9.5	4
	Nominal mesh size (mm)	44	44	44	40
	Measured mesh size (mm)	43.9	43.9	43.8	40.4
	Mesh configuration	Diamond	Diamond	T90	Square
	No. meshes in circumference	240	170	170	170

During the towing operations, the two nets were equipped with acoustic sensors (SIMRAD, Norway) to monitor their geometry, i.e., the net vertical opening and the wing horizontal openings. The average duration of each haul was 60 minutes (range 50 to 70 minutes) and the towing speed was maintained at 3.5 to 3.6 knots, as in commercial fishing conditions. The catches of the two nets were kept separate. In each haul, the total weight and number of the most abundant species were recorded. Regarding the two target species (European hake and red mullet) and the monkfish (*Lophius* spp.), the individual lengths were measured to the lowest 0.5 cm without sub-sampling. An exception concerned the red mullet, where in case of large catches, measurements were conducted on a randomly selected subsample.

Data analysis

The Kruskal–Wallis H test (χ^2) was first applied to seek differences between the wing horizontal openings and vertical net openings of the three configurations tested. The check of the net geometry was preparatory to further analyses, to be sure to have the same fishing effort between the trawls simultaneously towed.

Catch comparison and catch ratio analysis

The catch data were analysed with the statistical software SELNET (Herrmann et al., 2012). Although the experimental design was based on six paired hauls for each combination (T90 vs. Standard, Reduced vs. Standard, Reduced vs. T90), each net configuration was tested two times, by comparing it to the other two configurations. Therefore, data were treated as unpaired (Herrmann et al., 2017), to be able to include in the comparison analyses all 12 hauls obtained from each net configuration.

The length measurements for the red mullet, the European hake, and the monkfish obtained with the Standard, Reduced and T90 extension pieces in the trawl were used to perform a catch comparison and catch ratio analysis. The analysis investigated the size dependent effect on the catch efficiency by changing the extension piece configuration and was carried out independently for each species following the description below.

To assess the relative length-dependent catch comparison rate (CC_l) of changing from one trawl net configuration to another, we used Equation 1 (Herrmann et al., 2017):

$$CC_l = \frac{\sum_{j=1}^{ht}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{i=1}^{hb}\left\{\frac{nb_{li}}{qb_i}\right\}+\sum_{j=1}^{ht}\left\{\frac{nt_{lj}}{qt_j}\right\}} \qquad (1)$$

where nb_{li} and nt_{lj} are the number of fish of length l of a given species retained by the codend of the baseline (*b*) and test (*t*) net, respectively. Parameters qb_i and qt_j are the subsampling ratios, i.e. the ratio of the measured to the total number individuals retained by the baseline and the test net, respectively. Parameters *hb* and *ht* represent the total number of hauls conducted with baseline and test extension piece, respectively. The catch comparison rate $CC(l,v)$, experimentally expressed by Equation 1, was estimated using the maximum likelihood estimation by minimizing the Expression 2:

$$-\sum_l\left\{\sum_{i=1}^{hb}\left\{\frac{nb_{li}}{qb_i}\times ln[CC(l,\boldsymbol{v})]\right\}+\sum_{j=1}^{ht}\left\{\frac{nt_{lj}}{qt_j}\times ln[1.0-CC(l,\boldsymbol{v})]\right\}\right\} \qquad (2)$$

where the outer summation is over the length classes *l* and the inner summation is over the hauls *ht* and *hb* in the experimental dataset. The *v* parameter describes the catch comparison curve defined by *CC(l,v)*. The experimental *CCl* was modelled by the function *CC(l,v)*:

$$CC(l,\boldsymbol{v}) = \frac{exp[f(l,v_0,\ldots,v_k)]}{1+exp[f(l,v_0,\ldots,v_k)]} \qquad (3)$$

where *f* is a polynomial of order *k* with coefficients v_0 to v_k, such that $v = (v_0, \ldots, v_k)$. We considered *f* of up to an order of 4. Leaving out one or more of the parameters $v_0 \ldots v_4$ yielded 31 additional candidate models for the catch comparison function *CC(l,v).* Among these models, the catch comparison rate was estimated using the multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017). The ability of the combined model to describe the experimental data was based on the *p*-value, which is calculated based on the model deviance versus the degrees of freedom (DOF; Wileman et al., 1996; Herrmann et al., 2017). Thus, suitable fit statistics for the combined model to describe the experimental data sufficiently well should include a *p*-value > 0.05. In case of poor fit statistics (*p*-value < 0.05 and deviance/DOF >> 1), the residuals were inspected to determine whether the result was due to structural problems when modelling the experimental data, or to overdispersion in the data (Wileman et al., 1996).

CC(l,v) quantifies the probability that a fish of length *l* is retained by the codend of the test net, provided that it is retained in one of the two nets compared. A *CC(l)* of 0.5 indicates that a fish of length *l* has the same probability of being retained by either gear. Therefore, *CC(l,v)* cannot be used to provide a direct relative value of the catch efficiency between the test and the baseline nets. The following catch ratio *CR(l,v)* equation was then used:

$$CR(l,\boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{[1-CC(l,\boldsymbol{v})]} \qquad (4)$$

In this case a *CR(l,v)* of 1.0 indicates that the catch efficiency of both nets is equal, while a *CR(l,v)* = 0.25 indicates that the test net is catching only 25% of the fish of length *l* compared to the baseline net.

The 95% confidence intervals (*CIs*) for the catch comparison and catch ratio curves were estimated using a double bootstrapping method with 1000 bootstrap repetitions, following the description in Lomeli (2019).

Discard ratio analysis

For the species analysed with a MCRS we estimated the discard ratio, i.e., the ratio between the individuals below MCRS to the total individuals retained in the codends of each net configuration (Sala et al., 2015). The indicators provided below represent a summary of the relative catch performance of the technical modifications applied. The discard ratios were estimated (in percentage) directly from the experimental catch data by using the following equation:

$$NDRatio = 100 \times \frac{\sum_{l<MCRS}\sum_{j=1}^{h}\left\{\frac{n_{lj}}{q_j}\right\}}{\sum_{l}\sum_{j=1}^{h}\left\{\frac{n_{lj}}{q_j}\right\}} \qquad (5)$$

The outer summations include the length classes that were below the MCRS (in the nominator) and over-all length classes (in the denominator). The above indicators are based on number of individuals, but since the value of catch is more related to weight, we estimated similar indicators based on weight (*WDRatio*) where the weight W_l, for individual belonging to length class l, have been estimated by:

$$W_l = a \times L^b \qquad (6)$$

The length-weight relationships of the species analysed were derived from the study of Bolognini et al. (2013) carried out in the same area.

We estimated the uncertainties (in 95% *CIs*) for both *NDRatio* and *WDRatio* by using the double bootstrapping method described in Lomeli (2019).

Catch dominance analysis

Catch dominance curves are often used to quantify information about the pattern of relative species abundances for a given sample. In the present study, the objective was to assess if the species abundances significantly changed among the three configurations tested. Generally, dominance curves are based on ranking of species in a sample in decreasing order of their abundance (Clarke, 1990). Here we assigned a fixed rank to the most abundant species caught in the sea trials following these criteria (in order of importance): i) the abundance in the commercial catch, ii) the importance in the fishery, iii) the abundance in the discarded catch, iv) the belonging to a vulnerable category.

We then estimated the catch dominance curve for each net configuration using the following equation (Warwick et al., 2008):

$$d_{ij} = \frac{n_{ij} \times \frac{w_{ij}}{W_{ij}}}{\sum_{i=1}^{Q}\left\{n_{ij} \times \frac{w_{ij}}{W_{ij}}\right\}} \qquad (7)$$

where j represents the haul and i is the species index (species rank) that was predefined. n_{ij} is the number of individuals of the species i being counted in the subsample in haul j. w_{ij} is the weight of the counted subsample of species i in haul j, whereas W_{ij} is the total weight caught of species i in haul j. Q is the total number of species considered.

To better represent species dominance patterns, we also estimated the cumulative dominance curves as follows:

$$D_{Ij} = \frac{\sum_{i=1}^{I} n_{ij} \times \frac{w_{ij}}{W_{ij}}}{\sum_{i=1}^{Q} \left\{ n_{ij} \times \frac{w_{ij}}{W_{ij}} \right\}} \text{ with } 1 \leq I \leq Q \qquad (8)$$

where *I* is the species index summed up to in the nominator.

The 95% *CIs* for the dominance patterns were estimated by using (7) and (8) inside each of the bootstrap iterations applied to estimate the uncertainties for the catch comparison and catch ratio curves.

Results

Gear performance and catch data

The Kruskal–Wallis H test (χ^2) revealed no significant differences in the net openings (m) between the nets towed (χ^2 = 4.46, df = 2, *p* = 0.1075 for wing horizontal opening; χ^2 = 4.13, df = 2, *p* = 0.1266 for vertical net opening; see Table 2 for details).

Table 2. Hauls performed during the cruise.

ID Haul	Date	Nets Tested	Haul duration [min]	Mean depth [m]	Mean wing horizontal opening [m]			Mean vertical net opening [m]			Total catch [kg]		
					Standard	Reduced	T90	Standard	Reduced	T90	Standard	Reduced	T90
1	22/02/2021	Standard VS T90	64	76.6	17.0 ± 0.8		17.7 ± 1.3	1.2 ± 0.1		1.1 ± 0.1	53.4		52.5
2	22/02/2021	Standard VS T90	60	74.4	15.9 ± 0.5		15.4 ± 1.0	1.4 ± 0.2		1.2 ± 0.3	66.7		51.3
3	22/02/2021	Standard VS T90	65	74.7	15.4 ± 0.6		17.1 ± 0.7	1.5 ± 0.1		1.6 ± 0.1	103.1		119.2
4	22/02/2021	Standard VS T90	70	71.0	16.1 ± 0.8		18.6 ± 1.2	1.8 ± 0.2		0.9 ± 0.2	143.4		136.3
5	22/02/2021	Standard VS T90	55	75.1	17.1 ± 0.6		16.6 ± 0.5	1.8 ± 0.1		1.0 ± 0.0	49.7		40.8
6	22/02/2021	Standard VS T90	50	74.9	17.1 ± 0.8		16.3 ± 1.5	1.6 ± 0.1		1.0 ± 0.2	27.8		20.2
7	23/02/2021	Standard VS Reduced	60	76.2	14.9 ± 1.2	17.6 ± 1.2		1.6 ± 0.2	1.1 ± 0.2		33.1	20.5	
8	23/02/2021	Standard VS Reduced	57	75.2	16.1 ± 0.8	15.7 ± 1.3		1.4 ± 0.0	1.4 ± 0.3		91.8	106.9	
9	23/02/2021	Standard VS Reduced	58	75.2	16.5 ± 1.4	15.8 ± 0.4		1.3 ± 0.2	1.1 ± 0.0		90.3	71.8	
10	23/02/2021	Standard VS Reduced	63	73.3	16.1 ± 0.4	16.4 ± 0.8		1.5 ± 0.1	1.5 ± 0.1		92.4	95.8	
11	23/02/2021	Standard VS Reduced	60	74.3	15.0 ± 0.6	17.0 ± 0.9		1.1 ± 0.1	1.6 ± 0.1		69.1	62.2	
12	23/02/2021	Standard VS Reduced	65	81.2	17.1 ± 0.9	16.3 ± 0.6		1.1 ± 0.2	1.5 ± 0.4		67.7	52.2	
13	25/02/2021	Reduced VS T90	68	76.6		16.2 ± 0.7	17.2 ± 0.7		1.3 ± 0.1	1.2 ± 0.2		61.2	71.4
14	25/02/2021	Reduced VS T90	68	78.5		17.5 ± 0.9	16.2 ± 1.3		1.4 ± 0.0	1.2 ± 0.1		71.1	145.7
15	25/02/2021	Reduced VS T90	68	74.7		16.6 ± 0.9	16.0 ± 1.0		1.3 ± 0.3	1.2 ± 0.2		92.0	65.4
16	25/02/2021	Reduced VS T90	62	74.1		17.8 ± 0.4	18.5 ± 0.9		0.7 ± 0.4	0.9 ± 0.2		92.6	76.1
17	25/02/2021	Reduced VS T90	64	78.2		16.9 ± 0.4	16.4 ± 0.8		0.8 ± 0.2	1.6 ± 0.3		116.9	132.4
18	25/02/2021	Reduced VS T90	69	81.0		17.8 ± 0.8	18.0 ± 1.4		1.4 ± 0.4	1.7 ± 0.3		59.7	58.0

The red mullet represented the largest portion of the commercial catch (up to 24 kg per haul and net; avg. 9.1 ± 5.0 kg), while the European hake catch showed a maximum of 10 kg per haul and net (avg. 6.2 ± 2.2 kg). The average catch of monkfish in each haul and net was 4.4 ± 2.0 kg. Additional 21 species (fish, cephalopods, and crustaceans) caught in large amounts in most of the hauls, were counted and weighted in each haul and net.

Catch comparison analysis

For the three species included in the catch comparison analysis, the summary of the individuals measured in each haul from the three net configurations is reported in Table 3. The fit statistics of the combined model are given in Table 4. Regarding red mullet and monkfish, the p-values were always ≤ 0.05. However, the visual inspection of the modelled catch comparison curves against the experimental rates for these species did not indicate any length dependent patterns in the deviations (Figures 4, 5). Therefore, we assumed that the low p-values were due to overdispersion in the experimental rates rather than a lack of fit.

Table 3. Number of individuals of the three species (European hake, red mullet, monkfish) measured in each haul from each net configuration. Values in parentheses are the subsampling factors.

Haul	European hake			Red mullet			Monkfish		
	Standard	**Reduced**	**T90**	**Standard**	**Reduced**	**T90**	**Standard**	**Reduced**	**T90**
1	22 (1)	-	36 (1)	92 (1)	-	76 (1)	26 (1)	-	25 (1)
2	41 (1)	-	43 (1)	128 (0.43)	-	179 (1)	17 (1)	-	11 (1)
3	57 (1)	-	52 (1)	139 (0.26)	-	109 (0.27)	15 (1)	-	10 (1)
4	83 (1)	-	70 (1)	137 (0.21)	-	117 (0.37)	22 (1)	-	17 (1)
5	66 (1)	-	55 (1)	95 (0.35)	-	80 (0.49)	18 (1)	-	15 (1)
6	29 (1)	-	23 (1)	88 (0.7)	-	26 (1)	17 (1)	-	15 (1)
7	46 (1)	33 (1)	-	121 (1)	96 (1)	-	13 (1)	14 (1)	-
8	102 (1)	76 (1)	-	96 (0.20)	98 (0.65)	-	28 (1)	23 (1)	-
9	81 (1)	44 (1)	-	109 (0.31)	95 (0.64)	-	15 (1)	22 (1)	-
10	93 (1)	66 (1)	-	106 (0.30)	131 (0.28)	-	13 (1)	18 (1)	-
11	64 (1)	45 (1)	-	103 (0.31)	119 (0.27)	-	18 (1)	13 (1)	-
12	44 (1)	43 (1)	-	116 (0.25)	114 (0.37)	-	19 (1)	20 (1)	-
13	-	39 (1)	42 (1)	-	116 (0.19)	126 (0.27)	-	17 (1)	23 (1)
14	-	62 (1)	76 (1)	-	145 (0.32)	109 (0.50)	-	11 (1)	19 (1)
15	-	75 (1)	51 (1)	-	146 (0.13)	114 (0.67)	-	14 (1)	28 (1)
16	-	42 (1)	30 (1)	-	143 (0.17)	87 (0.66)	-	9 (1)	17 (1)
17	-	62 (1)	51 (1)	-	156 (0.20)	112 (0.25)	-	9 (1)	21 (1)
18	-	30 (1)	34 (1)	-	107 (0.39)	95 (0.70)	-	12 (1)	19 (1)

Table 4. Fit statistics of the combined model used in the three catch comparisons (T90 VS Standard, Reduced VS Standard, Reduced VS T90).

		T90 VS Standard	Reduced VS Standard	Reduced VS T90
European hake	***p*-value**	0.384	0.3691	0.386
	Deviance	50.26	55.83	54.32
	DOF	48	53	52
Red mullet	***p*-value**	0.0289	0.0002	0.001
	Deviance	37.49	54.99	46.7
	DOF	23	23	21
Monkfish	***p*-value**	0.0018	0.0006	0.0454
	Deviance	100.81	105.45	85.38
	DOF	63	63	66

Figures 3-5 show the catch comparison and catch ratio results of T90 vs. Standard, Reduced vs. Standard, Reduced vs. T90 for European hake, red mullet, and monkfish, respectively.

The use of the two modified net configurations (Reduced, T90) did not affect the catch efficiency of European hake, since the *CIs* of both the catch ratio and catch comparison curves overlapped the horizontal line representing equal catch rates between the two configurations compared, for the full length range observed (Figure 3).

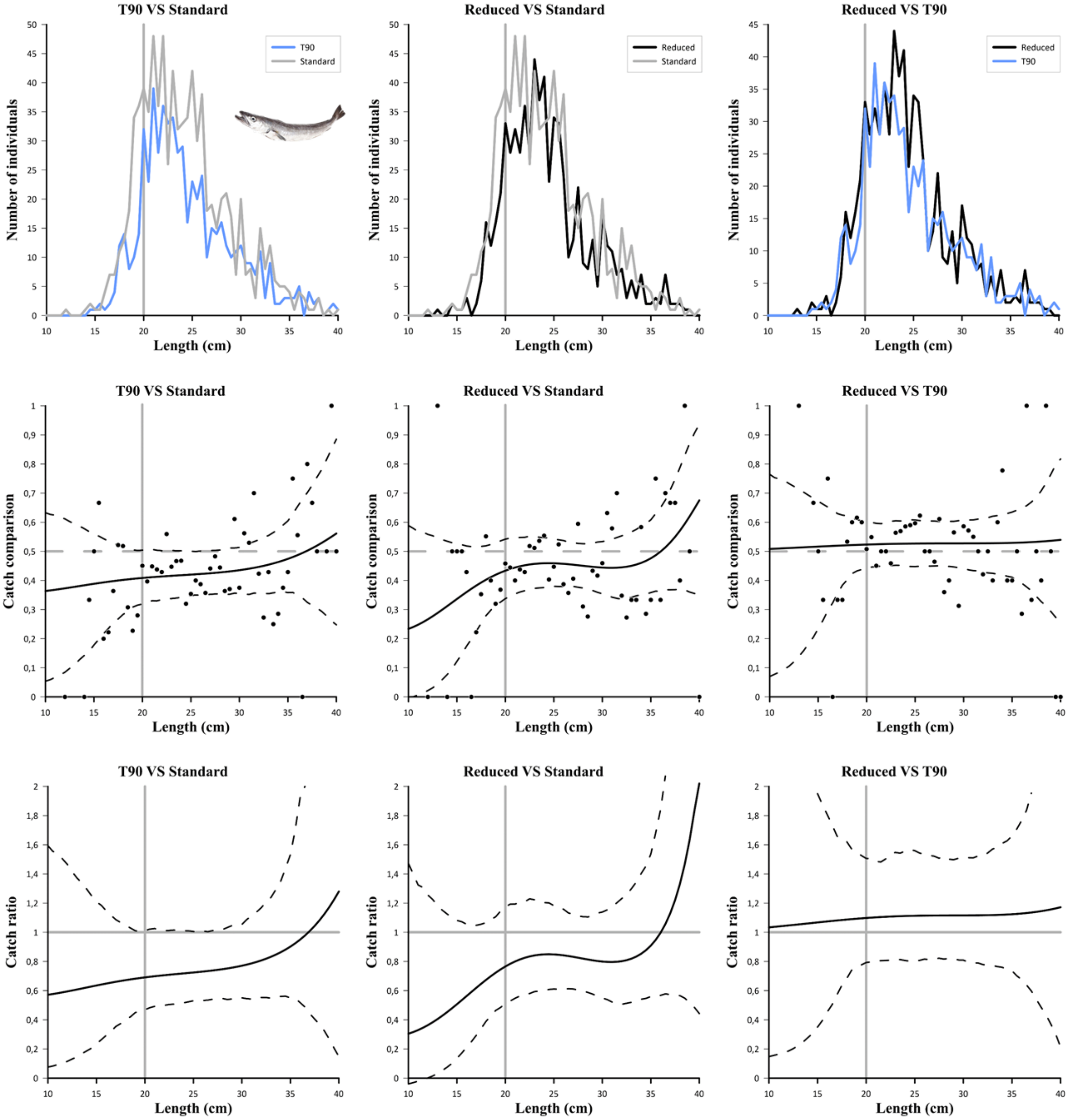

Figure 3. Upper graph: Length frequency distribution of European hakes caught by the configurations tested (Standard, Reduced and T90). Middle graph represents the modelled catch comparison rate, and lower graph the catch ratio (black line). Black circles represent the experimental rate, and the black stippled curves represent 95% CIs. The grey horizontal line at 0.5 and 1.0 represents the point at which both configurations have equal catch rates. The grey vertical line represents the MCRS for hake.

Regarding red mullet, a significant difference was found in all three comparisons (Figure 4). The length frequency distribution obtained in the T90 was different from that of Standard, especially in the 13 to 16 cm length range. This was reflected in both catch comparison and catch ratio curves, which displayed a significantly lower catch efficiency of T90 compared to Standard for those length classes. The catch comparison and catch ratio curves of Reduced vs. Standard and Reduced vs. T90 had a similar trend. In both cases, a significantly higher retention of Reduced was observed for the lengths ranging from 6 to 12 cm (vs. Standard) and from 6 to 14 cm (vs. T90). Moreover, in the comparison between Reduced and Standard, the former had a significantly lower catch efficiency than the latter for around 16 to 18 cm long individuals.

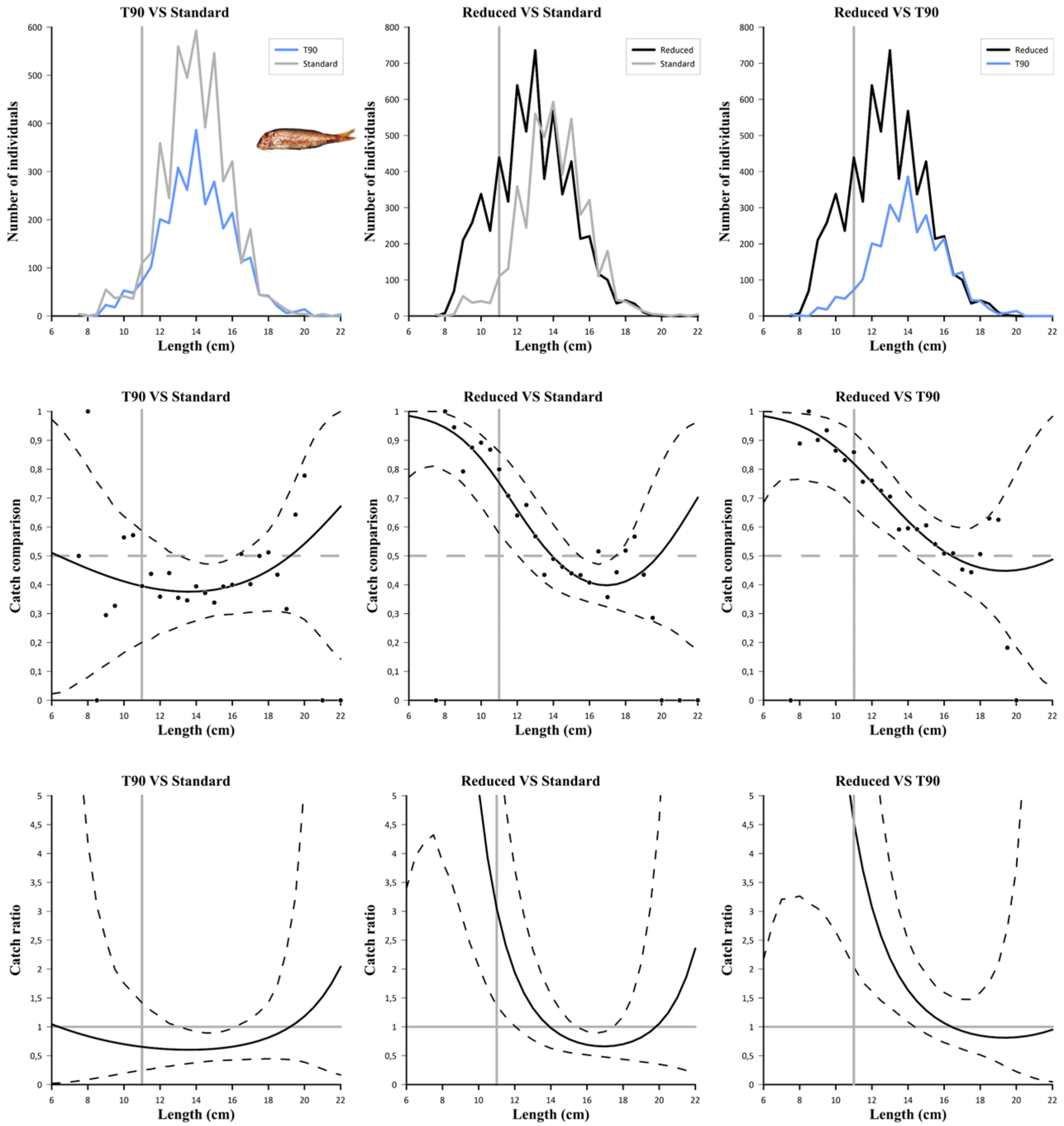

Figure 4. Upper graph: Length frequency distribution of red mullets caught by the configurations tested (Standard, Reduced and T90). Middle graph represents the modelled catch comparison rate, and lower graph the catch ratio (black line). Black circles represent the experimental rate, and the black stippled curves represent 95% CIs. The grey horizontal

line at 0.5 and 1.0 represents the point at which both configurations have equal catch rates. The grey vertical line represents the MCRS for red mullet.

The results displayed for monkfish did not reveal any significant differences in T90 vs. Standard and Reduced vs. Standard (Figure 5). A significant difference was found in the Reduced vs. T90 comparison: the catch efficiency of the latter was found to be lower than that of the former for the 30 to 35 cm length range. However, the difference was minimal, since the upper *CI* of both the catch comparison and catch ratio curves almost reached the equal catch rate values of 0.5 and 1.0, respectively.

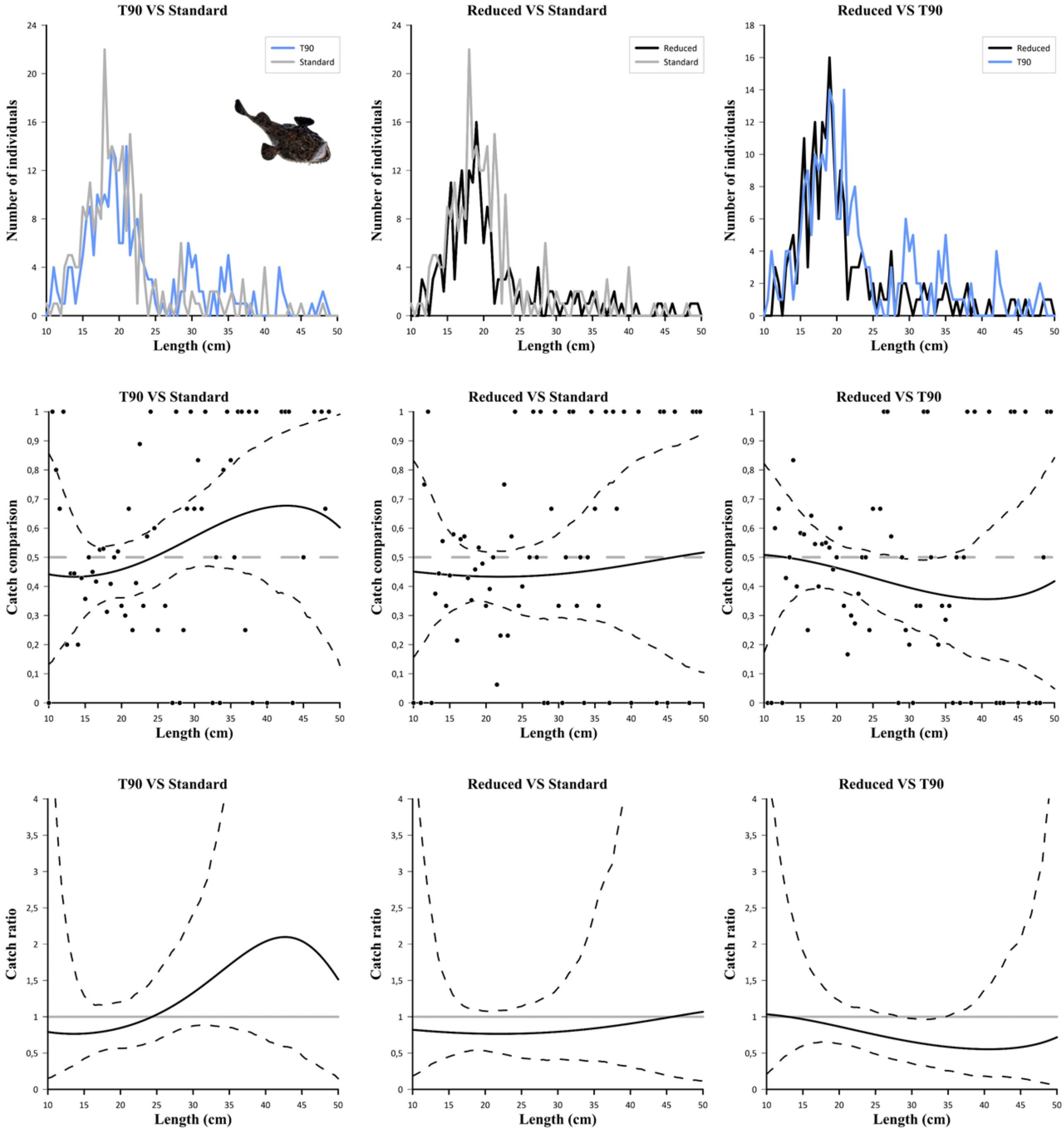

Figure 5. Upper graph: Length frequency distribution of monkfish caught by the configurations tested (Standard, Reduced and T90). Middle graph represents the modelled catch comparison rate, and lower graph the catch ratio (black line). Black circles represent the experimental rate, and black stippled curves represent 95% CIs. The grey horizontal line at 0.5 and 1.0 represents the point at which both configurations have equal catch rates.

Discard ratio analysis

Regarding European hake, the discard ratios representing the proportion of individuals below the MCRS did not significantly differ between the Reduced net (*NDRatio*: 11.8%, *CI*s: 8.7%–15.1%; *WDRatio*: 4.1%, *CI*s: 2.9%-5.5%) and the other two nets (Table 5).

Regarding red mullet, the discard ratios of the Reduced net (*NDRatio*: 17.9%, *CI*s: 11.8%–22.4%; *WDRatio*: 7.3%, *CI*s: 4.5%-9.6%) were significantly higher than those of Standard (*NDRatio*: 3.8%, *CI*s: 2.6%–5.1%; *WDRatio*: 1.2%, *CI*s: 0.8%-1.6%) and T90 (*NDRatio*: 5.0%, *CI*s: 1.8%–9.3%; *WDRatio*: 1.7%, *CI*s: 0.6%-3.2%) nets (Table 5).

Table 5. Estimated discard ratios (%) in both numbers (NDRatio) and weight (WDRatio) of European hake and red mullet obtained from the three net configurations. Values in brackets represent the lower and upper 95% CIs.

		Standard	**Reduced**	**T90**
European hake	*NDRatio (%)*	16.1 (13.7 - 18.6)	11.8 (8.7 - 15.1)	11.3 (9.2 - 13.7)
	WDRatio (%)	5.9 (4.7 - 7.2)	4.1 (2.9 - 5.5)	3.8 (3.0 - 4.7)
Red mullet	*NDRatio (%)*	3.8 (2.6 - 5.1)	17.9 (11.8 - 22.4)	5.0 (1.8 - 9.3)
	WDRatio (%)	1.2 (0.8 - 1.6)	7.3 (4.5 - 9.6)	1.7 (0.6 - 3.2)

Catch dominance analysis

All 24 species counted and weighted in each haul were included in the catch dominance analysis. Table 6 shows the catch dominance percentages in weight of each species in each net configuration (Standard, Reduced, T90). In all three configurations, the red mullet was found to be the dominant species, ranging from 24.3% (*CIs* 19.1%-29.4%) of the total catch in the T90 to 31.5% (*CIs* 27.0%-35.8%) in the Standard and 35.6% (*CIs* 27.3%-42.4%) in the Reduced; the differences among nets were not significant. The European hake showed a similar percentage among the three nets (around 20%, *CIs* between 17.3% and 26.3%). Regarding monkfish, the T90 showed a significantly higher percentage (20.1%, *CIs* 16.2%-25.3%) than the Reduced (11.8%, *CIs* 9.4%-14.8%); the difference was not significant when compared to the Standard (13.5%, *CIs* 10.3%-17.4%). The spotted flounder (*Citharus linguatula*) resulted to be the fourth commercial species in terms of weight in all the nets (around 5%-8% of the total catch). Among the discarded species, the common Pandora (*Pagellus erythrinus*) and the small-spotted catshark (*Scyliorhinus canicula*) had the highest percentages (around 4%-6%), without significant differences among the three nets.

Table 6. Catch dominance percentages of each species in the three net configurations tested (Standard, Reduced, T90). Values in brackets represent the lower and upper 95% CIs.

Species	**Rank**	**Standard**	**Reduced**	**T90**
Mullus barbatus	S1	31.5 (27.0 – 35.8)	35.6 (27.3 - 42.4)	24.3 (19.1 - 29.4)
Merluccius merluccius	S2	22.4 (18.7 - 26.3)	19.6 (16.4 - 22.6)	20.9 (17.3 – 25.0)
Lophius spp.	S3	13.5 (10.3 - 17.4)	11.8 (9.4 - 14.8)	20.1 (16.2 - 25.3)
Chelidonichthys lucerna	S4	3.0 (1.4 - 6.9)	1.8 (1.2 - 2.6)	1.8 (1.2 - 2.5)
Eledone spp.	S5	2.6 (1.3 - 4.5)	1.9 (1.0 – 3.0)	3.1 (1.9 - 4.5)
Illex coindetii	S6	1.6 (1.1 - 2.2)	1.8 (1.0 - 2.8)	2.4 (1.1 - 4.5)
Citharus linguatula	S7	6.9 (5.7 - 8.4)	6.1 (4.9 - 7.4)	6.1 (5.1 - 7.2)
Loligo vulgaris	S8	0.9 (0.5 - 1.5)	1.0 (0.5 - 1.6)	0.9 (0.4 - 1.7)
Sepia officinalis	S9	0.6 (0.0 - 1.4)	1.3 (0.2 - 2.8)	0.2 (0.0 - 0.7)
Octopus vulgaris	S10	0.2 (0.0 - 0.6)	1.3 (0.3 - 4.8)	1.2 (0.2 - 3.4)
Zeus faber	S11	0.6 (0.2 - 2.5)	0.3 (0.0 – 1.0)	0.7 (0.2 - 2.5)
Scorpaena scrofa	S12	0.1 (0.0 - 0.4)	0.7 (0.1 - 2.2)	1.8 (0.3 – 5.0)
Scorpaena notata	S13	0.6 (0.2 - 1.4)	0.9 (0.3 - 2.2)	1.4 (0.6 - 2.2)
Pagellus erythrinus	S14	4.4 (2.5 - 6.5)	5.8 (3.9 - 8.2)	5.8 (3.3 – 9.0)
Trachinus draco	S15	0.5 (0.3 - 0.9)	0.8 (0.4 - 1.2)	0.6 (0.3 - 0.8)
Trachurus mediterraneus	S16	0.4 (0.1 - 0.8)	1.1 (0.4 – 2.0)	0.7 (0.2 - 1.3)
Trachurus trachurus	S17	0.0 (0.0 - 0.0)	0.5 (0.0 - 1.2)	0.7 (0.1 - 1.9)
Scomber scombrus	S18	0.1 (0.0 - 0.3)	0.2 (0.0 - 0.5)	0.2 (0.0 - 0.5)
Trisopterus minutus capelanus	S19	0.6 (0.3 - 0.8)	0.9 (0.5 - 1.4)	0.8 (0.3 - 1.4)
Uranoscopus scaber	S20	0.4 (0.1 - 0.7)	0.2 (0.0 - 0.6)	0.3 (0.0 - 0.8)
Scyliorhinus canicula	S21	4.5 (3.3 - 6.0)	4.8 (3.2 - 6.6)	3.8 (2.5 - 5.2)
Mustelus mustelus	S22	3.2 (0.6 - 9.2)	0.3 (0.1 - 1.3)	1.1 (0.2 - 3.7)
Squalus acanthias	S23	0.8 (0.2 - 2.9)	0.4 (0.2 - 1.7)	0.0 (0.0 - 0.0)
Squilla mantis	S24	0.3 (0.1 - 0.7)	1.1 (0.4 – 2.0)	1.4 (0.4 - 2.5)

The catch dominance cumulative curves obtained by summing the percentages of the 24 species for each net configuration are presented in Figure 6. No significant differences were detected between the three nets since the *CIs* always showed overlap. The three main target species (red mullet, European hake, and monkfish) represented 60%-70% in weight of the total species selected.

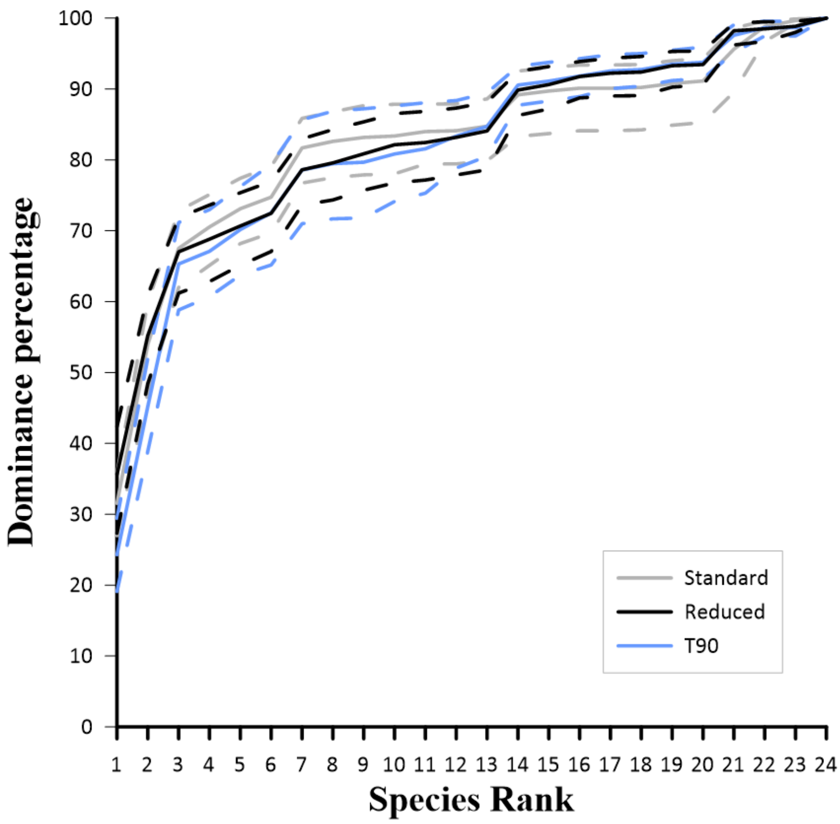

Figure 6. Catch dominance cumulative curves for the three configurations tested (Standard, Reduced, T90). The stippled curves represent the 95% CIs.

Discussion

The modification of standard trawls to decrease unwanted size and species retention is one of the most intensively investigated approaches in Mediterranean bottom trawl fisheries in light of the landing obligation regulation (EU, 2013), which encourages the adoption of technical solutions to reduce discards (Petetta et al., 2021). The aim of the present study was to test, in the extension piece section, simple technical modifications, the efficacy of which has been demonstrated at the codend level (Wienbeck et al., 2011; Sala et al., 2016).

The main finding was that the design changes that work in the codend do not necessarily work in other parts of the trawl, and the outcomes can even opposite to expected outcomes. This was evident from the results of the red mullet, where the only modification of reducing the number of meshes in extension circumference led to a higher retention of the smallest size classes compared to the standard net. One can speculate that the combination of two mechanisms led to these results:

i) Although a reduction of number of meshes in circumference increases the mesh openness in the extension piece, the main behaviour of red mullets is to stay clear of the meshes in this section until they reach the codend. This is a common behaviour of several fish species when entering the relatively confined section of netting ahead of the codend; after swimming in the towing direction without escape attempts, the progressive exhaustion leads to a consequent drift towards the codend (Grimaldo et al., 2007; He et al., 2008; Winger et al., 2010). In particular, the size of the smallest red mullets (6 to 12 cm) prevents them from swimming for long periods in the opposite direction to the water flow, so that there is little chance of contact with the extension piece netting. On the contrary, most of the escape attempts occur at the codend, especially during the haul-back operations (Madsen et al., 2012). Therefore, in this hypothesis, the extension piece does not contribute to the size selection.

ii) The fewer meshes in circumference reduces the diameter of the extension piece and, since it is connected to the codend, it also reduces the diameter of the codend. In fact, the change in the ratio between the fewer extension meshes and the codend meshes, which remain constant, leads to a smaller circumferential length for each codend mesh, causing a reduced mesh openness or creating a folding of the codend netting (Figure 7). The netting folding is an important factor to take into account when addressing selectivity issues, since it can contribute to decreasing the codend size selectivity (Wienbeck et al., 2011). It is also possible that a selectivity improvement through the extension piece occurred, and it was hidden by a reduced selectivity in the codend due to folding. However, this issue is already prevented by EC, 2006, which establishes that, in gears equipped with 40 mm square mesh codends, the circumference of the posterior ending of the extension must be between 2 and 4 times the circumference of the anterior part of the codend. Hence, in a commercial context, it is not possible to apply this mesh reduction without modifying the codend accordingly, to maintain the proportions defined in the Regulation.

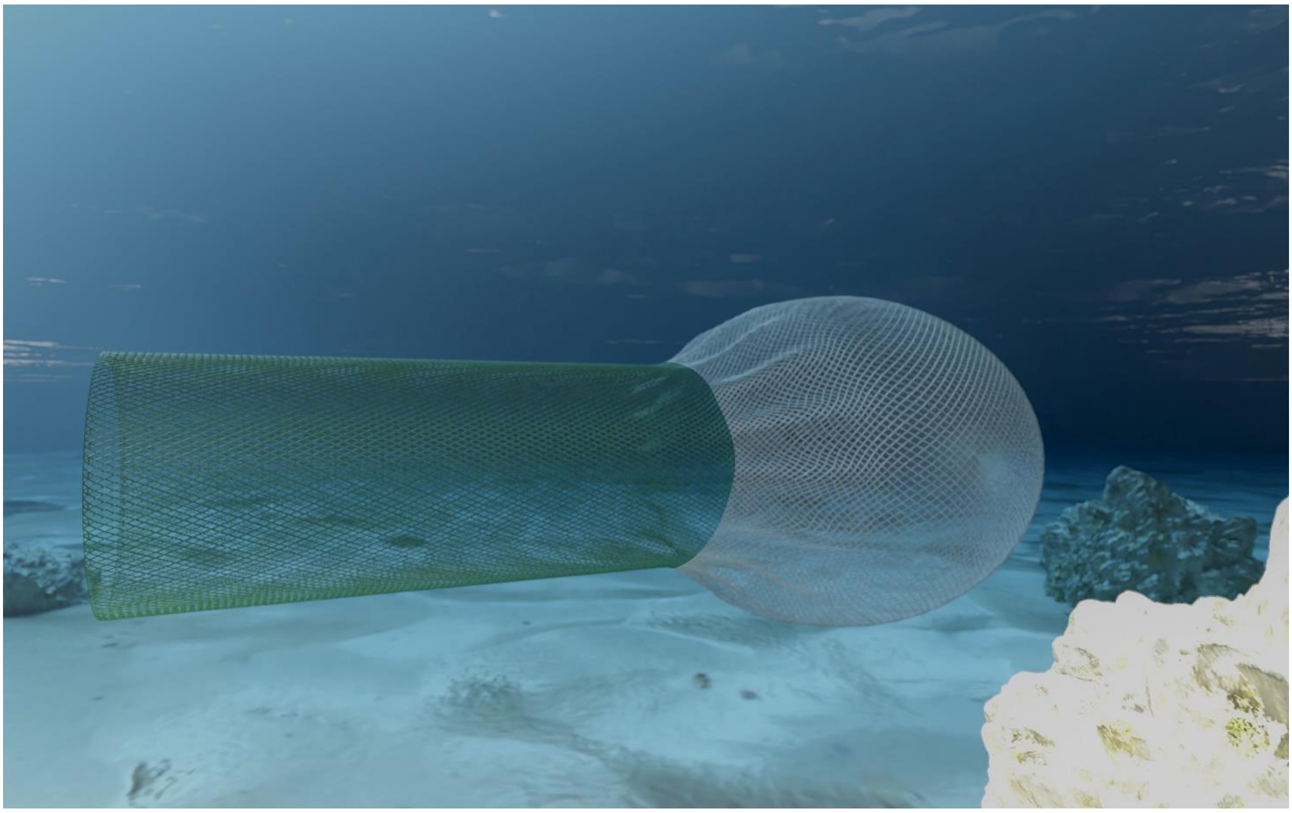

Figure 7. Illustration of the hypothetical codend folding due to a reduction of the number of meshes in the extension piece circumference.

We also cannot rule out that these mechanisms described in i) and ii) occurred simultaneously. As a result, they reduced the escape possibilities for red mullets up to a certain length which, with the actual 40.4 mm codend mesh size, should be around 11 to 14 cm, based on the average L50 range estimated for codends with similar properties in the Mediterranean (Table 7). This length range well fits the obtained catch ratio curve for this species in the Reduced vs. Standard comparison (Figure 4).

Table 7. Selectivity values (L50 and selection range, SR) obtained for red mullet, European hake and monkfish in selectivity experiments carried out in different FAO Geographical Sub-Areas (GSAs) of the Mediterranean with a 40 mm square mesh codend.

Red mullet				European hake				Monkfish			
GSA	**L50**	**SR**	**Reference**	**GSA**	**L50**	**SR**	**Reference**	**GSA**	**L50**	**SR**	**Reference**
24	14.2	3.1	Ateş et al., 2010	22	14.7	5.4	Aydin and Tosunoğlu, 2010	22	4.4	5.9	Mytilineou et al., 2021
22	14.4	2.4	Aydin et al., 2011	1	16.2	2.8	Baro and Muñoz de los Rejes, 2007				
1	11.5	1.8	Baro and Muñoz de los Rejes, 2007	9	15.8	3.3	Brčić et al., 2018				
14	11.8	2.0	Bdioui, 2015	22	14.3	3.4	Dereli and Aydin, 2016				
24	14.1	3.4	Demirci and Akyurt, 2017	5	15.3	2.2	Guijarro and Massutí, 2006				
22	12.9	2.0	Dereli and Aydin, 2016	17	13.0	3.7	Lucchetti, 2008				
29	11.9	1.3	Kaykaç et al., 2018	5	15.2	3.3	Ordines et al., 2006				
22	13.3	2.2	Mytilineou et al., 2021	22	15.1	5.7	Petrakis and Stergiou, 1997				
24	14.1	2.6	Özbilgin et al., 2015	17	13.8	7.4	Sala and Lucchetti, 2010				

17	10.9	1.4	Sala et al., 2008	17	14.2	3.6	Sala et al., 2008	
22	13.2	1.9	Tokaç et al., 1998					

The same effect was not observed in the T90, when compared to Standard, since the reduced number of meshes was applied together with the T90 configuration. In fact, the T90 configuration allowed meshes to remain more open and therefore did not consistently reduce the extension diameter (Herrmann et al., 2007). This explains why we observed the same catch pattern in Reduced vs. T90 as in Reduced vs. Standard, while there was no difference in the catch efficiency of T90 vs. Standard for the smallest length classes (< 12 cm). On the contrary, the lower catch efficiency of T90 than of Standard for larger individuals (13 to 16 cm long) could be related to their more active swimming behaviour, and their consequent greater use of the T90 meshes to escape. Concerning the biggest individuals (> 16 cm), they were probably not able to pass through the 43.8 mm meshes due to physical impediments. Therefore, the selectivity improvement carried out by the T90 meshes was essentially concentrated on individuals between 13 and 16 cm, which represented the most abundant size classes. These results are in line with the catch patterns observed by Bonanomi et al. (2020) for the same species in the same area, when applying lateral 70 mm square mesh panels in the extension piece.

Regarding the European hake, the reason why we did not observe the same catch pattern as in red mullet could reside in the size of the individuals caught. In fact, very few individuals below 15 cm were caught in the experiment, and this is confirmed by the average L50 range (13 to 16 cm) estimated for the 40 mm square mesh codend in several Mediterranean studies (Table 7). Most of the hakes caught in our experiment were simply too big for being released through the codend meshes, regardless of their openness. Therefore, the effect of the Reduced net on the reduction of codend selectivity especially due to the folding was not evident for this species. Both catch ratio curves and discard ratio indicators showed that the T90 net had a lower catch efficiency for 15 to 30 cm long hakes than the Standard net. Even if this trend was not significant, we could speculate that hakes used the 43.8 mm T90 meshes of the extension piece to escape, as assumed for the larger red mullets. We might have provided slightly different results with a higher sampling effort on the smaller individuals. Therefore, further tests may be needed in autumn or late spring, when the juveniles are more abundant in the study area (Sion et al., 2019; Zorica et al., 2021). We can also speculate if hakes made use of the whole extension piece to escape or only specific sections. In the Atlantic Ocean, Cuende et al. (2020) observed that placing an 82.7 mm square mesh panel in the lower extension piece section improved the release efficiency of 11 to 28 cm long hakes. On the contrary, Alzorriz et al. (2016) found that a 100 mm square mesh panel mounted on the top of the net was not an effective strategy to improve escape possibilities for hake. The underwater observations carried out by the authors showed that hakes simply drifted towards the codend when passing through the extension piece, without contacting the netting. The contact probability is a key issue for the selection devices placed in the extension piece, since fish must first physically contact the device for a size-dependent escape process to occur (Brčić et al., 2016; Cuende et al., 2020). This probability has been shown to increase when increasing the size of the selection devices and inserting guiding panels to enhance hake contact with the devices (Santos et al., 2016).

The results here displayed for both European hake and red mullet are different from those obtained in the Spanish Mediterranean. Sola and Maynou (2018) compared two extension pieces made of 50 mm T90 meshes and 53 mm diamond meshes, respectively. The authors observed a significant reduction, in the experimental net, of the catch of undersized individuals, but also legal sized individuals. The same results were obtained by Maynou et al. (2021). They tested two experimental nets that, besides reducing the extension piece mesh size (50 mm T90 vs. 53 mm diamond of standard net), maintained or increased the number of meshes around extension circumference (210 and 220 vs. 210 of standard net) and, in the 40 mm square mesh codend, reduced the number of meshes around circumference (106 and 104 vs. 130 of standard net). Also, the length and position (forwards in the extension piece and immediately in front of the codend) of the T90 panels were changed. The simultaneous application of these several design changes could have caused additional processes to the ones described above, which influenced the overall trawl catch pattern. Moreover, it is difficult to examine and understand the effect of single modifications, compared to the present study.

The size selectivity of the 40 mm square mesh codend is very low for monkfish (L50 of 4.4 cm; Table 7). Therefore, the barely significant reduction in the catch efficiency of T90 compared to Reduced for 30 to 35 cm long individuals is probably due to the low number of measured individuals for that length range. Few individuals mean a higher possibility of finding differences in their distribution in the surfaces swept by each trawl, even using a twin trawl, with the consequent high dispersion in the retention rates.

The catch dominance analysis did not show any significant differences in the catch composition among the three configurations tested. However, this method, innovative in the selectivity field, can provide useful information on the dynamics of species composition when applying different technical modifications.

The lesson learnt from this study is that the design changes that worked for the codend in previous studies do not necessarily work for other parts of the trawl such as the extension piece, which seems not to be the main part of the trawl where fish are willing to escape. This is in line with a dated study from Clark (1963), who showed that approximately 90% of the haddock (*Melanogrammus aeglefinus*) and silver hake (*Merluccius bilinearis*) escapement takes place in the very last few rows of meshes of the codend (also confirmed by Beverton, 1963). The only reduction in number of meshes around extension circumference produced an opposite result than expected, since it jeopardized the size selection obtained in the trawl with a standard extension piece. The T90 netting, which has been suggested as a cheap and practical solution in the codend to improve the size selectivity of Mediterranean bottom trawl fisheries (Tokaç et al., 2014; Kaykaç et al., 2018; Petetta et al., 2020), in the extension piece did not significantly help excluding juveniles of target species.

This study confirms that, to assess the validity of a technical solution, the factors involved (e.g., the T90 mesh in the extension and the reduction in number of meshes in circumference) should be tested one at a time, since the combination of different factors could mislead the obtained results. The design changes in the codend remain the most urgent measures to be tested and applied in the commercial fisheries, to mitigate the biological impacts of bottom trawling in the Mediterranean. In fact, the simple use of a 40 mm square mesh codend is not sufficient to reduce the bycatch of juveniles of several species (Lucchetti et al., 2021).

Data availability statement

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

Author contributions

AL, AP, and MV conceived and performed research; AP, DL, and MV collected data; AP, BH, and JB analysed data; AP wrote the paper with support of BH, MV, JB, and DL. AL was the scientific responsible of the research. All authors contributed to the article and approved the submitted version.

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Paper IV

Dredge selectivity in a Mediterranean striped venus clam (*Chamelea gallina*) fishery

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Dredge selectivity in a Mediterranean striped venus clam (*Chamelea gallina)* fishery

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Abstract

The striped venus clam *Chamelea gallina* is the target of a large fleet of hydraulic dredgers, which represent an important fishing sector in terms of income and landings in the Mediterranean Sea. Although there is information on the catch rates, impact and discards related to this fishery, the size selection process carried out by the dredge during trawl under commercial conditions is practically unknown. The present study aimed to fill this gap, assessing the selectivity of the gear at different haul durations. We demonstrated that 25% of the clams entering the dredge were not size selected by it. Clams with a length (i.e. maximum distance between anterior and posterior margins) of 18.9 mm had 50% retention probability and tow duration did not affect the size selection process in the dredge. The dredge catch efficiency was 79% in numbers of clams and 89% in weight. 58% of the clams caught were below the minimum conservation reference size of 25 mm. The study demonstrates that to land only the legal sizes of clams, the additional size selection process carried out on board the fishing vessels by the sorting sieves is necessary.

Keywords

Hydraulic dredge; Striped venus clam; *Chamelea gallina;* Selectivity; Mediterranean Sea

Introduction

Dredge fisheries are widely spread in the Mediterranean Sea to harvest commercially important burrowing bivalve shellfish, which represent an important seafood product across the whole region (FAO, 2018). The striped venus clam *Chamelea gallina* is one the most important infaunal bivalves exploited by dredgers, with relevant socio-economic importance particularly in the Italian coastal waters of northern and central Adriatic Sea (Scarcella and Cabanelas, 2016). The design of the dredge employed to harvest this resource, in soft bottoms with depths ranging from 3 to 12 m, have evolved over the past decades (Froglia, 1989) from rakes operated by hands until the advent of the modern hydraulic dredges, which enabled the development of a very profitable fishery for a large number of vessels (over 700 in Adriatic; DGPEMAC, 2019).

The typical hydraulic dredge consists of a sort of parallelepiped shape metal cage, which is commonly made of metal bars in its lower, upper and rear parts (Figure 1).

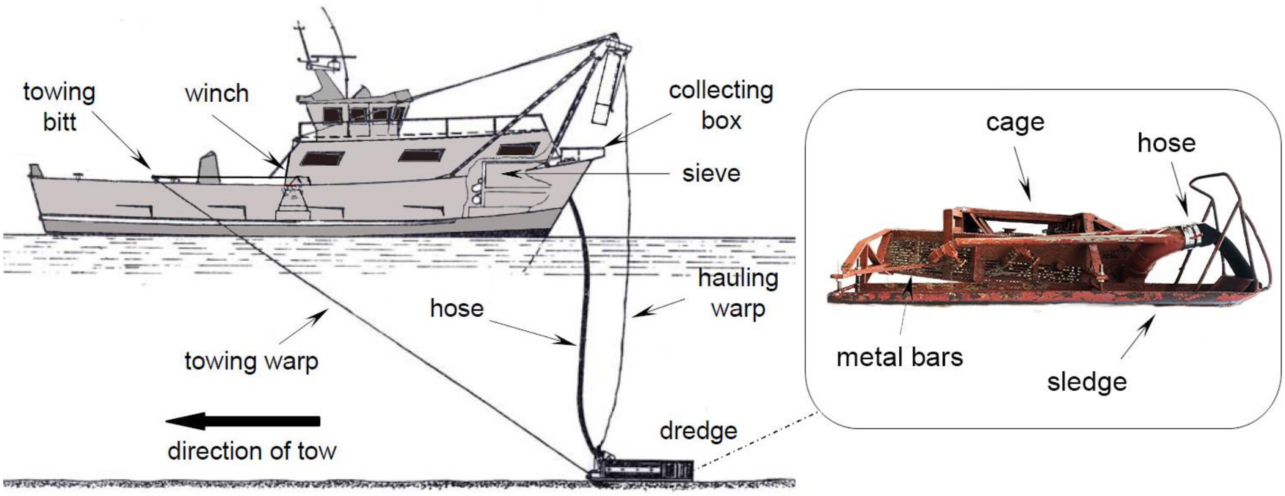

Figure 1. Commercial hydraulic dredging gear characteristics and method of deployment (adapted from Lucchetti and Sala, 2012).

The cage rests on two skid-sledge runners that facilitate the sliding motion on the seabed during towing (Lucchetti and Sala, 2012). The adjective "hydraulic" derives from the pressurised water that is injected from a centrifugal water pump to different types of nozzles mounted on the dredge. These nozzles are arranged in parallel rows and placed both at the dredge mouth and inside the dredge (Sala et al., 2017). The former spray pressurised water downwards to penetrate the sea bottom and suspend the sediment, to make the bivalves emerge and at the same time to assist the movement of the dredge in the substrate. The latter are positioned backwards to help clearing the cage from materials such as sand, mud and debris that often clog it. The dredge towing on the seabed is responsible for the first selection of the striped venus clam by size. After towing, the cage is hauled on board and all the catch gathered is conveyed to vibrating sieves, which are made up of a series of successive grids with holes of decreasing diameter (Sala et al., 2017). The mechanical sorting carried out by the sieves represents the second selection process to obtain the commercial sized clams. The actual minimum conservation reference size (MCRS) is temporarily set at 22 mm of maximum distance between anterior and posterior margins (length, hereafter) along the Italian coasts (Commission Delegated Regulation 2376/2016; Italian Ministerial Decreee, 27/12/2016), by way of derogation of (European Regulation EU 1967/2006, 2006) that set the MCRS at 25 mm.

The size selectivity of the dredge is primarily dependent on the spacing of metal bars that compose the cage (Sala et al., 2017). The bar spacing of the cage has a minimum width of 12 mm with a tolerance of less than 1 mm, according to the Italian regulation (Italian Ministerial Decreee, 12/22/2000), which is based on dated laboratory experiments with different sieving equipment (Froglia and Gramitto, 1981). While the size selectivity of vibrating sieves currently in use in the Adriatic *C. gallina* fishery has already been assessed (Sala et al., 2017), the first size selection process carried out by the dredge under fishing is practically unknown.

Studies on toothed dredges have established that tooth spacing is of no importance for the selectivity of these dredges, because the tooth bar located in front acts exclusively as a hoe, while mesh bar of the netting bag is responsible for the size selection (Gaspar et al., 2003, 1999). Moreover, Kim et al. (2005) pointed out that a percentage of the total clams caught have not come into contact with the dredge, due to clogging of tooth spacing by the sediments; as a consequence, these clams are not size sorted (Mituhasi et al., 2005). The clogging phenomenon could play an important role also in the selectivity of hydraulic dredges (Sala et al., 2017), where a large amount of material (clams, sand, mud, shells etc.) is usually hauled on board, despite the presence of the washing nozzles. This phenomenon could affect the actual number of clams that physically contact the metal bars of the cage and create the conditions for a size dependent escape process (i.e. the selectivity contact, Olsen et al., 2019). Moreover, Carlucci et al. (2015) suggested that the selectivity of the hydraulic dredge decreases with the increasing of tow duration, as clams larger than the bar spacing accumulate in the bottom of the cage and block the escapement of smaller clams.

Given these premises, the goals of the present study are:

i) to assess the first size selection process of the dredge under fishing with different tow durations.

ii) to estimate the amount of undersized and target-sized striped venus clam retained by the dredge, and the resulting discard ratio, considering both MCRS of 22 and 25 mm.

iii) to investigate the adequacy of the gear configuration currently used from a management point of view.

Materials and Methods

Sea trials and data collection

Sea trials were conducted the 13th of February 2020 on board a commercial fishing vessel (110 kW; LOA 15.82 m; 9.97 GT) in the coastal waters of northern-central Adriatic Sea. The hydraulic dredge had a total weight of 600 kg and dredge mouth was 280 cm wide (Figure 2 A). Bar spacing was on average 11.5 ± 0.6 (s.d.) mm, as obtained from measurement with a calliper at 12 points selected at random. To assess the size selectivity of the dredge, a net sampler (40 cm wide and 18 cm high steel frame) adapted to the dredge height, was fixed inside the dredge mouth (Figure 2 B, C). The net sampler had 12 mm meshes to act as a control, while the remaining portion of the dredge (240 cm wide) was our test. Hauls were carried out close to each other in the same fishing area, to minimize differences due to the patchy distribution of the species (Morello et al., 2005a).

Figure 2. Illustration of hydraulic dredge targeting Chamelea gallina and details of the net sampler used as a control to assess the size selectivity of the dredge: (A) metal cage located at the bow; (B) particular of the steel frame (40 × 18 cm) fixed inside the dredge mouth; (C) lateral view of the net sampler inside the cage; (D) emptying of the net sampler.

The average towing speed was maintained at 1.8 knots, which falls inside the range of the commercial fishing procedures (Romanelli et al., 2009). The haul duration was set at 3, 6 and 9 min, respectively, since the average duration range of commercial hauls was 5-10 min during the sampling period. After each haul, and once being washed from the sediment, shells and other benthonic species, the total catch of *C. gallina* derived from both test and control compartment was weighted.

Before this process, a non – washed subsample of 2.5–3 kg from each compartment had been put aside for following clam measurements. The length measurements were performed by video analysis, according to Stagioni (2010) protocol. Groups of 60–80 individuals of clam sample were consecutively placed on a backlit table to be photographed by a digital camera mounted at a fixed distance above the table. Photographs were processed with ImageJ software (Rasband, 2018) that provides for each clam the *Feret X* parameter, which is the longest distance between any two points along the selection perimeter, thus representing the individual length (Figure 3 B). For each photograph, the central clam was manually measured with the calliper, to calibrate the analysis and minimize any error due to any lens movement or distortion among photographs. The length measurements were performed to an accuracy of 0.2 ± 0.1 mm. Consequently, clams were grouped into 1 mm length classes for each haul in the test and control compartments, respectively.

Finally, a random subsample of around 1000 clams obtained from the previous 2.5–3 kg subsamples and including a wide range of length classes, was taken for determination of length-weight and shell morphometric relationships (length-height, length-width, following Gaspar et al. (2002); Figure 3 A) using a manual calliper (precision of 0.1 mm) and a digital balance (precision of 0.1 g). Length (L)-weight (We) relationship was determined according to the following equation:

$$We = a \times L^b$$

while length-height (H) and length-width (W) relationships were modelled by linear regressions with slope and intercept.

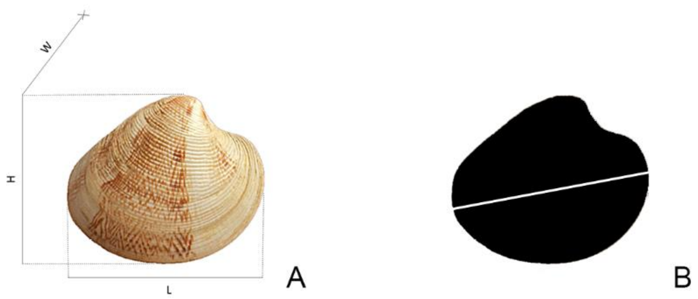

Figure 3. A: Schematic representation of the striped venus clam shell measurements. H: height; L: length; W: width. B: Example of photograph processing with ImageJ software, that provides the Feret X (white line), which is the longest distance between any two points along the selection perimeter, thus representing the individual length (L).

Size selectivity analysis

The catch data (i.e. the numbers of clams of each length class obtained from the video analysis for each compartment and haul, and the associated subsampling ratios) were used for the size selectivity analysis.

Data were analysed using the method described below, which was implemented in the software tool SELNET (Herrmann et al., 2012). The catch data from test and control were collected in pairs. Therefore, it was realistic to assume that both compartments of the dredge were fishing a population of clams with the same size distribution. The catch data from individual hauls were analysed separately for the three tow durations (3, 6, 9 min), and the paired gear estimation method (Wileman et al., 1996) was applied to the data pooled over hauls to determine the average size selectivity of the test compartment for each tow duration. Thus, the average size selectivity of the test was estimated by minimizing the following equation:

$$-\sum_l \sum_{i=1}^{m} \left\{ \frac{nT_{li}}{qT_i} \times ln\left(\frac{SP \times r(l,\boldsymbol{v})}{SP \times r(l,\boldsymbol{v}) + 1 - SP}\right) + \frac{nC_{li}}{qC_i} \times ln\left(1.0 - \frac{SP \times r(l,\boldsymbol{v})}{SP \times r(l,\boldsymbol{v}) + 1 - SP}\right) \right\} \qquad (1)$$

where nT_{li} and nC_{li} represent the number of clams of each length class l retained and length measured in the i^{th} haul for the test and control, respectively. qT_i and qC_i represent the fractions of the catch in haul i that were length measured for the test and control, respectively (i.e. the subsampling ratio). m represents the total number of hauls for the specific duration. *SP* is the split parameter that quantifies the sharing of the total catch between the test and the control, and $\boldsymbol{v}$ is a vector of parameters in the size selection model $r(l,\boldsymbol{v})$. Differences in the entrance of clams between test and control compartments will be reflected in the value of *SP*, and therefore will not bias the estimation of the size selectivity $r(l,\boldsymbol{v})$ for the test. In fact, high *SP* values are expected in case of a marked difference between the areas of the two compartments. In the present experimental design, the *SP* can be calculated as a ratio between the width of the test and the width of the test + control (240 / 280 = 0.86). Minimizing the expression (1) is equivalent to maximizing the likelihood for the experimental data based on a formulation of the negative log-likelihood for binominal data.

Since the dredge is made up of a single bar spacing, the size selection carried out by the test compartment would traditionally be described by the standard *Logit* model (Wileman et al., 1996):

$$r(l,\boldsymbol{v}) = r_{Logit}(l,\boldsymbol{v}) = \frac{exp\left(\frac{ln(9)}{SR} \times (l - L50)\right)}{1.0 + exp\left(\frac{ln(9)}{SR} \times (l - L50)\right)} \qquad (2)$$

$$\boldsymbol{v} = (L50, SR)$$

Where *L50* is the length of a clam with 50% probability of being retained, given it has entered the test, whereas *SR* is the difference in length of clams having respectively 75% and 25% probability of being retained by the test, conditioned they entered it. Model (2) assumes that every clam that enters the test compartment is size selected by the bar spacing before the dredge is retrieved on board the fishing vessel. However, a fraction of all clams entering the test may not be size sorted, for example due to the clogging of the dredge. Therefore, instead of modeling the size selection based only on the Logit model (2), we also considered the *CLogit* model (3), which can account for the possibility that only a fraction C of the clams entering the test compartment makes contact with the bar spacing and is subjected to a size selection process (Herrmann et al., 2013):

$$r(l, \boldsymbol{v}) = r_{CLogit}(l, C, L50_c, SR_c) = (1 - C) + C \times Logit(l, L50_c, SR_c) = 1.0 - \frac{C}{1.0 + exp\left(\frac{ln(9)}{SR_c} \times (l - L50_c)\right)} \quad (3)$$

Where $L50_c$ and SR_c account only for the clams that make selectivity-contact with the bar spacing. The parameter *C* holds a constant value that ranges between 0.0 (no clams make selectivity-contact with the bar spacing) and 1.0 (all clams entering the test make selectivity-contact with the bar spacing). When $C = 1.0$, the *CLogit* model simplifies to the traditional *Logit* model.

Estimation of the average size selection with a *CLogit* model requires finding the values for the parameters *C*, $L50_c$, SR_c, and *SP* that minimize (1), conditioned by the collected catch data. Knowing the values of contact selectivity parameters $L50_c$ and SR_c is important to evaluate whether dredge bar spacing is appropriate for the desired selection pattern in the fishery.

Based on $L50_c$, SR_c and *C*, the available selection parameters $L50_a$ and SR_a, which account for all the clams entering the test compartment, are calculated using the procedure presented in Herrmann et al. (2013):

$$\begin{aligned} L50_a &= L50_c + \frac{SR_c \times ln(2 \times C - 1)}{ln(9)} \\ SR_a &= \frac{SR_c \times ln\left(3 \times \frac{(C - 0.25)}{(C - 0.75)}\right)}{ln(9)} \end{aligned} \quad (4)$$

Here, SR_a becomes undefined if $C < 0.75$, as the retention probability cannot then reach a value as low as 0.25. Contrary to contact selectivity parameters, $L50_a$ and SR_a incorporate the effect that not necessary all clams get size selected by the dredge bar spacing; knowing their values also has importance.

The ability of the size selection models (*Logit* and *CLogit*) to describe the experimental data was evaluated based on the p-value, which expresses the probability of obtaining by chance alone at least as big a discrepancy between the experimental data and the model as observed, assuming that the model is correct, and based on the model deviance versus the degrees of freedom (DOF). However, in situations of strong subsampling and pooled data (as in our case), the p-value could be < 0.05, that is the lower limit for the selection model to describe the experimental data sufficiently well (Wileman et al., 1996), and the ratio deviance / DOF could be >> 1. With poor fit statistics, the residuals were visually inspected to determine whether the poor result was due to structural problems when modeling the experimental data, or overdispersion in the data (Wileman et al., 1996). In addition, the models were evaluated by plotting the fitted curves against the experimental length-dependent retention rates, to visually check if the curves reflected the main trend in the experimental data.

The size-selection models were compared using the Akaike information criterion (AIC; Akaike, 1974), with the lowest-value model subsequently selected.

We estimated the uncertainties for each size selection curve and the associated selection parameters resulting from the three tow durations. Specifically, confidence limits were estimated using a double bootstrap method for paired data. This method accounted for between-haul variation in the dredge size selection, by selecting m hauls with replacement from the pool of hauls for the specific tow duration. Within each resampled haul, an inner bootstrap was used on data for each length class, to account for the uncertainty in the haul, due to a finite number of clams being caught and length measured (i.e. within-haul variation). This inner resampling was performed prior to the raising of the data with subsampling factors qT_i and qC_i, to avoid underestimation of the uncertainty derived by subsampling (Eigaard et al., 2012). The resulting dataset obtained from each bootstrap repetition was analysed as described above. Based on the bootstrap results, we estimated the Efron percentile 95% confidence intervals (CIs; Efron, 1982) for both the selection curve and the selection parameters. We performed 1000 bootstrap repetitions.

To examine differences between the selection curves, quantified as the difference (Delta) in retention probability, we used a method based on separately obtained bootstrap files. This method is described in Larsen et al. (2018). Specifically, the potential effect of changing from tow duration *Y* to another *Z* on the dredge size selection curve *r(l)* was estimated by:

$$\Delta r(l) = r_Z(l) - r_Y(l) \quad (5)$$

Where $r_Y(l)$ represents the selection curve obtained for *Y*, and $r_Z(l)$ represents the selection curve obtained for *Z*. The Efron percentile 95% *CIs* for $\Delta r(l)$ were obtained based on the two bootstrap populations of results (1000 bootstrap repetitions in each) for both $r_Y(l)$ and $r_Z(l)$. As they were obtained independently, a new bootstrap population of results was created for $\Delta r(l)$ by:

$$\Delta r(l)_i = r_Z(l)_i - r_Y(l)_i \;\; i \in \; [1 \dots 1000] \qquad (6)$$

Where *i* denotes the bootstrap repetition index. As the bootstrap resampling was random and independent for the two groups of results, it is valid to generate the bootstrap population of results for the difference based on (6), by using the two independently generated bootstrap files (Herrmann et al., 2018). Based on this bootstrap population, the Efron percentile 95% *CIs* were obtained for $\Delta r(l)$ as described above. If these *CIs* contained the value 0.0 for all *l* then no significant difference between the selection curves was detected.

In case of lack of significant differences among the selection curves derived from the three tow durations, catch data obtained from all the hauls were pooled, and an additional double bootstrap method with 1000 repetitions was applied to determine a single selection curve with 95% *CIs* and associated selection parameters.

The density function d_l of the size structure of the population present at seabed contacting the gear was estimated, from the clams collected in the control compartment of the dredge, by:

$$d_l = \frac{\sum_{i=1}^{m}\left\{\frac{nC_{li}}{qC_i}\right\}}{\sum_l \sum_{i=1}^{m}\left\{\frac{nC_{li}}{qC_i}\right\}} \qquad (7)$$

The estimation by (7), incorporated into the double bootstrap method described above, allowed us to obtain the Efron percentile 95% *CIs* for this density function and a population of bootstrap results for it. The latter was then applied by multiplying it with the population of bootstrap results for the dredge selection curve, also to obtain an estimate for the retained proportion of the population entering the dredge, together with its 95% *CIs*. This method is identical to the one described in Melli et al. (2020). Last, we used the result for the retained population to calculate the proportion out of the total population of clams retained, also considering the clams under and above the MCRS (both 22 mm and 25 mm), and the resulting discard ratio (in number and weight). This last step in the analysis also followed the procedure described in Melli et al. (2020).

Results

Catch data

A total of 18 hauls (6 for each tow duration) were carried out; the number of clams measured for each haul and each compartment, together with the subsampling ratio from the total catch, are listed in Table 1. The length-weight (*L – We*) and shell morphometric regression parameters (*L – H; L - W*) are represented in Table 2; *a* and *b* values were used in the selectivity results section below.

Table 1. Number of hauls carried out in the selectivity experiments, with the number of clams (Nr) measured and the subsampling ratio (in parentheses).

Haul	**Duration (min)**	**Nr in dredge (Test)**	**Nr in net sampler (Control)**
1	3	615 (0.03)	434 (0.13)
2	3	586 (0.03)	349 (0.12)
3	3	598 (0.03)	464 (0.11)
4	3	553 (0.03)	390 (0.11)
5	3	564 (0.03)	332 (0.11)
6	3	604 (0.07)	171 (0.12)
7	6	648 (0.02)	354 (0.08)
8	6	655 (0.02)	523 (0.08)
9	6	553 (0.01)	334 (0.06)
10	6	599 (0.03)	391 (0.06)
11	6	453 (0.02)	423 (0.06)
12	6	589 (0.03)	438 (0.08)
13	9	659 (0.02)	307 (0.05)
14	9	546 (0.01)	458 (0.07)
15	9	635 (0.01)	268 (0.07)
16	9	476 (0.01)	440 (0.07)
17	9	422 (0.01)	379 (0.07)
18	9	364 (0.01)	157 (0.11)

Table 2. Summary of the length-weight and morphometric relationships derived from individuals of Chamelea gallina collected during the sea trials.

Relationship	**Model**	**Nr of measured clams**	***a***	***b***	**Adjusted R^2**	**std error *a***	**std error *b***	**p-value**
Length - Weigth	We = a*L^b	1155	0.308	2.875	0.987	0.016	0.010	< 0.001
Length - Heigth	H = a + b*L	765	0.827	1.152	0.984	0.004	0.093	< 0.001
Length - Width	W = a + b*L	765	0.426	0.906	0.937	0.004	0.097	< 0.001

Size selectivity results

A comparison of the AIC values obtained for the *Logit* model (1) and the *CLogit* model (2) revealed that the latter better described the experimental size selectivity data for each tow duration (Table 3). These results confirmed our hypothesis that a percentage of clams did not make contact with the bar spacing of the cage and therefore were not subject to a size selection process. Consequently, the *CLogit* model was selected to describe the experimental data.

Table 3. Value of AIC (Akaike information criterion) for the Logit and CLogit models for each tow duration.

	AIC		
	3 min	**6 min**	**9 min**
Logit	103479.9	186016.4	192884.3
CLogit	103239.4	185941.8	192587.2

The *p*-values were always below 0.05. However, the inspection of the modeled curves against the experimental rates did not indicate any length dependent patterns in the deviations (Figure 4 A, C, E). Therefore, we assumed that the low p-values were due to overdispersion in the experimental rates rather than a lack of fit.

The selectivity curves with *CIs* are represented in Figure 4 B, D, F, and their associated selectivity parameters and fit statistics are summarized in Table 4. It was observed that the expected *SP* fell within the *SP CIs* estimated for 3 and 6 min duration, but not for 9 min duration (Table 4).

The average *C* was estimated to be 0.70 for 3 min hauls, 0.86 for 6 min hauls and 0.78 for 9 min hauls; it was significantly below 1.0 only for 3 min hauls (Table 4).

$L50_a$ and SR_a accounted for the available selectivity, i.e. considering all the clams entering the dredge, while $L50_c$ and SR_c reflected the selectivity only for those clams that effectively made contact with the dredge; the latter parameters have higher values than the former, as expected (Table 4). Moreover, the lower *CIs* of SR_a were never estimated because of *C* being lower than 0.75 that did not allow the model to define a *L25*.

*Table 4. Selectivity parameters and fit statistics from the CLogit model. SP: split parameter. C: contact parameter. L50a and SRa (Selection Range): selection parameters considering all the clams (available selectivity). L50c and SRc: selection parameters considering only the clams that effectively make contact with the dredge. DOF: degree of freedom. *: undefined. Values in parentheses indicate the Efron 95% confidence intervals.*

	SP	**C**	**$L50_a$**	**SR_a (mm)**	**$L50_c$**	**SR_c**	**p-value**	**Model deviance**	**DOF**
3 min	0.87 (0.85-0.90)	0.70 (0.58-0.95)	19.11 (17.72-20.56)	* (*-9.45)	20.13 (18.54-21.59)	2.38 (0.1-6.42)	0.02	48.79	24
6 min	0.86 (0.80-0.90)	0.86 (0.60-1.00)	17.54 (15.09-20.73)	5.67 (*-8.50)	18.19 (15.15-21.22)	4.49 (0.39-8.28)	<0.01	109.36	23
9 min	0.92 (0.90-0.95)	0.78 (0.61-1.00)	19.17 (16.91-22.32)	6.17 (*-10.10)	20.07 (17.03-23.39)	3.41 (0.1-8.8)	<0.01	64.35	23
pooled data	0.89 (0.86-0.92)	0.75 (0.62-0.92)	18.92 (17.65-20.36)	* (*-9.13)	19.91 (18.58-21.19)	3.04 (1.24-6.78)	<0.01	109.47	24

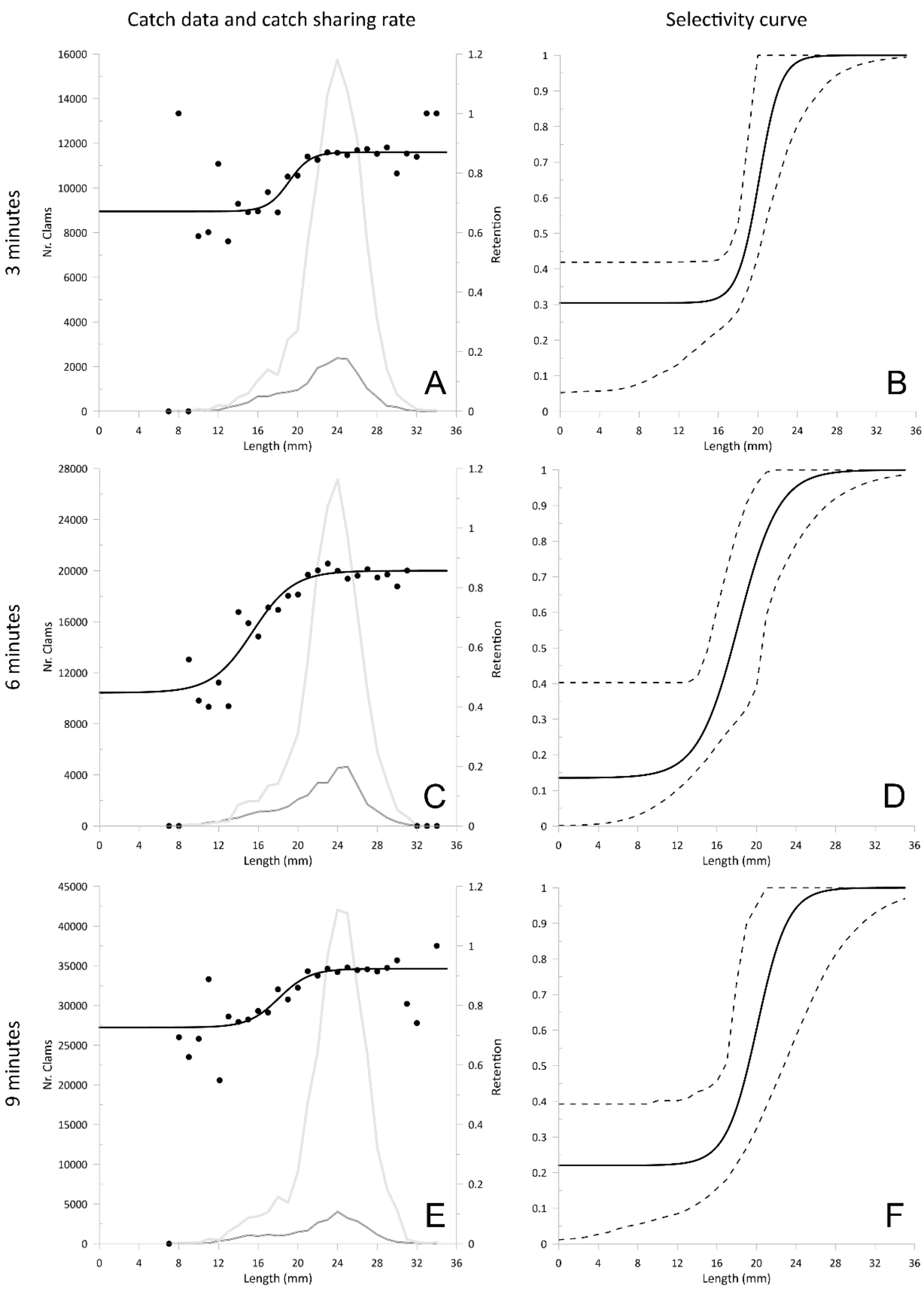

Figure 4. Selectivity representation of the three different haul durations: the left column (A, C, E) shows the size distributions of the clams caught with the test (i.e. dredge; light grey) and control (i.e. net sampler; dark grey) together with the experimental retention data obtained (black dots) and the CLogit curve (black line). The right column (B, D, F) shows the size selectivity curve (full line) with confidence intervals (dashed lines).

No significant differences between the selection curves for the three haul durations were detected, since the *CIs* for the curves in the delta plot contained 0.0 in all cases (Figure 5 B, D, F).

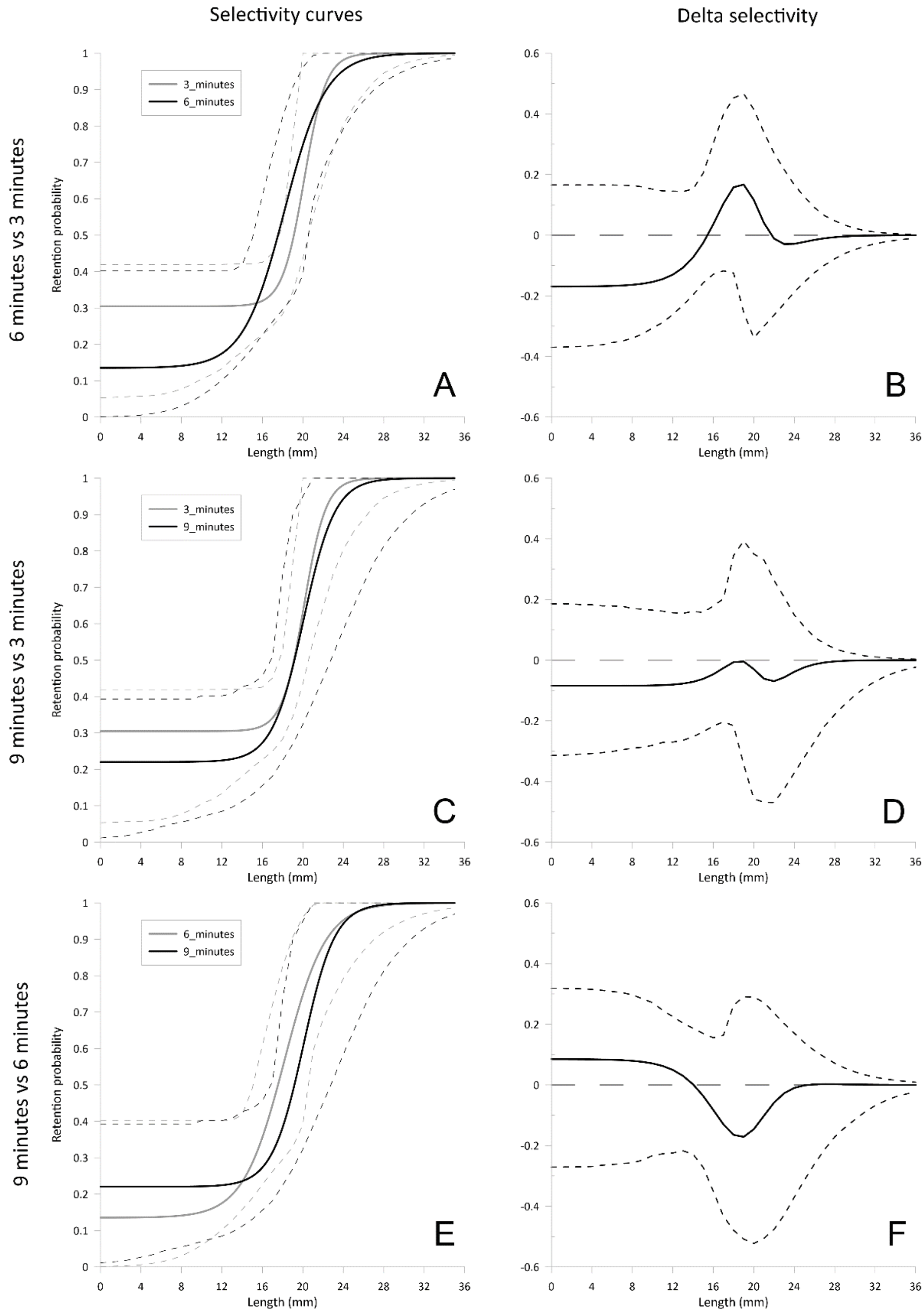

Figure 5. Comparisons between the different haul durations: the left column (A, C, E) shows the selectivity curves (black and grey full lines) with confidence intervals (dashed lines). The right column (B, D, F) shows the differences between the two selectivity curves compared (delta plot).

Therefore, we subsequently applied the *CLogit* model to the pooled data considering all the 18 hauls, regardless of the tow duration. The resulting selectivity curve with *CIs* derived from the double bootstrap is represented in Figure 6, and the associated estimated parameters are listed in Table 4. On average, *C* was 0.75 and *SP* 0.89; $L50_a$ was 18.92 mm, while $L50_C$ and SR_C were 19.91 and 3.04 mm, respectively.

The regression parameters derived from the shell morphometric relationships were used for checking the maximum height and width that allowed a clam to pass through the average bar spacing of the gear (11.5 mm), since the escape process mainly depends on the clam orientation in these two sides of the shell. We demonstrated that the interval between these two measures (vertical red lines, Figure 6) is perfectly included into the size selection range of the selectivity curve. On the contrary, clams with a height lower than bar spacing were able to escape through both the orientations, while clams with a width higher than bar spacing could not pass in any way through the metal bars of the cage.

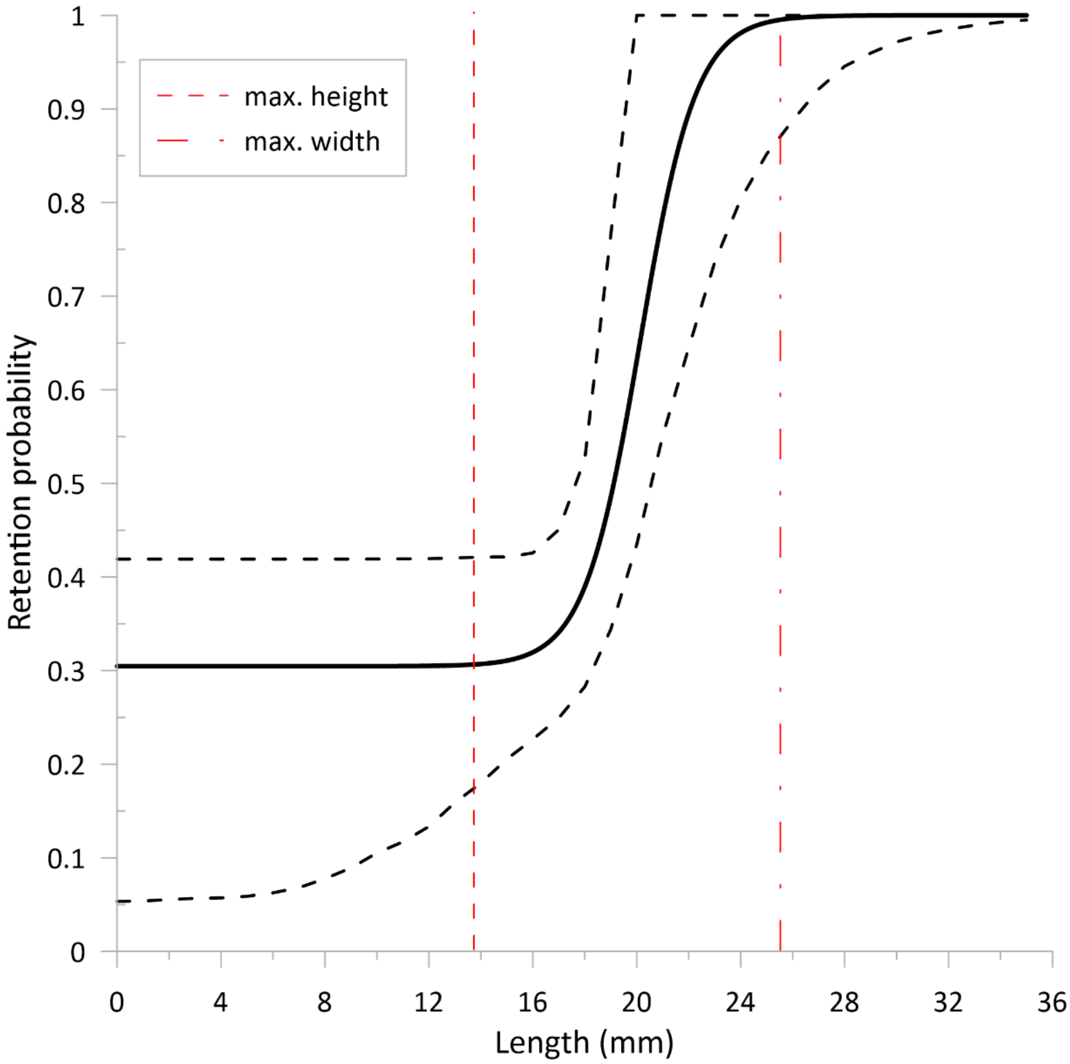

Figure 6. Selectivity curve for the pooled data (black full line) with confidence intervals (stippled lines). The two vertical red lines show the maximum height and width that allowed a clam to pass through the average bar spacing of the gear (11.5 mm), since the escape process mainly depends on the clam orientation in these two sides of the shell.

The size structures of both the total population encountered and the population retained by the dredge are represented in Figure 7, with vertical red lines representing the actual (22 mm) and the previous (25 mm) MCRS.

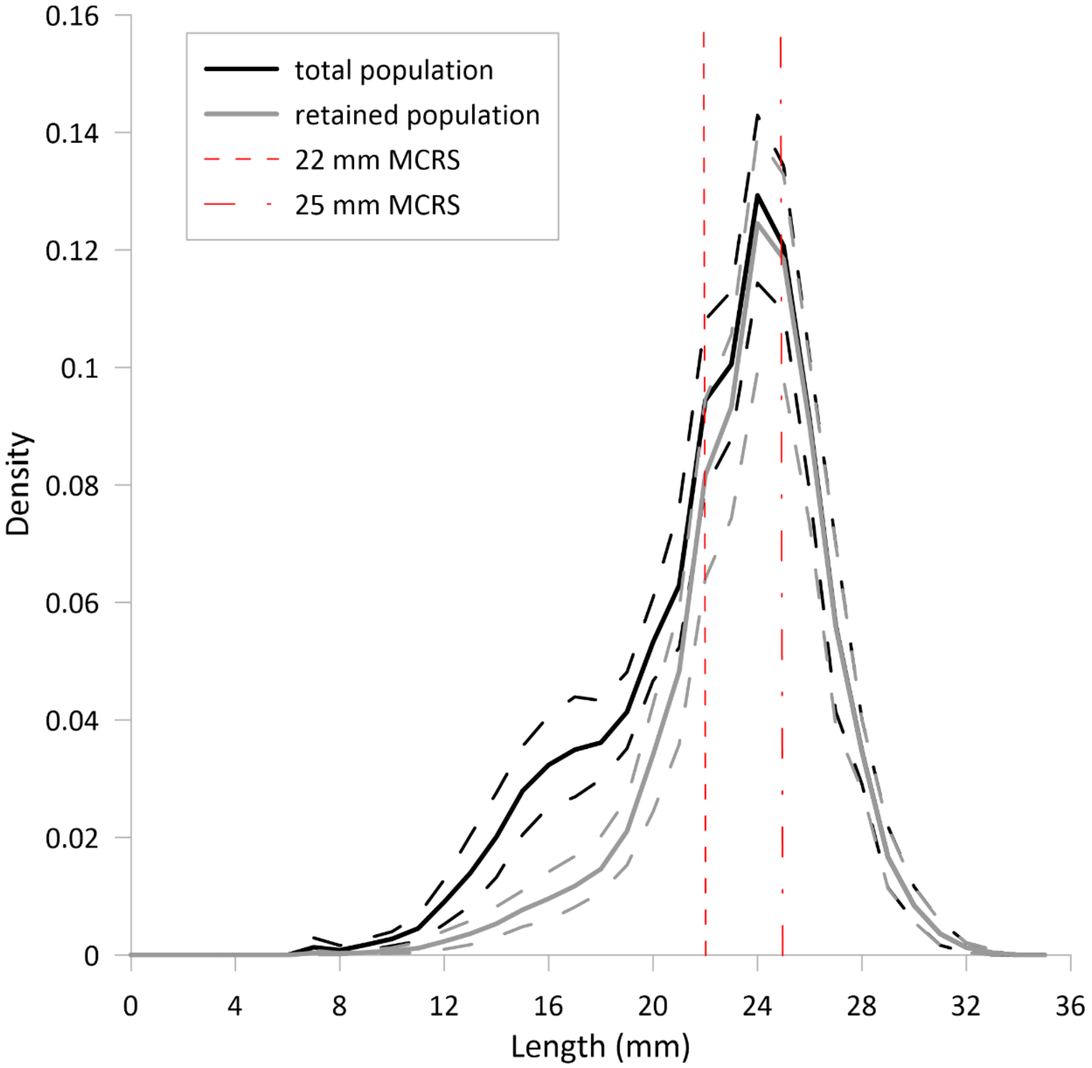

Figure 7. Density functions of the size structure of the population present at seabed contacting the gear (black full line), and of the effective population retained by the dredge (grey full line). Both curves are represented with confidence intervals (dashed lines). The two vertical red lines show the actual (22 mm) and the previous (25 mm) MCRS.

The respective proportions of clams caught by the dredge (test compartment) out of the total population contacting the gear (control compartment) are listed in Table 5. Overall, the dredge had a great catch efficiency, being able to retain, on average, 78.99% in number (*Nr*) and 89.37% in weight (*We*) of the total population of clams encountered. Moreover, the average percentages of undersized clams retained decreased from 69.03 to 46.98% (*Nr*) and from 79.73 to 54.43% (*We*) when lowering the MCRS from 25 to 22 mm. On the contrary, while the average percentage of the oversized clams retained was almost 100% (*Nr* and *We*) considering the 25 mm MCRS, it decreased to around 96%

(*Nr* and *We*) if we considered the 22 mm MCRS (Table 5). Finally, the clams discard ratio fell from 58.32% to 20.41% (*Nr*) lowering the MCRS from 25 to 22 mm, and this difference was more pronounced using the percentages in weight (from 44.78% to 10.40%), because of the nonlinear length-weight regression.

Table 5. Percentages of both total clams and clams below and above MCRS (22 and 25 mm), caught by the dredge (test compartment) out of the total population encountered (control compartment), and the subsequent discard ratio (in number Nr and weight We). Values in parentheses indicate the Efron 95% confidence intervals.

%	22 mm		25 mm	
	Nr	**We**	**Nr**	**We**
Total	78.99 (64.46-85.88)	89.37 (74.91-94.34)	78.99 (64.46-85.88)	89.37 (74.91-94.34)
Below MCRS	46.98 (35.68-58.29)	54.43 (40.70-66.90)	69.03 (56.83-81.24)	79.73 (62.09-88.36)
Above MCRS	95.72 (79.70-99.71)	96.56 (82.13-99.79)	98.98 (87.86-100.00)	99.08 (88.42-100.00)
Discard ratio	20.41 (17.21-23.82)	10.40 (8.65-12.19)	58.32 (55.07-61.25)	44.78 (41.59-47.67)

Discussion

Scientific studies on the benthic impact, discards, and selectivity of the hydraulic dredge should be given priority for management purposes in the striped venus clam fishery. The impact of hydraulic dredging on the benthic community is well discernible (Morello et al., 2006; Vasapollo et al., 2020), although the species belonging to these soft bottoms are already naturally adapted to constant environmental stress and exceptional phenomena (in particular, significant wave movements, strong currents). The proportion of discards (small clams and other species) produced by this fishery is estimated to be high, reaching almost 50% of total catch, with 30% of which is composed of small individuals of *C. gallina* (Morello et al., 2005b). Regarding the selectivity, the first size selection process carried out by the dredge during trawl under commercial conditions had never been explored, contrary to that of the vibrating sorting sieves (Sala et al., 2017). The present study represents the first, to our knowledge, to fill this gap, through assessing the selectivity of the gear at different haul durations.

The analyses demonstrated that a clogging phenomenon occurred in the dredge, as it was hypothesized by Carlucci et al. (2015) and Sala et al. (2017) because not all the clams caught had come into contact with the metal bars of the cage, thus not creating the conditions for a size dependent escape process to occur. We applied this selectivity contact concept through the *CLogit* model, which provided a better fit to the data than the traditional Logit model, after comparing the AIC values obtained. The *CLogit* model allowed us to calculate the fraction *C* of the striped venus clams that were effectively size sorted.

The causes of clogging could be multiple: presence of thickened sand and mud that are not suspended by the pressure water jets; presence of large amounts of shells and other benthonic organisms (non-target molluscs, polychaetes, crustaceans and sea urchins; Morello et al. (2005a, b, 2006)); presence of large quantities of the target species which gradually accumulate in the cage. Contrary to what suggested by Carlucci et al. (2015), the increasing of the tow duration (from 3 to 6 and 9 min) did not have significant effect neither on *C* nor on selectivity parameters (*L50* and *SR*, respectively). Although selectivity is not supposed to change within the range of the durations tested, the results could be different for longer hauls (> 15 min), which are carried out occasionally due to several reasons, such as favorable fishing conditions (i.e. optimal sediment type and sea conditions) or scarce availability of the resource (DGPEMAC, 2019).

Both the $L50_a$ and $L50_C$ values reported for the pooled data (considering all the 18 hauls) were below the actual MCRS of 22 mm. These results underline that it is not sufficient to carry the selection on the seabed, and stress the importance of the additional size selection process carried out on board by the sorting sieves. Sala et al. (2017) demonstrated that it is possible to obtain a satisfactory selection (low values of the SR and almost knife-edge logistic curve) using specific hole diameters on the grids composing the sieves, which can be changed according to the MCRS set for the species. Although the sorting sieves are potentially able to ensure less than 5% retention of undersized individuals (Sala et al., 2017), the high proportion of the small clams that are returned to the sea after the mechanical sorting could be subjected to physiological stress (Morello et al., 2005b), and physical damage (Moschino et al., 2003). Nevertheless, clams show high potential of survivability after fishing operations (STECF, 2020), but the high and prolonged fishing effort on the same grounds (multiple criss-crossed trawl marks on bottoms; Lucchetti and Sala, 2012) should not be overlooked, as clams may be harvested up to 20 times a year (Morello et al., 2005b). According to Ballarin et al. (2003), this repeated disturbance caused by dredging may weaken the undersized clams, making them more susceptible to pathogens, predators and environmental stressors.

In this respect, our findings showed that when the 22 mm MCRS is applied, the percentage of the undersized clams caught, and thus the discard ratio, markedly decreased from the situation with the 25 mm MCRS applied. As a consequence, the temporary reduction of the MCRS along the Italian coasts (Commission Delegated Regulation 2376/2016) would lead to a lesser fishing time spent to reach the daily quota of 400 kg of target-sized clams per each fishing vessel (DGPEMAC, 2019), and thus a decreased number of times a given area is swept. Therefore, a reduced impact on the associated benthic community and generally on the seabed is expected, thus favoring the recovery (Vasapollo et al., 2020).

The reduction of the MCRS is not incompatible with the length of first maturity (LFM) of about 15–17 mm, that is reached by the species in the first year of life, as stated for Atlantic Ocean (Gaspar et al., 2004), Marmara Sea (Deval, 2001) and Adriatic Sea (Bargione et al., 2020). Therefore, a clam of 22 mm, which is around 2 years old, has already theoretically had the chance to reproduce. Despite this, the scientific community, together with the fishing sector, aim to bring the MCRS back to 25 mm in the next future (DGPEMAC, 2019). In fact, larger clams have a greater reproductive capacity, which guarantee a larger recruitment and a stronger population size structure (Delgado et al., 2013), and have a higher economic value that leads to a more competitive product on the market (Spagnolo, 2007).

Considering the LFM, the results here displayed for the selectivity of the dredge showed that the gear seems to be able to avoid the catch of the smallest immature individuals. Nevertheless, the average total catch efficiency of the gear found in this study is very high, and in line with other works (80–100 %; Romanelli et al., 2009). To reduce direct and indirect mortality of the undersized clams due to mechanical sieving, Scarcella and Cabanelas (2016) suggested to improve the hydraulic dredges selectivity through increasing the width between the bars of the cage. However, further works are needed to determine how the selectivity changes with the increasing of bar spacing. The possible outcomes, together with the results presented in this paper, could be used for updated limitations regarding bar spacing, since at present the regulation is supported by dated scientific studies carried out with sorting equipment in the laboratory (Froglia and Gramitto, 1981), without reflecting the actual selection process at seabed.

Future works should also include other additional factors that are known to affect dredge selectivity, such as the technical properties of the dredge (blade length and angle, dredge weight, water pressure on the nozzles), other operational factors than tow duration (i.e. towing speed) and environmental conditions (sea state, type of sediment).

Author contributions

AL, MV and AP conceived and performed research; MV and AP collected data; AP and BH analysed data; AP wrote the paper with support of BH, MV, AL, GB and CV. AL was the scientific responsible of the research.

Data availability

The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request.

Declaration of Competing Interest

The authors report no declarations of interest.

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Paper V

Pots vs trammel nets: a catch comparison study in a Mediterranean small-scale fishery

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Pots vs trammel nets: a catch comparison study in a Mediterranean small-scale fishery

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Abstract

Passive bottom-set nets are the most widely used fishing gears in Mediterranean small-scale fisheries (SSFs). Trammel nets, in particular, have key advantages such as their ease of use and handling and high capture efficiency for numerous commercial species. However, they entail high discard rates (5-44% of the total catch) connected to high mortality, thus exerting an adverse impact on benthic communities, besides catching individuals of commercial species under the minimum conservation reference size (MCRS) and specimens of protected species. Fish pots are seen as alternative and a more sustainable gear type that allow reducing discards in SSFs. In this study, a collapsible pot was tested at three coastal sites in the north-western Adriatic Sea (GFCM GSA 17) to compare its catch efficiency of commercial species with that of the local traditional trammel nets. Data analysis demonstrated a similar catch efficiency for the commercial species, both among sites and as a whole. Moreover, the trammel net caught a larger amount of discards, both in terms of species number and of $CPUE_W$. The catch comparison study involved the two most abundant landed species, common cuttlefish *Sepia officinalis* and annular sea bream *Diplodus annularis*. The pots were more effective for *S. officinalis*, whereas the trammel net was more effective for the shorter length classes for *D. annularis*, which were mostly under the MCRS (12 cm). The innovative pots could provide a

valuable alternative to the trammel nets traditionally used in the Adriatic Sea, at least in certain areas and periods. Their main advantages include that they do not require a different rigging and they can be used without bait, while their foldable design allows large numbers to be easily loaded on board SSF vessels. The results of this pilot study indicate that pots can achieve the objectives of reducing discards and bycatch in SSFs without penalizing the catch of commercial species.

Keywords

Alternative fishing gears, Small-scale fisheries, Fish pots, Experimental pot, Discard reduction, Catch comparison, Mediterranean sea, Sustainable fishery, Passive gears, Set nets

Introduction

Gillnets and trammel nets (or set/passive nets) are the most widely used fishing gears in Mediterranean small-scale fisheries (SSFs) (Lucchetti et al., 2015), which account for more than 70,000 vessels (FAO, 2018) and approximately 150,000 jobs. Set nets consist of netting panels hanging in the water column, where they are held perpendicular to the bottom by floaters and sinkers. Bottom-set fixed nets passively exploit the movements of target species (Gabriel et al., 2005). The fish swimming into them are caught by being gilled, tangled or wedged in gillnets, which are constituted of a single netting panel. On the contrary, the typical catching method of trammel nets is trapping the fish in a pocket of netting thanks to three panels: an inner panel with small mesh size and two outer panels with larger mesh size (Fabi et al., 2002). The success of the passive nets is due to their ease of use and handling (especially on small boats) (Dinçer & Bahar, 2008), high selectivity (especially gillnets) (Holt, 1963; Fabi et al., 2002) and their high capture efficiency for numerous commercial species (Amengual-Ramis et al., 2016). Their technical parameters, for example, mesh size, netting twine, hanging ratio and net drop, vary widely in relation to the characteristics of target species and fishing areas (e.g., depth, seafloor), as do their selection properties (Stergiou et al., 2006; Lucchetti et al., 2017a). Although passive nets are considered as selective gears, they nonetheless produce a large amount of discards (Goncalves et al., 2007; Tzanatos et al., 2007) that range from 5% to about 40% of the total biomass caught (Tsagarakis, Palialexis & Vassilopoulou, 2014). SSFs discards consist of species with low commercial value, individuals that are found in poor condition and specimens under the minimum conservation reference size (MCRS; Regulation EU, 2019). The proportion of undersized individuals in the catch is variable and for some commercial species it can be quite high (20% for *Sparus aurata*, 28.2–74.8% for *Diplodus* spp., 93.8% for *Pagellus acarne* in the eastern Mediterranean, Tzanatos et al. (2008); large numbers of *Diplodus bellottii*, *Argyrosomus regius* in Cadiz and *Diplodus* spp., *Pagrus pagrus* in the Cyclades, Goncalves et al. (2007)). Notably, species that are caught in excessively small amounts for the fishers' target market may also become discards (Goncalves et al., 2007). Moreover, set nets can be also responsible for the incidental catch of protected species such as sea turtles (Lucchetti & Sala, 2010; Casale, 2011; Lucchetti, Vasapollo & Virgili, 2017a, 2017b) and elasmobranches with no economic value (Morey et al., 2006; Saidi, Enajjar & Bradai, 2016; Bradai, Saidi & Enajjar, 2018).

The reduction of discards and bycatch has become a priority for fisheries worldwide, by means of measures to improve selectivity and to preserve the environment (FAO, 2011). The Common Fishery Policy, through the article 15 of Regulation EU (2013), calls for the development of more selective technical solutions, to avoid the catch of unwanted species and sizes. Several solutions are being tested in the Mediterranean. They include: (i) gear modifications to improve size and species selection (Lucchetti et al., 2015, 2017a); (ii) time/area fishing closures to minimize bycatch (Lucchetti, Vasapollo & Virgili, 2017b); (iii) mitigation devices to avoid catching some protected species (e.g., UV lights for sea turtles; Virgili, Vasapollo & Lucchetti, 2017); and (iv) alternative and more sustainable fishing gears (Amengual-Ramis et al., 2016).

As regards the latter point, experimental pots developed in the past few years in certain areas have ensured catch efficiencies comparable to those of traditional set nets (Furevik & Hågensen, 1997; Iskandar et al., 2006; Furevik et al., 2008; Königson et al., 2015; Amengual-Ramis et al., 2016). Pots are passive gears to which fish, crustaceans and molluscs are attracted by bait or pasture, whereas cephalopods are caught because use them as a refuge or a site to spawn. Pots have several appealing features—in particular a minimal habitat impact and low manufacturing cost—which have led them to be classified as LIFE (low-impact fuel-efficient) gears (Suuronen et al., 2012). Moreover, bycatch can be minimized by acting on bait, mesh size, materials, and position/design of the entrance and the escape gap(s) (Furevik & Løkkeborg, 1994; Furevik & Hågensen, 1997; Boutson et al., 2009).

In Mediterranean SSFs traditional pots are locally employed to target molluscs and crustaceans (Grati et al., 2010; Amengual-Ramis et al., 2016), ensuring high catch efficiency and low discard rates (0.8–6.6%; Fabi et al., 2001). They are usually deployed in specific seasons (e.g., the spawning period of *Sepia officinalis*, Melli et al., 2014), in circumscribed areas (e.g., north western Adriatic Sea for *Squilla mantis*, Grati et al., 2018; Gulf of Càdiz (Spain), Thracian Sea (Greece) and Gulf of Gabès (Tunisia) for *Octopus vulgaris*, Ezzeddine-Najai, 1992; Tsangridis, Sánchez & Ioannidou, 2002; Sobrino et al., 2011), or in replacement of other gears (e.g., for *Nephrops norvegicus* during trawl fishing closures in Croatian northern Adriatic waters, Brčić et al., 2018). A major disadvantage of traditional pots is their large volume, which entails that vessels can carry only a limited number of units per trip.

In the Mediterranean Sea, studies of alternative fishing gears such as innovative pots are still limited (ICES, 2008, 2009; Pol, He & Winger, 2010) and mainly regard those targeted to cephalopods like *O. vulgaris* (Sbrana et al., 2008) and crustaceans such as *N. norvegicus*, *Plesionika* spp. (Colloca, 2002; Sartor et al., 2006) and *Palinurus elephas* (Amengual-Ramis et al., 2016).

Based on these considerations, a pilot study was devised to test a fully collapsible pot design and to compare it to a traditional set net in commercial fishing conditions. The main goals of the study were to evaluate the respective catch compositions and to assess the effectiveness of the pots in terms of their use and handling, discards and bycatch reduction.

Materials and Methods

Study area

The pilot study was conducted in FAO Geographical Sub-Area 17 (north-western Adriatic Sea) and involved three coastal areas (Marina di Ravenna, Portonovo and Senigallia), where depth ranges from 5 to 19 m (Figure 1). Specifications of bottom type and average depth of the three sites are listed in Table 1. In these areas, SSFs mostly employ gillnets and trammel nets to catch cuttlefish (*S. officinalis*), various fish species (e.g., *Solea solea, Lithognathus mormyrus, Diplodus* spp., *S. aurata, Sciaena umbra, Umbrina cirrhosa, Dicentrarchus labrax*) and crustaceans (*S. mantis, Paeneus kerathurus*) (Fabi & Grati, 2005). Moreover, artisanal pots are deployed in spring to specifically target cuttlefish.

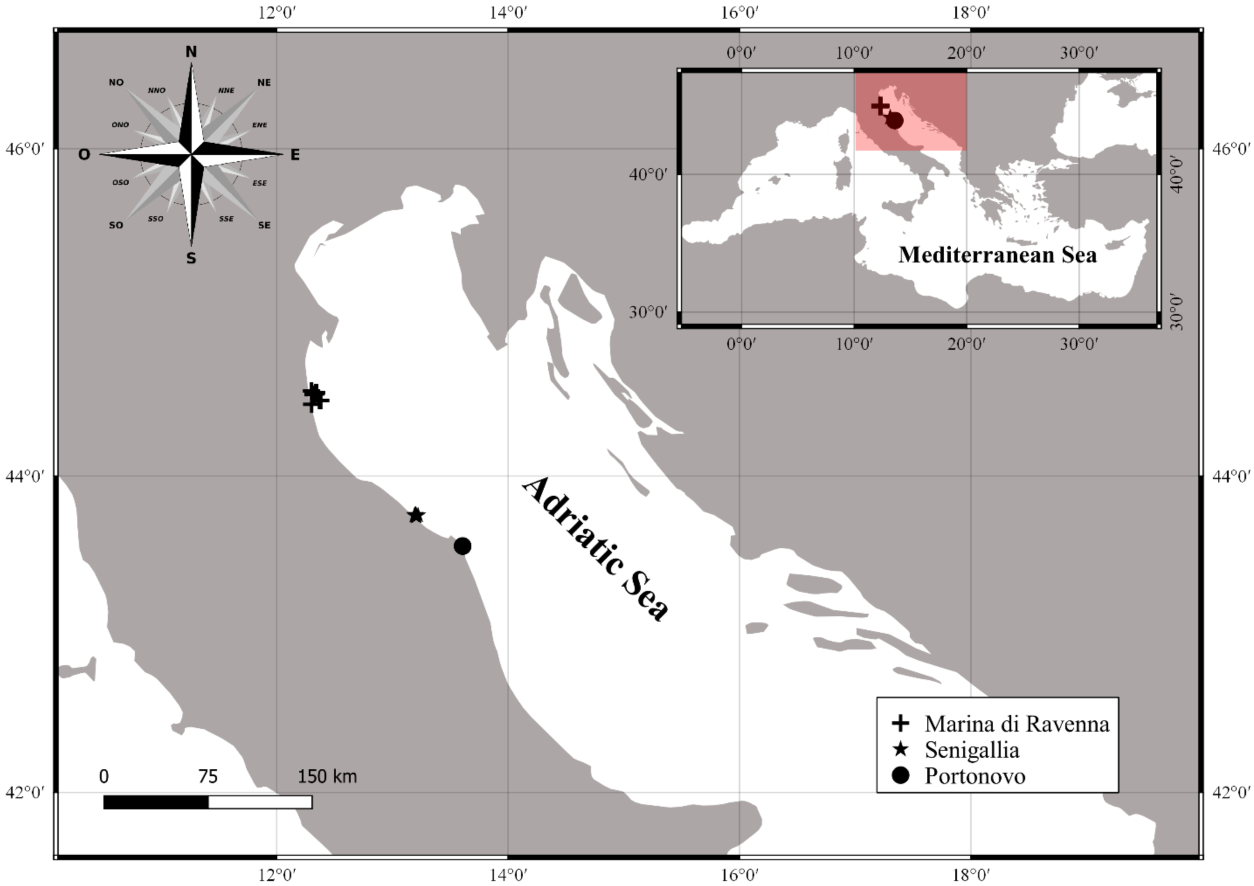

Figure 1. Map of the study area where the trials were performed in 2016 and 2017 (April–August).

Table 1. Summary of the fishing trials carried out at the three sites (Marina di Ravenna, Senigallia, Portonovo). AVG: Average; LOA: Length all out; GT: Gross tonnage; GTR: Trammel net; LP: Large pots; SP: Small pots.

	Marina di Ravenna	**Senigallia**	**Portonovo**
Bottom type	Sandy-mud with scattered rocky outcrops	Sandy-mud	Rocky
AVG depth [m] ± SD	9.9 ± 2.5	10.7 ± 0.43	6.0 ± 0.57
Vessel characteristics	LOA 12.4 m; 10 GT; 350 kW	LOA 12.4 m; 6 GT; 130 kW	LOA 6.6 m; 1 GT; 100 kW
Study period	April-July 2017	April-June 2016	May-August 2016
No. of sets	20	10	12
GTR length [m]	500	300	500
No. of LPs	20	9-10	0
No. of SPs	20	19-20	20
AVG GTR soak time [h] ± SD	19.9 ± 3.3	17.4 ± 2.0	17.2 ± 1.8

AVG LP soak time [h] ± SD	91.4 ± 28.7	73.9 ± 9.1	-
AVG SP soak time [h] ± SD	87.3 ± 25.6	76.6 ± 10.1	90.1 ± 21.3

Fishing gears and experimental setup

The trials were conducted on board local professional fishing vessels (Table 1). The characteristics of the traditional trammel nets (GTRs) employed and the fishing grounds were selected by the fishers, and similarly the fishing operations (e.g., fishing time) and the sorting of the catch were carried out following the fishers' procedures, without interferences from the scientists on board. Experiments to compare the GTRs and the foldable pots were carried out from April to August, in 2016 and 2017, and involved a total number of 42 fishing trials: 20 at Marina di Ravenna, 12 at Portonovo and 10 at Senigallia. To minimize differences due to patchy species distribution, GTRs and pots were deployed close to each other (a few tens of meters).

The technical features of the GTRs are reported in Figure 2. The three netting panels were made of transparent polyamide multifilament: 210/4 mm multifilament and 36 mm mesh bar for the inner panel and 210/3 mm multifilament and 140 mm mesh bar for the outer panels. The net had a nominal height of 2.5 m (35 meshes), although its effective vertical opening in the water was around 1.5 m. The float line and lead line were in propylene (diameter, 8 and 10 mm, respectively); the float line was reinforced with external oval-shaped floats (diameter, 8 cm); the lead line weighed 120 g/m. The total length of the set nets used in each site was: 500 m at Marina di Ravenna and Portonovo, 300 m at Senigallia (Table 1). The GTRs were set early in the morning and hauled in the afternoon.

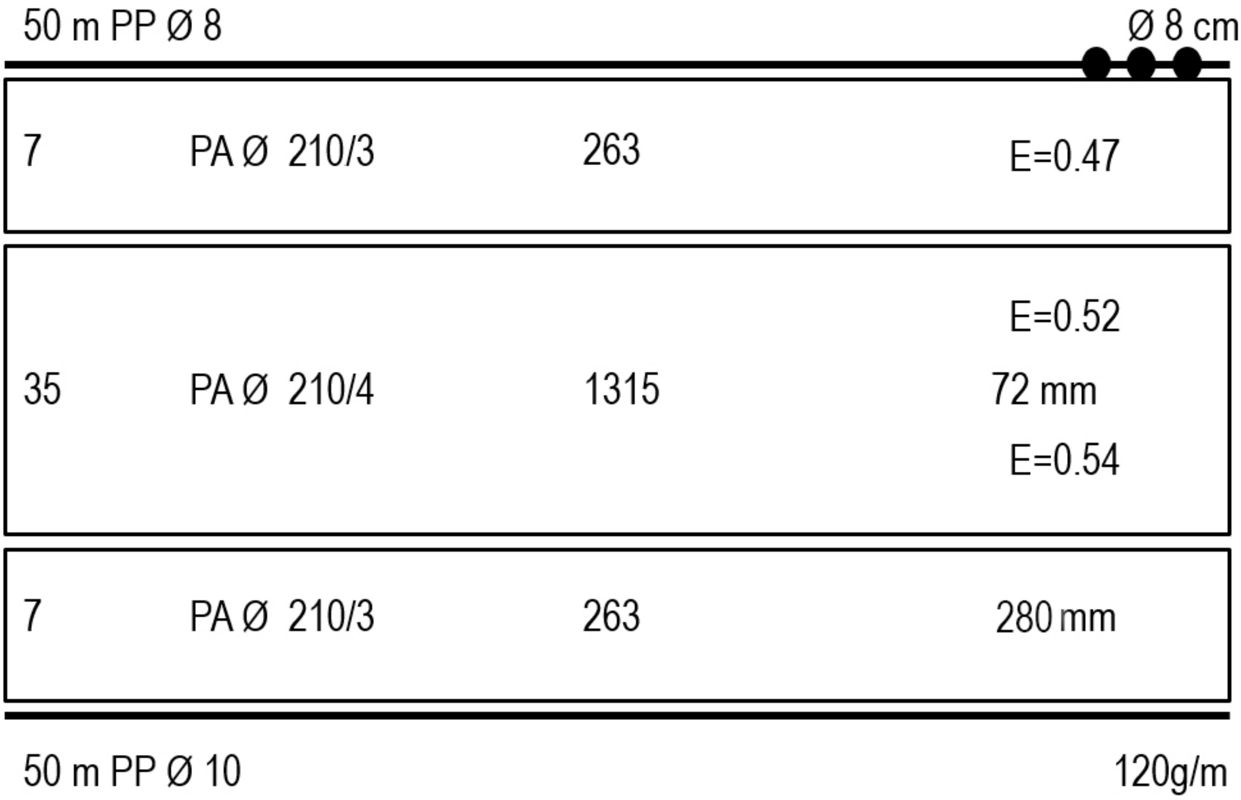

Figure 2. Scheme of the trammel net used in the study. Inner panel: middle; outer panel: top and bottom. PA, polyamide; PP, propylene; ø: diameter; E: hanging ratio.

The pots (manufactured by Trapula Ltd., Croatia; Figure 3) have a stainless-steel bar frame with a pentagonal shape and a single oval entrance. Two steel structures on the top and bottom allow folding them. A propylene rope 5 mm in diameter was externally reinforced with a nylon net (32 mm square-mesh bar). Flexible steel bars 2 mm in diameter allow manual adjustment of the opening. To establish whether catch efficiency was related to the volume of the chamber (Furevik & Løkkeborg, 1994), two different pot sizes were tested: a smaller pot (SP) measuring 40 × 100 cm (height × width) and a larger pot (LP) measuring 60 × 140 cm. The pots were attached to a main propylene line (namely a gang) 8 mm in diameter anchored to the seabed by 2 m plastic branch lines 5 mm in diameter, placed at 15 m intervals. The pots were set 15 m apart according to the traditional rigging used by the local fishers (Fabi et al., 2001). The number of pots of each type ranged from 9 to 20 per fishing trial. Soaking time (i.e., the period of time the pots were left on the bottom) depended on weather conditions and fishers' tactics (Table 1). They were commonly retrieved after 2–3 days, or more, in case of adverse weather conditions, to attract a wider range of commercial species other than cuttlefish, for which traditional pots are usually left 24 h (Fabi, 2001). The pots were not baited, but several black plastic ribbons were attached to the frame, to attract cuttlefish.

Figure 3. Picture of the "Trapula" pots tested in the study. See text for dimensions.

The GTR and pot hauls were paired: each haul consisted in setting and retrieving the GTR, the gang with SPs and the gang with LPs.

Data collection

For each haul, the crew sorted onboard the catch, that was kept separate by gear (GTR, LP, SP). The total catch for each gear was thus divided into a landed catch (species with commercial value, not necessarily target species) and discards, that is, species discarded for different reasons (invertebrates and fish species with no commercial value, commercial individuals under the MCRS or in poor conditions). All individuals were identified to the lowest taxonomic level possible, counted, weighed to the lowest 0.1 g and measured to the nearest 0.5 cm for total length (TL; fish) or mantle length (ML; cephalopods) and to the nearest 0.5 mm for carapace length (CL; crustaceans).

Data analysis

The catch per unit effort (CPUE) was calculated for GTRs and pots. The GTR catch was standardized for the number of individuals ($CPUE_I$) and total catch weight ($CPUE_W$; in kg) captured by 1,000 m of net in 12 h, considering that fishers commonly set 3,000 to 6,000 m of net and haul it up after about half a day. The pot catch was standardized for the $CPUE_I$ and $CPUE_W$ (in kg) captured by 66.6 pots (i.e., the number of pots corresponded to 1,000 m of set net considering 15 m distance between two subsequent pots, according to Fabi et al. (2001)) in 24 h. This duration corresponds to the commercial fishing time of the traditional pots used in the area to target cuttlefish (Fabi, 2001).

The Kruskal–Wallis H test (χ^2) was applied to seek differences between the $CPUE_W$ of GTRs and pots. A non-parametric test was adopted, because the data distributions were not normal and extremely skewed, with wide tails. If differences did emerge, a pairwise Wilcoxson's signed rank test based on Bonferroni correction for multiple comparisons was applied to establish the levels showing significantly different median values. Differences in the size of the individuals caught by the GTRs, LPs and SPs were explored by analysing the length frequency distribution (LFD) of the landed species. The catch efficiency of each pot type vs GTR was compared using generalized linear mixed models (GLMMs; Holst & Revill, 2009). The probability for an individual to be retained in a pot follows from:

$$Pr\{Pot/(Pot + GTR)\} = 1/\left(1 + e^{-(\beta_0 + \beta_1 \times length + \beta_2 \times length^2 + \beta_3 \times length^3)}\right)$$

A binomial error distribution was used to calculate the probability of the number of fish caught in a pot ($CPUE_I$) given that they were caught by both gears based on 1-cm size classes. A probability value of 0.5 corresponds to equal catches in both gears. According to Holst & Revill (2009), a third order polynomial would be adequate for most cases, although in some instances a first or second order would be enough. The best binomial model was chosen based on the lowest Akaike's Information Criterion (AIC) value. A random term was added to the models. Since the GTR and pot hauls were paired, the catches for each site and each gear were pooled and the term "site" was used as a random intercept.

The most abundantly caught species, *S. officinalis* and *Diplodus annularis,* were selected for the catch comparison analysis. Since only SPs were set at Portonovo, the catch comparison of LPs included only the Senigallia and Marina di Ravenna. The models are illustrated graphically with a 95% confidence interval (*CI*) calculated with a bootstrap method using 999 simulations. The free software R (R Core Team, 2018) and the R packages nlme (Pinheiro et al., 2018) and lme4 (Bates et al., 2014) were used for the analyses.

Results

Overall, the three gears caught 53 species, 38 of which belonged to the landed fraction (GTRs = 30, LPs = 15 and SPs = 22) and 28 to the discard species (GTRs = 25, LPs = 5 and SPs = 5), thus confirming that the pots were more species-selective than GTRs (Tables S1 and S2).

As regards the landed species, cuttlefish (*S. officinalis*) was the most abundant in terms of biomass at all 3 sites for all three gears. Two other abundant species caught by all three gears were annular seabream (*D. annularis*), caught at Marina di Ravenna and Senigallia but not at Portonovo, and striped seabream (*L. mormyrus*), caught at all three sites with greater abundance at Senigallia and Portonovo. Additional landed species caught by GTRs were *S. solea*, *S. mantis* and *S. umbra* at Marina di Ravenna; *Liza aurata*, *Sarda sarda* and *Scophthalmus rhombus* at Senigallia; and *Mugil cephalus* at Portonovo. Other landed species caught by the pots were *S. umbra* (LP, SP) and *Conger conger* (LP) at Marina di Ravenna and *Dentex dentex* (SP) at Portonovo (Table S1).

The mean biomass values (calculated as $CPUE_W$) and 95% *CIs* of the landed catch are reported in Table 2. The *CI* values of the three gears did overlap, indicating the lack of significant differences among them, both at each site and as a whole. Standardization of the landed catch weight failed to highlight significant differences in the medians among GTRs, LPs and SPs, either within the three sites or as a whole (χ^2 = 2.59, df = 2, p = 0.274; Figure 4).

Table 2: Mean biomass values ($CPUE_W$) with standard errors and confidence intervals of the commercial catch and of discards for the three gears. GTR (trammel net), LP (large pot) and SP (small pot), at each site (top) and as a whole (bottom). NA (not available).

	Site	GTR $CPUE_W$	LP $CPUE_W$	SP $CPUE_W$
Landed Catch	M. di Ravenna	5.41 ± 0.76 (3.92 - 6.89)	7.27 ± 1.77 (3.81 - 10.73)	3.72 ± 0.64 (2.48 - 4.97)
	Senigallia	4.34 ± 0.14 (2.16 - 6.52)	2.41 ± 0.35 (0.23 - 4.59)	3.08 ± 0.17 (2.20 - 3.97)
	Portonovo	2.90 ± 0.70 (1.53 - 4.27)	-	2.48 ± 0.59 (1.33 - 3.62)
Discards	M. di Ravenna	0.77 ± 0.20 (0.38 - 1.17)	0.14 ± 0.04 (0.07 - 0.21)	0.07 ± 0.05 (0.02 - 0.17)
	Senigallia	0.95 ± 0.57 (0.17 - 2.07)	-	0.04 ± 0.0 (NA)
	Portonovo	1.52 ± 0.79 (0.02 - 3.06)	-	0.06 ± 0.0 (NA)

	Gear	$CPUE_W$
Landed catch	GTR	4.35 ± 0.51 (3.35 - 5.34)
	LP	6.01 ± 1.39 (3.28 - 8.74)
	SP	3.21 ± 0.36 (2.49 - 3.93)
Discards	GTR	0.95 ± 0.23 (0.51 - 1.40)
	LP	0.14 ± 0.04 (0.06 - 0.21)
	SP	0.06 ± 0.03 (0.01 - 0.12)

The discards of LPs and SPs were lower than those of the GTRs both in terms of species number and of CPUEW; in fact, they were close to zero both at Senigallia and at Portonovo (Table S2). The GTRs captured large amounts of *Alosa fallax* and *Pteroplatytrygon violacea* at Marina di Ravenna; *A. fallax* and *Liocarcinus vernalis* at Senigallia and *Eriphia verrucosa*, *Hexaplex trunculus* and *Maja crispata* at Portonovo (Table S2).

The CIs of the mean biomass values ($CPUE_W$) of GTR discards did not overlap with those of LPs and SPs, whereas those of LPs and SPs did (Table 2). The discards showed significant differences in terms of standardized biomass ($\chi^2 = 11.34$, df = 2, p = 0.004, Figure 4) and were mostly caught by GTRs. Wilcoxson's pairwise test showed that the median differences between gears were significant for GTRs vs LPs and for GTRs vs SPs (p = 0.011 and p = 0.016, respectively), whereas the medians of LPs and SPs were not significantly different.

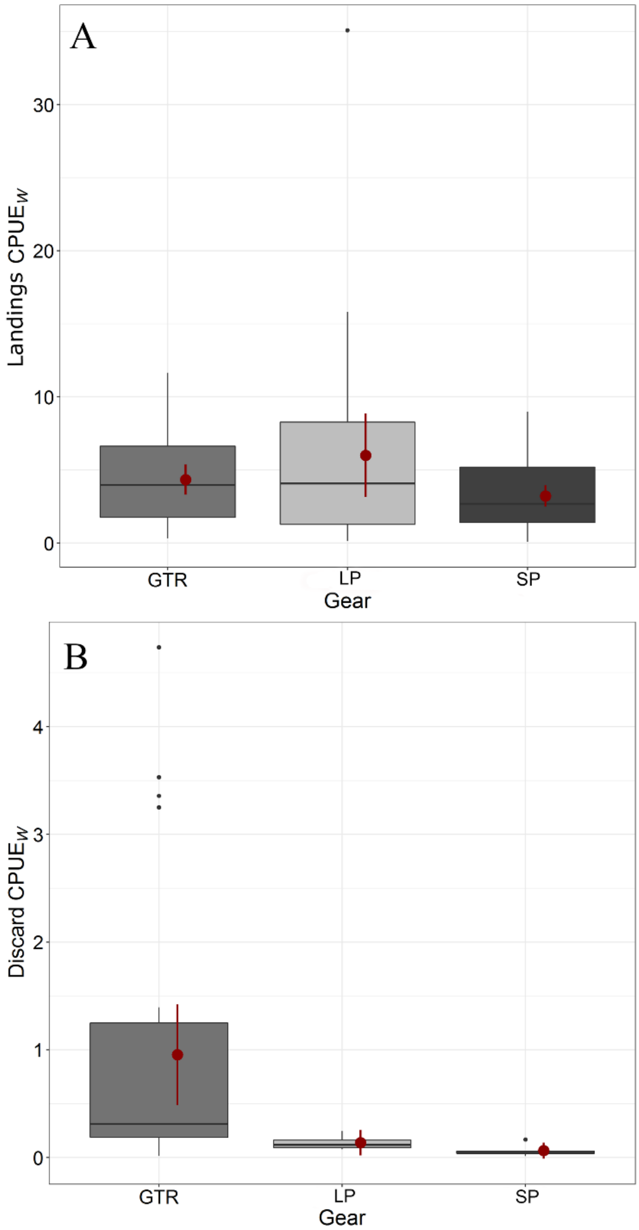

Figure 4. Overall CPUEW of landings and discards of the three gears tested in the study. GTR: trammel nets; LP: large pots; SP: small pots. Red dots: mean CPUEW; red bars: confidence intervals (CIs). (A) Commercial; (B) Discard.

The LFD of S. officinalis and D. annularis at each site and as a whole is reported in Figure 5. The lines of LPs and SPs were mostly above those of GTRs, indicating a greater catch efficiency.

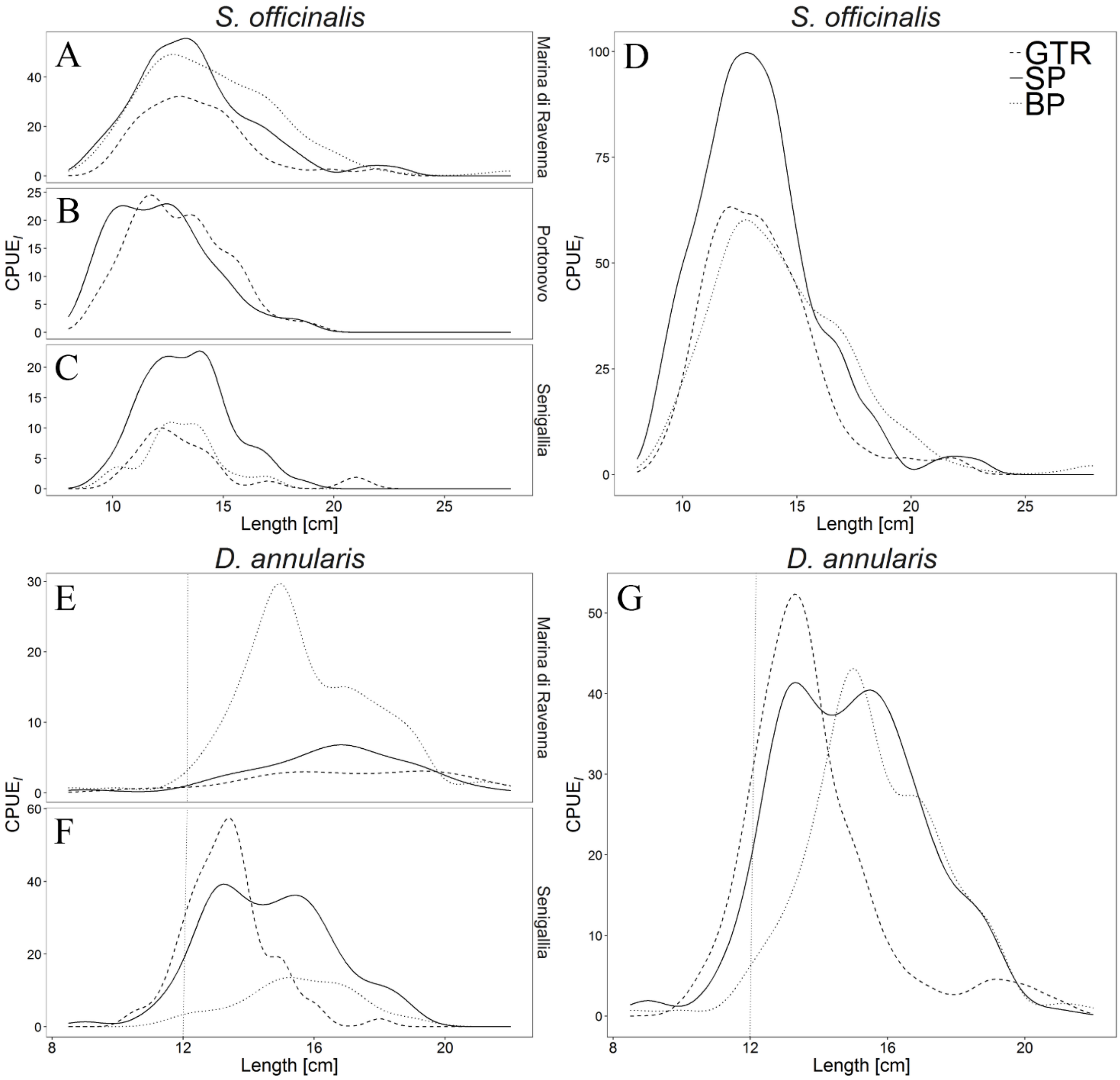

Figure 5. Length frequency distributions (LFDs) of Sepia officinalis in each site (A, B and C) and as a whole (D) and LFDs of Diplodus annularis in each site (E and F) and as a whole (G). (A and E) Marina di Ravenna; (B) Portonovo; (C and F) Senigallia. Dashed lines represent GTR (trammel nets); continuous lines represent SP (small pots); dotted lines represent LP (large pots); vertical dotted lines represent MCRS of 12 cm of D. annularis.

The catch comparison curves (Figure 6; Table 3) demonstrate that for *S. officinalis*, pots (both dimensions) were more efficient than GTRs. SPs were more efficient than GTRs for most *S. officinalis* sizes, except for the larger ones (above the 25 cm size class), for which the efficiency of both gears were similar, as the lower CI exceeds the limit of 0.5 indicating equal proportion of individual catches between both gears. In contrast, LPs showed the same efficiency as GTRs for the smaller individuals (below the 11 cm size class) and were more efficient for the larger individuals.

LPs and SPs showed overlapping *CIs* from the 10 cm size class, i.e. a similar catch efficiency. As regards *D. annularis*, the GTR reflected a greater efficiency than both LPs and SPs at the smaller sizes, usually under the MCRS of the species (12 cm). As a result, the percentage in number of undersized individuals of *D. annularis* caught by GTR was 15.1% (7.1% for Marina di Ravenna; 16.4% for Senigallia), while it was lower for both pots: 7.3% for SPs (3.3% for Marina di Ravenna; 8% for Senigallia) and 3.7% for LPs (3.3% for Marina di Ravenna; 4.5% for Senigallia).

Therefore, LPs and SPs both showed a high selectivity for larger fish, although they also caught some undersized individuals. However, there were no differences among the three gears in the catch efficiency for the larger *D. annularis* individuals.

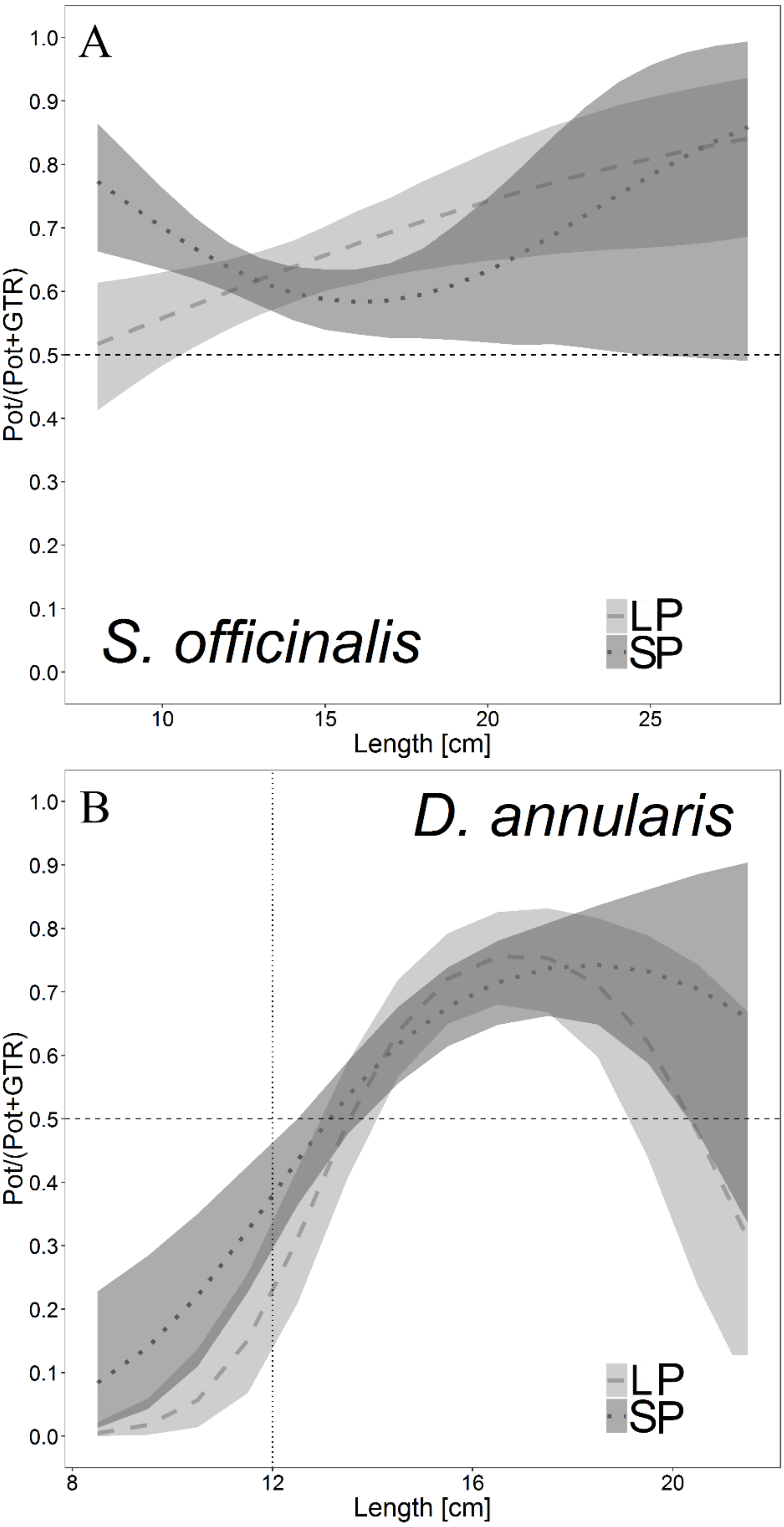

Figure 6. Catch comparison curves for Sepia officinalis (A) and Diplodus annularis (B), representing the GLMM proportions of the total catches of the three gears. GTR, trammel nets; LP, large pots; SP, small pots. Dashed and dotted lines represent the mean proportions of LP and SP, respectively; the vertical dotted line represents MCRS of 12 cm of D. annularis. Interpretation: a value of 0.5 indicates an even split between GTRs and Pots, whereas a value of 0.25 indicates that the Pots caught 25% of all the fish of that length class whereas 75% were caught by the GTRs. Shaded areas: 95% confidence intervals.

Table 3. Estimates of the parameters of the GLMM calculated for catch comparison. SE: standard error. GTR: Trammel net; LPs: Large pots; SPs: Small pots.

Species	Model		Parameter	Estimate	SE	p
Sepia officinalis	Linear	LPs vs GTR	β_0	-0.61	0.45	0.171
			β_1	0.08	0.03	0.009
	Quadratic	SPs vs GTR	β_0	4.07	1.47	0.006
			β_1	-0.46	0.20	0.022
			β_2	0.01	0.01	0.038
Diplodus annularis	Quadratic	LPs vs GTR	β_0	-27	5.62	<0.001
			β_1	3.33	0.71	<0.001
			β_2	-0.98	0.02	<0.001
	Quadratic	SPs vs GTR	β_0	-11.39	4.24	0.007
			β_1	1.35	0.56	0.017
			β_2	-0.04	0.02	0.048

Discussion

This study was aimed at testing the catching efficiency of an innovative pot design in the north-western Adriatic Sea; in particular, it was evaluated the pot's ability to provide an alternative to traditional trammel nets and to reduce discards in SSFs. The comparison implied a different standardization ($CPUE_W$ at 12 h for trammel nets and 24 h for pots) that represented a compromise to maintain the standardization unit as close as possible between the two gears, taking into account that they operate in different ways and with a different fishing time. The main finding, from the catch comparison analysis of the two most abundant species caught (cuttlefish and annular sea bream), was that the catch rates of the two types of pot tested, which differed only in dimensions, were comparable to those of the trammel nets. These data are in line with the high efficiency of the experimental pots reported in the Barents Sea (Furevik et al., 2008) and the Baltic Sea (Königson et al., 2015), where pots showed similar, if not higher, catch rates than those of passive nets, at least in a period of the year. Interestingly, the innovative pots caught a larger number of commercial species than the traditional ones used in the area by artisanal fishers, which are not collapsible, with a different shape and entrance, and mainly target cuttlefish (Fabi et al., 2001).

Regarding the annular sea bream, the poor selectivity of the trammel nets found for this species has been previously reported for *Diplodus* spp. by Tzanatos et al. (2008), who estimated a percentage (in weight) of the undersized individuals caught of 28.2% for *D. annularis* and 74.8% for *D. sargus*, being even higher than the average percentage of this study (15%). In contrast, pots seemed to be able to avoid *D. annularis* juveniles (average percentage of around 7%). Unlike studies in other areas (Munro, 1974; Furevik & Løkkeborg, 1994; Hedgärde et al., 2016), which concluded that larger pots are more effective than small ones, in this study, pot size seemed not to affect catch efficiency. However, the number of pots that actually produced a catch, ranged between 38.5 ± 3.3% for SPs to 42.5 ± 4.3% for LPs, stressing the need for increasing catch efficiency by using attractive baits.

The cost of a collapsible pot as the one tested in this study ranges from EUR 50 (SP) to EUR 100 (LP), whereas 100 m of the traditional trammel net used for the sea trials is around EUR 200. Assumed that 100 m of nets would correspond to more than six pots (as stated in the Materials and Methods section), the alternative gear is more expensive. Nevertheless, whereas the set nets usually last a single season and are then too damaged to be repaired, these kind of pots last up to 2 years. Another advantage of pots is that they afford a more limited access to the catch, making them less subject to depredation by large predators than set nets (e.g., seal-and dolphin-safe fishing gear; Königson, 2011; Königson et al., 2015). Moreover, they provide a greater catch quality, because they generally do not damage the specimens caught (Suuronen et al., 2012; Olsen, 2014). In addition, even if trammel nets require a shorter fishing time than pots, fishers could set different pots gangs in order to alternate the retrieve, and thus to haul them daily.

With reference to discards, the greater amount caught by the trammel nets clearly produces a greater impact on the benthic community, since discard mortality is high (Suuronen et al., 2012). Moreover, the cleaning of the trammel net implies an additional time and labor on deck for fishers, since discards must be released or untangled manually (Sartor et al., 2018; Szynaka et al., 2018). In contrast, the removal of discards from pots can be done without significantly reducing fishing time and leaving high probability for the unwanted organisms to survive (Suuronen et al., 2012). Discarding is a major issue for fisheries management worldwide (Tsagarakis, Palialexis & Vassilopoulou, 2014). In the Mediterranean, the Common Fisheries Policy (EU CFP Regulation, 2013) has introduced the obligation to land ("discard ban") all the individuals of the species with minimum legal size (MCRS, for example, those species reported in the Annex III of the Council Regulation (EC) No. 1967/2006), thus emphasizing the need to reduce discards (Damalas, 2015). The landing obligation is a matter of concern among fishers, which are facing difficulties related to storing and bringing to land the former discard, due to limited hold space, and to sorting time or personnel increasing (Maynou et al., 2018).

The introduction of a new and alternative technology in a fishery, such as innovative pots, could help to achieve this goal of discard reduction only if it is acceptable to both fishers and fishery policies. In this context, fish collapsible pots are revealed to be: practical (i.e., involving no major changes to common fishers' practices), cost-effective (i.e., easy to use and not expensive to maintain, no waste of time for cleaning the gear), efficient (i.e., large spectrum of species caught) and enforceable (i.e., easy to control by inspection authorities).

With reference to bycatch of sensitive and protected species, during our study the trammel nets caught five specimens of the pelagic stingrays (*Pteroplatytrigon violacea*), a frequent event in several Adriatic fisheries (Bonanomi et al., 2018). This Elasmobranch species, usually discarded due to its scarce commercial value, is considered as a 'Least Concern' species in the IUCN red list (Baum et al., 2016). Another bycatch species caught by the trammel nets was the twait shad (*A. fallax*), listed in Annexes II and V of the Habitats Directive (EU Directive, 1992) as requiring close protection. In addition, the passive nets deployed in the central and northern Adriatic are responsible for the bycatch—maybe as many as thousands individuals a year (Lucchetti, Vasapollo & Virgili, 2017c)—of loggerhead sea turtles (*Caretta caretta*), which are listed in Annex IV of the Habitats Directive. In contrast, the pots did not capture any of these species, substantially due of the small size of the pot entrance compared with the larger size of animals such as stingrays and sea turtles. As regards *A. fallax*, its absence in the pots catch may depend on their position close to the bottom, whereas trammel nets can also intercept pelagic fish species (*A. fallax, Sardina pilchardus, Engraulis encrasicolus, Scomber japonicus* etc.) which for different reasons can be discarded (Goncalves et al., 2007).

Conclusions

The innovative pots tested in this study seem to provide a sound alternative to the traditional trammel nets used in the Adriatic Sea, at least in spring and summer, as concerns the small-scale fishery targeting common cuttlefish. These pots do not require a different vessel rigging nor changes to the on board practices; moreover, they can be used without baits and their foldable design involves that they can be easily stored on board the typical artisanal boats used in Mediterranean SSFs. The findings of this pilot study, although not conclusive, clearly indicate that these alternative gears go some way towards reducing bycatch and discards in SSFs while maintaining the commercial catch. Similar tests should be extended to other areas and seasons, also using baits, to provide a clearer assessment of their efficiency.

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Additional information and declarations

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Competing Interests

The authors declare that they have no competing interests.

Author Contributions

Andrea Petetta analysed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.

Claudio Vasapollo analysed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.

Massimo Virgili conceived and designed the experiments, performed the experiments, authored or reviewed drafts of the paper, stakeholder engagement, and approved the final draft.

Giada Bargione performed the experiments, authored or reviewed drafts of the paper, and approved the final draft.

Alessandro Lucchetti conceived and designed the experiments, authored or reviewed drafts of the paper, and approved the final draft.

Data Availability

The following information was supplied regarding data availability: The raw data are available as a Supplemental File (Table S1, S2).

Supplemental Information

Table S1. Average catch per unit effort of the landed species, standardized in weight ($CPUE_W$), for the three gears in the three sites. The most important species commented in the text are highlighted in bold. SE: Standard Error; GTR: Trammel nets; LP: large pots; SP: small pots.

	Marina di Ravenna			**Senigallia**			**Portonovo**	
Species	**GTR $CPUE_W$ (mean ± SE)**	**LP $CPUE_W$ (mean ± SE)**	**SP $CPUE_W$ (mean ± SE)**	**GTR $CPUE_W$ (mean ± SE)**	**LP $CPUE_W$ (mean ± SE)**	**SP $CPUE_W$ (mean ± SE)**	**GTR $CPUE_W$ (mean ± SE)**	**SP $CPUE_W$ (mean ± SE)**
FISHES								
Boops boops	-	0.017 ± 0.001	-	-	-	-	-	-
Chelidonichthys lucerna	-	0.001 ± 0.001	-	0.024 ± 0.010	-	-	-	-
Conger conger	**-**	**0.462 ± 0.262**	**0.097 ± 0.097**	**-**	**-**	**-**	**-**	**-**
Dentex dentex	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**0.328 ± 0.328**
Diplodus annularis	**0.118 ± 0.118**	**0.356 ± 0.136**	**0.126 ± 0.054**	**0.569 ± 0.138**	**0.328 ± 0.131**	**0.730 ± 0.195**	**-**	**-**
Diplodus vulgaris	0.019 ± 0.019	0.007 ± 0.004	-	-	-	-	-	0.091 ± 0.091
Gobius niger	-	-	-	0.076 ± 0.037	0.023 ± 0.015	0.045 ± 0.020	0.028 ± 0.028	-
Gobius paganellus	-	0.001 ± 0.001	0.002 ± 0.002	-	-	-	-	-
Lithognathus mormyrus	**-**	**-**	**0.017 ± 0.013**	**0.067 ± 0.053**	**0.383 ± 0.246**	**0.195 ± 0.132**	**0.053 ± 0.036**	**0.359 ± 0.246**
Liza aurata	**-**	**-**	**-**	**0.543 ± 0.362**	**-**	**-**	**-**	**-**
Merlangius merlangus	-	0.001 ± 0.001	-	-	-	-	-	-
Mugil cephalus	**-**	**0.028 ± 0.019**	**0.013 ± 0.013**	**-**	**-**	**-**	**0.304 ± 0.125**	**-**
Mullus surmuletus	0.008 ± 0.008	0.005 ± 0.005	0.007 ± 0.007	-	-	-	-	-
Oblada melanura	-	0.010 ± 0.010	-	-	-	-	-	-
Pagellus erythrinus	-	-	-	0.021 ± 0.016	-	-	-	-
Raja asterias	0.016 ± 0.016	-	-	-	-	-	-	-
Sarda sarda	**-**	**-**	**-**	**0.452 ± 0.452**	**-**	**-**	**-**	**-**
Sciaena umbra	**0.316 ± 0.179**	**2.384 ± 1.547**	**0.488 ± 0.209**	**0.081 ± 0.081**	**-**	**-**	**-**	**0.011 ± 0.007**
Scomber scombrus	-	-	-	0.088 ± 0.059	-	-	-	-
Scophthalmus rhombus	**-**	**-**	**-**	**0.252 ± 0.252**	**-**	**-**	**-**	**-**
Scorpaena notata	-	-	-	0.014 ± 0.014	-	-	-	-
Scorpaena porcus	-	-	-	-	-	-	0.138 ± 0.058	0.006 ± 0.006
Scorpaena scrofa	-	-	-	-	-	-	0.024 ± 0.017	0.015 ± 0.015
Solea impar	-	-	-	0.011 ± 0.011	-	-	-	-
Solea lascaris	0.175 ± 0.121	-	-	-	-	-	-	-

Solea solea	**0.792 ± 0.455**	**0.012 ± 0.010**	**0.021 ± 0.012**	**0.445 ± 0.188**	**-**	**-**	**-**	**0.011 ± 0.011**
Sparus aurata	-	-	-	0.024 ± 0.024	-	-	-	0.005 ± 0.005
Sphyraena sphyraena	-	-	-	0.157 ± 0.082	-	-	-	-
Trachurus mediterraneus	-	-	-	-	-	-	0.014 ± 0.014	-
Trachurus spp.	-	-	-	0.015 ± 0.015	-	0.019 ± 0.019	-	-
Umbrina cirrosa	0.154 ± 0.154	-	-	0.105 ± 0.079	-	0.006 ± 0.006	0.030 ± 0.030	-
CRUSTACEANS								
Homarus gammarus	0.013 ± 0.013	-	-	-	-	0.041 ± 0.041	-	-
Maja crispata	-	-	-	-	-	0.004 ± 0.004	-	-
Maja squinado	-	-	-	0.222 ± 0.222	-	-	-	-
Melicertus kerathurus	-	-	-	0.120 ± 0.041	-	-	-	0.008 ± 0.008
Squilla mantis	**0.447 ± 0.181**	**-**	**0.001 ± 0.001**	**0.033 ± 0.024**	**-**	**-**	**-**	**-**
MOLLUSCS								
Octopus vulgaris	-	-	-	-	-	0.116 ± 0.116	-	0.091 ± 0.091
Sepia officinalis	**1.999 ± 0.518**	**4.007 ± 0.952**	**2.962 ± 0.562**	**1.024 ± 0.572**	**0.951 ± 0.570**	**1.931 ± 0.343**	**2.069 ± 0.552**	**1.558 ± 0.371**

Table S2. Average $CPUE_W$, standardized in weight, of the discarded species caught by the three gears in the three sites. The most important species commented in the text are highlighted in bold. SE: Standard Error; GTR: Trammel nets; LP: large pots; SP: small pots.

	Marina di Ravenna			**Senigallia**			**Portonovo**	
Species	**GTR $CPUE_W$ (mean ± SE)**	**LP $CPUE_W$ (mean ± SE)**	**SP $CPUE_W$ (mean ± SE)**	**GTR $CPUE_W$ (mean ± SE)**	**LP $CPUE_W$ (mean ± SE)**	**SP $CPUE_W$ (mean ± SE)**	**GTR $CPUE_W$ (mean ± SE)**	**SP $CPUE_W$ (mean ± SE)**
FISHES								
Alosa fallax	**0.240 ± 0.143**	**-**	**-**	**0.577 ± 0.473**	**-**	**-**	**-**	**-**
Blennius ocellaris	-	-	-	-	-	-	0.007 ± 0.007	-
Boops boops	-	0.011 ± 0.008	-	0.026 ± 0.018	-	-	-	-
Chelidonichthys lucerna	0.034 ± 0.021	0.001 ± 0.001	-	0.048 ± 0.033	-	-	-	-
Engraulis encrasicolus	-	-	-	0.051 ± 0.051	-	-	-	-
Gobius paganellus	-	0.001 ± 0.001	0.009 ± 0.007	-	-	-	-	-
Liza aurata	0.031 ± 0.031	-	-	-	-	-	-	-
Merlangius merlangus	0.048 ± 0.024	-	-	-	-	-	-	-
Pteroplatytrygon violacea	**0.184 ± 0.088**	**-**	**-**	**-**	**-**	**-**	**-**	**-**

Raja asterias	-	-	-	0.026 ± 0.024	-	-	-	-
Sardina pilchardus	-	-	-	0.019 ± 0.013	-	-	-	-
Sardinella aurita	0.013 ± 0.013	-	-	-	-	-	-	-
Sciaena umbra	-	0.012 ± 0.012	0.008 ± 0.008	-	-	-	-	-
Scomber japonicus	0.019 ± 0.019	-	-	-	-	-	-	-
Solea solea	0.006 ± 0.006	0.002 ± 0.002	-	-	-	-	-	-
Sparus aurata	-	-	-	-	-	-	-	0.005 ± 0.005
Symphodus tinca	-	-	-	-	-	-	0.067 ± 0.067	-
Umbrina cirrosa	-	-	-	0.015 ± 0.015	-	-	-	-
CRUSTACEANS								
Eriphia verrucosa	**-**	**-**	**-**	**-**	**-**	**-**	**0.137 ± 0.090**	**-**
Homarus gammarus	0.011 ± 0.011	-	-	-	-	-	0.013 ± 0.013	-
Liocarcinus depurator	0.068 ± 0.038	-	-	-	-	-	0.019 ± 0.019	-
Liocarcinus vernalis	**0.051 ± 0.032**	**-**	**-**	**0.109 ± 0.089**	**-**	**-**	**0.009 ± 0.009**	**-**
Maja crispata	**-**	**-**	**-**	**-**	**-**	**0.004 ± 0.004**	**0.173 ± 0.112**	**-**
Squilla mantis	0.036 ± 0.020	-	0.001 ± 0.001	-	-	-	-	-
MOLLUSCS								
Hexaplex trunculus	**-**	**-**	**-**	**-**	**-**	**-**	**0.101 ± 0.082**	**-**
Mytilus galloprovincialis	-	-	-	-	-	-	0.078 ± 0.060	-
Nassarius mutabilis	-	-	-	-	-	-	0.016 ± 0.016	-
Ostrea edulis	-	-	-	-	-	-	0.014 ± 0.014	-

The raw data (in excel format) used for this article can be found online at http://dx.doi.org/10.7717/peerj.9287#supplemental-information.

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6 Discussion

The studies carried out within the present thesis have involved the three main commercial fisheries operating in the Italian Adriatic Sea (Western GSA 17): bottom trawl fishery, hydraulic dredge fishery and small-scale fishery. These fisheries exert a significant impact on the demersal resources of the area, contributing to the alarming stocks overexploitation (Colloca et al., 2017); thus, a great effort is required by the scientific community to provide options and solutions for more sustainable exploitation.

6.1 Understanding the impact of traditional fishing gears

The first step towards a fisheries' management based on the improvement of the size and species selectivity of traditional fishing gears is to describe the selection processes occurring in those gears currently in use in commercial fisheries. In this regard, Paper I and Paper IV were focused on understanding the selectivity, and consequently the impact, of bottom trawl and hydraulic dredge fisheries, respectively.

Discarding is among the largest impacts produced by bottom trawl fisheries, which are currently insufficiently size-selective (Tsagarakis et al., 2017) since they target species that often inhabit areas occupied by a wide range of other species (multi-species fisheries; Fiorentino and Vitale, 2021). An initial review work (published in Review I; Annex I) investigated the bottom trawl selectivity at Mediterranean level, demonstrating the unsustainability of the current legal codend meshes for the majority of the targeted species and highlighting the need of mitigating the biological impacts of bottom trawling.

The novelty brought in Paper I is that the impact of the bottom trawl fishery was evaluated from a species community perspective. In fact, this holistic approach carried out through the catch dominance analysis, allowed to account not only for those species having a commercial interest or requiring close protection or management measures, but for all the species caught by the two legal codends established for the Mediterranean (SM40, DM50). As a result, we demonstrated that a large number of species is present in the catches of the two codends, most of which contribute to the discarded fraction of the catch, accounting for the 50% in weight of all the catches obtained with both codends. This percentage gives a clear insight into the high impact exerted by this fishing gear on the benthic community. Moreover, we confirmed that both the legal codends are insufficiently size selective for the European hake, since individuals below the MCRS and/or the length of first maturity were always retained in the catches. Interestingly, from the catch comparison results, SM40 seemed to be less suitable than DM50 for the sustainability of many commercial species (e.g. European hake, red mullet, Mediterranean scaldfish, spotted flounder), for which it produced significantly more discards. Further investigations are therefore needed to revise or continue to support the use of a 40 mm square mesh codend in the Italian GSA17 bottom trawl fishery and, more in general, in the Mediterranean trawl fisheries.

The importance of Paper IV, conducted on the hydraulic dredge fishery targeting *C. gallina*, which is one of the most important landed resources in the area, lies in the description of the first size selection process carried out by the dredge under fishing. It was demonstrated that the average catch efficiency of the dredge is very high since around 90% in weight and 80% in number of clams contacting the gear were retained. Therefore, the second size selection process carried out on board the vessels through the sorting sieves is necessary to retain only legal-sized individuals (Sala et al., 2017). A fishery management advice was then provided concerning the reduction of MCRS from 25 mm to 22 mm, to which the species is temporarily subjected along the Italian coasts (EU Commission Delegated Regulation, 2376/2016). In fact, when the 22 mm MCRS is applied, the percentage of the undersized clams caught, and thus the discard ratio, markedly decreased from the situation with the 25 mm MCRS applied. As a consequence, this temporary reduction of the MCRS would lead to a lesser fishing time spent to reach the daily quota of 400 kg of target-sized clams per fishing vessel, and thus a decreased number of times a given area is swept. A reduced impact on the small clams (which are rejected at sea after sieving, with a demonstrated high survival probability; Bargione et al., 2021) and generally on the seabed is expected, thus favouring the recovery (Vasapollo et al., 2020). The temporary reduction of the MCRS is not incompatible with the LFM of about 15–17 mm, which is reached by the species in the first year of life in the area (Bargione et al., 2020). Of course, the aim is to reduce the impact exerted by the fishery on *C. gallina*, to bring the MCRS back to 25 mm in the next future (DGPEMAC, 2019). The results provided in this study are important to develop a new Italian National Management plan for hydraulic dredges.

6.2 Reducing discards through technical modifications

There is an urgent need to find and propose technical modifications to traditional gears to reduce the discards produced by commercial fisheries. The established Landing Obligation in the Mediterranean of all the catches of species subjected to the MCRS (EU Regulation, 1380/2013) is in fact a matter of concern among fishers, due to difficulties related to storing and bringing to land the former discard and to sorting time or personnel increasing (Maynou et al., 2018) thus emphasizing the need to reduce discards (Damalas, 2015). In bottom trawl fisheries, the T90 mesh configuration is claimed to be a practical and inexpensive technical solution to reduce discards (ICES, 2009b, 2010, 2011). In the Mediterranean Sea, the European Commission has been promoting, through several research projects (e.g. MINOUW, IMPLEMED), the experimental trials of this mesh configuration. Further discussions on this solution have followed in the latest meetings of the FAO-GFCM Working Group on Fishing Technology (WGFIT 2021, 2022) encouraging the replication of T90 tests in new areas and fisheries. Papers II and III have contributed to these efforts of the scientific community by testing the T90 netting for the first time in the Adriatic Sea. The results markedly differed based on the section of the trawl net where this modification was applied.

In the codend, T90 provided a significantly higher size selection for all the main commercial species of the fishery, at least for some length classes, compared with the traditional DM codend of the same mesh size (Paper II). Nevertheless, the 54 mm nominal mesh size used in the study was too large for most of the species, since a large fraction of commercial individuals was lost from the catch, except for hake, whose average *L50* was above the MCRS of 20 cm for the first time in Mediterranean selectivity studies. Further sea trials can demonstrate if a compromise in the mesh size between the 40-50 mm legal meshes and the 54 mm tested in Paper II could provide a T90 codend that is able to reduce discards without significantly penalizing the fishers' revenues. Such a T90 codend could be then included in the European Regulations as an alternative codend, as happened in other trawl fisheries (e.g. the Baltic Sea cod trawl fishery; Wienbeck et al., (2011)).

In Paper III, the T90 was applied, together with a reduced number of meshes in circumference, in the trawl extension piece. Both modifications, which are well known to improve trawl selectivity in the codend (e.g. Herrmann et al., 2007; Wienbeck et al., 2011), did not display the same results in the extension piece, and the outcomes were even opposite to expected. The lesson learnt from the study was that the extension piece seems not to be the main part where fish are willing to escape. The only reduction in number of meshes around the extension piece circumference jeopardized the size selection obtained in the trawl with a standard extension piece, especially for red mullet, where higher retention of the smallest size classes was observed compared to the standard net. The T90 netting in the extension piece did not significantly help to exclude juveniles of target species (hake, red mullet, monkfish). By revealing the ineffectiveness of such modifications, these results can push other scientists and decision-makers towards alternative technical solutions to mitigate the biological impacts of bottom trawling in the area. In particular, this study highlighted that the design changes in the trawl codend remain the most urgent measures to be tested and applied in commercial fisheries.

6.3 Reducing discards through alternative more sustainable gears

The adoption and promotion of alternative fishing gears represent another solution to reduce discards, bycatch and seabed impacts and thus ensure more sustainable exploitation of resources. In this regard, Paper V described the testing of innovative fish collapsible pots and compared their catch efficiency and performance to that of a traditional trammel net used in the Adriatic SSFs. Prior to this study, a review work (published in Review II; Annex I) explored the passive net selectivity in the whole Mediterranean region, highlighting that, despite being less harmful to stocks and habitats than other gears such as trawls, they can produce (especially trammel nets) high rates of bycatch of protected species and discards of non-commercial ones.

The experimental trials of Paper V revealed a similar catch efficiency, between the traditional and alternative gears, for the main commercial species, while the discards produced by the fish pots were significantly lower than those produced by the trammel net. Therefore, these innovative pots were found to provide a valuable alternative to the trammel nets traditionally used in the Adriatic Sea, at least in the spring/summer period (i.e. when the trials were conducted).

The additional information collected on the pot designs employed in different areas of the Mediterranean Sea was summarized in a review work (published in Review III; Annex I), which highlighted the main pot technical parameters affecting the catch efficiency for the different species targeted with pots. The review can be useful for other scientists to test and eventually promote the use of pots as alternative gears to catch certain species in areas where these fisheries are not currently conducted.

Concerning the GSA 17, which is already one of the Mediterranean areas with the highest number of species targeted by pots (Grati et al., 2018), a wider diffusion of pot fisheries is already encouraged by projects such as TartaLife and Life Delfi, in which the present thesis program was included, to stimulate fishing fleet conversion and increasingly attracting fishers' interest. The use of these low-impact gears would be not a return to the past, or to a lower technological level, but rather a step towards a more sustainable future. Their limited environmental impact also involves that the product of pot fisheries could be certified with a quality mark, such as the Marine Stewardship Council sustainability label, which in 2003 was awarded to Scotland's Loch Torridon *Nephrops* creel fishery (Macher and Talidec, 2008). A label of this kind is likely to capture the fishers' engagement and promote fishery sustainability.

7 Final remarks

The main goal of a reasonable fisheries' management is that fishing activities are conducted in such a way that the environmental impact is minimized, the waste reduced, the biodiversity of aquatic ecosystems preserved and the stocks' abundance maintained within safe limits. The adoption of more selective fishing gears is one of the main management measures that can be implemented in those Italian Adriatic fisheries that generate large quantities of discards.

The introduction of an innovation in a fishery, be it a technical modification or a new and alternative gear, could help to achieve this goal of bycatch and discard reduction only if it is acceptable to both fishers and fishery policies. The biggest challenge is to convince the fisheries sector that a change is necessary, since fishers are generally reluctant to implement changes that imply losses of commercial catch and revenues in the short term, though benefits are expected in the long term. The economic consequences of introducing gear modifications are likely the most important constraint. Despite this, fishers acknowledge that the recent enforcement of the LO implies additional costs both in terms of time and money, and this is likely to encourage them to adopt measures able to reduce discards.

Any introduction of a technical measure should be presented to fishers as an opportunity, rather than an additional burden as it is often perceived. There is a need to open a discussion among stakeholders (fishers, net makers, suppliers, scientists, enforcement officers, managers and environmental bodies), to know what they think about the new solution and what they suggest. Stakeholders need to be clearly informed on the capital costs (maintenance and running costs) and on the effects on fishing operations. Meetings and publicity are considered as an essential step to make the new technology more acceptable. The principle is that it is better to have rules that everybody agrees with (even if enforcement is necessary) than to have a *top-down* imposition of an innovation that the majority ignores except the managers. Finally, a reasonable timetable should be set to smoothly introduce a new technology to make fishers 'digest' even mentally the new management measures. The use of economic incentives and rewards for fishers that make use of these technologies is also strongly suggested. This will result in higher compliance with the rules and regulations.

In this context, among the studies conducted within the present thesis, the T90 codend in bottom trawl fishery and the fish collapsible pots in SSFs were found to be the most promising solutions. Both measures were presented to fishers through *ad hoc* meetings and tested in fishing vessels to involve fishers in the research process. They both revealed to be practical (i.e., involving no major changes to common fishers' practices), cost-effective (i.e., easy to use and not expensive to maintain) and enforceable (i.e., easy to control by inspection authorities). The pots tested (Paper V) also proved to be efficient for a larger spectrum of species than traditional pots, while the efficiency of the T90 codend tested (Paper II) was hampered by the excessively large mesh size which was too size selective for most of the target species. In both cases it is advisable to continue collecting data, increasing the number of experiments, both at spatial and temporal levels. Also, the methodology described in Paper I can contribute to assess the economic and environmental viability of these solutions, by evaluating more thoroughly their impact and comparing the catches obtained with them and the traditional gears currently in use from a species community perspective. Eventually, before introducing both pots and T90 codend in commercial fisheries, it is appropriate to carry out a final distribution of these devices to a reasonable number of vessels that can adopt them on a voluntary basis.

In conclusion, the results obtained in this thesis confirm that fisheries technology is one of the key aspects to be considered for the sustainable management of resources. The outcomes here presented can provide management bodies with useful elements to help define technical measures aimed at the conservation of stocks.

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Annex I

List of reviews

Review I: Lucchetti, A., Virgili, M., Vasapollo, C., Petetta, A., Bargione, G., Li Veli, D., Brĉic, J. & Sala, A. (2021). An overview of bottom trawl selectivity in the Mediterranean Sea. *Mediterranean Marine Science*, 22(3), 566-585. https://doi.org/10.12681/mms.26969.

Review II: Lucchetti, A., Virgili, M., Petetta, A., & Sartor, P. (2020). An overview of gill net and trammel net size selectivity in the Mediterranean Sea. *Fisheries Research*, 230, 105677. https://doi.org/10.1016/j.fishres.2020.105677.

Review III: Petetta, A., Virgili, M., Guicciardi, S., & Lucchetti, A. (2021). Pots as alternative and sustainable fishing gears in the Mediterranean Sea: an overview. *Reviews in Fish Biology and Fisheries*, 1-23. https://doi.org/10.1007/s11160-021-09676-6.