Discards regulation vs Mediterranean fisheries sustainability
M. Demestre and F. Maynou (eds)

Scientia Marina 82S1
December 2018, 199-208, Barcelona (Spain)
ISSN-L: 0214-8358
https://doi.org/10.3989/scimar.04752.03A

Modelling the effects of more selective trawl nets on the productivity of European hake (*Merluccius merluccius*) and deep-water rose shrimp (*Parapenaeus longirostris*) stocks in the Strait of Sicily

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Summary: Single-species Gadget models were used to assess the effects of using a sorting grid mounted on the traditional trawl net used by Sicilian trawlers to exploit the deep-water rose shrimp in the Strait of Sicily. The main commercial by-catch species of this fleet is the European hake (*Merluccius merluccius*), often caught at sizes well below the minimum conservation reference size. Selectivity curves based on the results of an experimental survey carried out in the area using a commercial trawler equipped with an ad hoc-designed sorting grid were incorporated into single-species Gadget models to forecast the effects of changing fishery selectivity on the performance of the two stocks in terms of catch and biomass. The models included catch data from the Italian, Tunisian and Maltese fleets as well as MEDITS trawl survey data for the period 2002-2016. Several scenarios were defined to simulate the effect of the Italian trawlers' adopting the sorting grid under different stock-recruitment assumptions. The results obtained, when compared with status quo simulations of fishing without a sorting grid mounted on the trawl net, indicated a beneficial effect for both stocks in terms of an increase in biomass and for the fleets in terms of the amount and size composition of annual landings.

Keywords: Gadget; forecast; selectivity; sorting grids; trawl net; Strait of Sicily.

Modelización de los efectos de redes de arrastre más selectivas sobre la productividad de stocks de merluza europea (*Merluccius merluccius*) y gamba blanca (*Parapenaeus longirostris*) en el estrecho de Sicilia

Resumen: Se usaron modelos monoespecíficos Gadget para evaluar el efecto del uso de una rejilla separadora acoplada a la red de arrastre tradicional que usan los arrastreros sicilianos para explotar la gamba blanca en el estrecho de Sicilia (SoS). La principal especie en las capturas accesorias de esta flota es la merluza europea (*Merluccius merluccius*), que contiene a menudo tallas muy por debajo de la Talla de Referencia Mínima de Conservación (MCRS). Se incorporaron en Gadget las curvas de selectividad obtenidas en una campaña experimental en la misma área con un arrastrero comercial equipado con un modelo de rejillas separadora diseñado específicamente para el estudio, para pronosticar los efectos del cambio de la selectividad pesquera en la evolución de los dos stocks en términos de captura y biomasa. Los modelos incluyen datos de captura de las flotas italiana, tunecina y maltesa, así como datos de las campañas MEDITS para el periodo 2002-2016. Se definieron distintos escenarios para simular el efecto de la adopción de la rejilla separadora por parte de los arrastreros italianos bajo distintas asunciones del modelo stock-reclutamiento. La comparación de los resultados obtenidos con simulaciones de pesca sin montar la rejilla separadora en la red de arrastre (*status quo*) indican un efecto neto beneficioso para los dos stocks debido al incremento de biomasa y, en consecuencia, para las flotas en términos de cantidad y composición de las capturas anuales.

Palabras clave: Gadget; pronóstico; selectividad; rejillas separadoras; red de arrastre; estrecho de Sicilia.

Citation/Cómo citar este artículo: Vitale S., Enea M., Milisenda G., Gancitano V., Geraci M.L., Falsone F., Bono G., Fiorentino F., Colloca F. 2018. Modelling the effects of more selective trawl nets on the productivity of European hake

(*Merluccius merluccius*) and deep-water rose shrimp (*Parapenaeus longirostris*) stocks in the Strait of Sicily. Sci. Mar. 82S1: 199-208. https://doi.org/10.3989/scimar.04752.03A

Editor: F. Maynou.

Received: January 17, 2018. **Accepted:** September 10, 2018. **Published:** November 9, 2018.

INTRODUCTION

The Mediterranean basin is affected by a very high level of different human pressures (Micheli et al. 2013). Fisheries are considered one of the main sources of impact, with about 22 countries fishing stocks that are mostly overfished (Colloca et al. 2013, Vasilakopoulos et al. 2014, Colloca et al. 2017). The increasing level of fishing effort applied in the last three decades has led to a profound modification of the marine ecosystem in terms of loss of biodiversity and biomass of several species (Coll and Libralato 2012, Piroddi et al. 2017). Furthermore, trawl fishing is a non-selective fishing method resulting in significant quantities of unwanted catch, including the incidental catch of non-target species and juveniles, which are either retained or discarded because of their low economic value or legal issues (Pravin et al. 2011). Unwanted catch has been considered a major problem in fisheries management as it accounts for a great part of the overall impact of fishing activities on the environment (Ramsay et al. 1998, Sánchez et al. 2000, Gorelli et al. 2016). Discarding is also considered a moral issue as the waste of natural resources is considered ethically wrong.

The promotion of a sustainable use of the marine environment is now the objective of several European actions, such as the EU's Common Fisheries Policy (CFP, reg. EU 1380/2013) and the Marine Strategy Framework Directive. The CFP prohibits discarding of the main commercial species through a landing obligation or discard ban. In the Mediterranean Sea, any discard of species subject to minimum conservation reference size (MCRS) above 5% of the total catch is prohibited. Experiences from other countries (e.g. Alaska, British Columbia, New Zealand, Iceland and Norway) on the effects of discard bans highlight that a policy of mandatory landings cannot result in long-term benefits to stocks unless total removals are reduced, through the avoidance of undersized, non-commercial or over-quota catch. Additional management measures are therefore required to incentivize a switch towards more selective fishing gear (Condie et al. 2014).

In the last few years, experiments have been carried out on the use of sorting grids mounted on trawl nets to reduce the discard rate or the catch of undersized individuals in poorly selective fisheries such as those targeting crustaceans (Fonseca et al. 2005). In Norway lobster (*Nephrops norvegicus*) fisheries for example, selective sorting grids have been tested in many areas and their use is specified by legislation in some sectors of Kattegat and Skagerrak. Grids are very selective, but they can lead to loss of commercial Norway lobster and valuable fish species (Madsen et al. 2016). Trade-offs associated with the use of sorting grids were investigated in the brown shrimp (*Crangon crangon*) fine-mesh trawl fishery in the North Sea, where a positive reduction of fish by-catch (>70%) and benthos (65%) was associated with a reduction of only 15% of brown shrimp catch (Polet 2002). Similarly, experiments in Portuguese waters have shown that the use of ad hoc-designed grids in trawl crustacean fishery led to a substantial decrease in fish by-catch, although the benefits were partially counteracted by a loss in Norway lobster catch (Fonseca et al. 2005). Fishing trials in the Mediterranean Sea have highlighted that sorting grids can be substantially beneficial in increasing the size at first capture of commercial fish and crustaceans, thus making trawling more selective (Sardà et al. 2006, Bahamon et al. 2007, Massuti et al. 2009).

Historically, within the Mediterranean basin the Strait of Sicily has been one of the most important fishing ground exploited by the fleets of several countries (Italy, Tunisia, Libya, Malta, Egypt) and features a high biological diversity, productivity and habitat heterogeneity. Recently, the General Fisheries Commission for the Mediterranean decided to close three stable nurseries of deep-water rose shrimp, *Parapenaeus longirostris* Lucas, 1847 (hereinafter DPS) and European hake *Merluccius merluccius* Linnaeus, 1758 (hereinafter HKE) in the northern sector of the Strait of Sicily (REC.CM-GFCM/40/2016/4), although the measure has not yet been implemented. In this area the deep-water crustaceans fisheries is the most important in terms of biomass and commercial value of the landings, although a non-negligible amount of catch comes from inshore demersal and pelagic fisheries targeting several fish species (Gancitano et al. 2016).

Among the targeted crustaceans, DPS made up more than 40% of landings in the Strait of Sicily in 2015, the annual landing being about 6150 t with a value of €39 million. One of the main by-catches of this fishery is HKE (Milisenda et al. 2017). However, the amount of landings of undersized HKE specimens is considerable. The discarded fraction of DPS trawl fisheries ranged between 25% and 40% of the total catch, being formed mainly by horse mackerel, *Trachurus trachurus* Linnaeus, 1758, DPS and HKE specimens below the MCRS (Milisenda et al. 2017).

The management of these stocks is based on technical measures such as the prohibition of trawling within three miles of the coastline and minimum mesh sizes (MMS, 40 mm square) of trawl cod-end established by Council Regulation (EC) 1967/2006 and the MCRS of 20 cm total length for HKE and 20 mm carapace length for DPS.

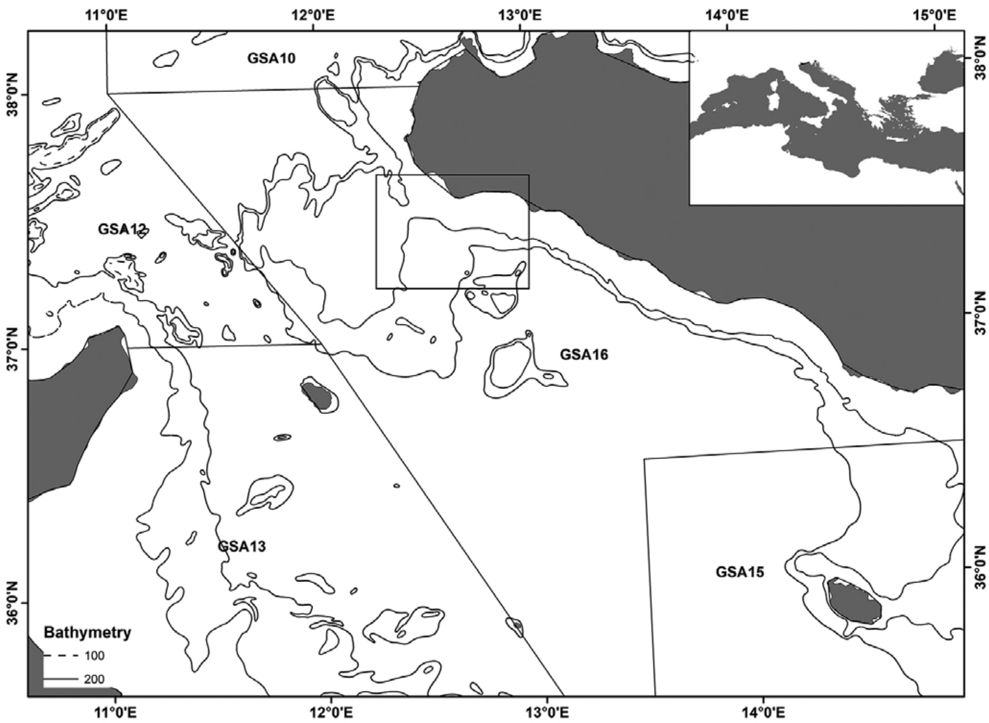

Fig. 1. – Map of the study area where fisheries data are collected for the assessment of deep-water rose shrimp and hake. The black square box indicates the area where the experimental survey was carried out in 2015.

The new CFP prohibits discarding of species subject to an MCRS, such as deep-water rose shrimp and hake, amounting to more than 5% of the total catch. As things stand, it is urgent to decrease the amount of unwanted catch in trawl fisheries through more selective trawl nets. Since the adoption of a minimum legal mesh size in trawling does not prevent the catch of undersized HKE (Bethke 2004, Lucchetti 2008), sorting grids are considered one of the simplest and most efficient ways to increase the selectivity of trawl nets among several by-catch reduction devices (e.g. Pravin et al. 2011).

The objective of this study was to determine whether the adoption of an ad hoc-designed sorting grid, called Juveniles Trash Excluder Device, by the Italian trawlers exploiting the deep-water rose shrimp and hake in the Strait of Sicily can positively contribute to stock rebuilding and fisheries landings. The new estimated selectivity curves for DPS and HKE were incorporated into single-species Gadget (Globally applicable Area-Disaggregated General Ecosystem Toolbox; Begley and Howell 2004) models to forecast the grid effects on the stocks and the fishery. The potential use of sorting grids as a tool for consistently reducing by-catch of juveniles of the two species is discussed, considering the requirement of the EU-CFP for more selective and sustainable fisheries.

MATERIALS AND METHODS

Study area and data collection

An experimental survey was conducted in 2015 on the continental shelf off the southwestern coast of Sicily (Geographical Sub-Area 16, Fig. 1) using a commercial trawler equipped with three different types of sorting grids and 40 mm square mesh (SM 40) in the cod-end. Only the grid constituted by a net of 40 mm SM (G1-SM40, Fig. 2) was considered in this study because of its higher efficiency in the reduction of DPS and HKE juveniles. Three different sources of data were used to perform the study: i) data collected during the above mentioned survey, ii) commercial catch data from the Italian, Tunisian and Maltese fleets (Table 1), and iii) MEDITS trawl survey data for the period 2002-2016.

Gadget models

Gadget is an acronym for the “Globally applicable Area-Disaggregated General Ecosystem Toolbox”, which is a statistical model of marine populations and/

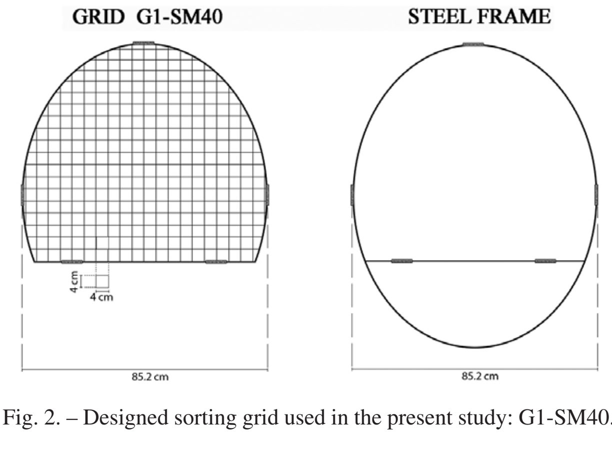

Fig. 2. – Designed sorting grid used in the present study: G1-SM40.

Table 1. – Total landings of deep-water rose shrimp (DPS) and hake (HKE) in the Strait of Sicily by fleet and stock in 2016.

Trawl fleet	n. vessels	Landings (t)			
		DPS	%	HKE	%
Italy	468	5293	70.2	1202	45.2
Tunisia	70	2229	29.6	1439	54.0
Malta	14	13	0.2	21	0.8
Total	552	7535		2662	

or ecosystems designed to be multi-fleet and capable of including predators and mixed fisheries issues (Begley and Howell 2004). In her review of ecosystem models, Plagányi (2007) classified Gadget as a "minimum realistic model" to describe the concept of restricting a model to those species most likely to have important interactions with the species of interest. Gadget can also be used for single-species assessment, and in European waters it is currently used to assess stocks in the ICES area (e.g. southern stock of hake in divisions 8.c and 9.a, and tusk and golden redfish in Icelandic waters). In the Mediterranean, it has been applied for the assessment of hake in Geographical Sub-Area 9 (Bartolino et al. 2011).

Gadget is an age-length–structured parametric forward simulation model coupled with an extensive set of data comparison and optimization routines. Processes are generally modelled as dependent on length, making Gadget a suitable tool for addressing selectivity problems. Age is however tracked in the model, and data can be compared on a length and/or age scale. Gadget works by running an internal model based on many parameters and then comparing the data from the output of this model with observed data to get a goodness-of-fit likelihood score (Begley and Howell 2004). The parameters can then be adjusted and the model re-run until an optimum is found, which corresponds to the model with the lowest likelihood score. The Gadget framework consists of three parts: 1) a parametric model to simulate the ecosystem, 2) statistical functions to compare the model output with data, and 3) search algorithms to optimize the model parameters. The internal structure of Gadget and various potential sub-models and options available are described in detail by Begley (2004) and Begley and Howell (2004).

For the purpose of this study, we used two single-species Gadget models, for DPS and HKE, with populations defined by 2 mm carapace length and 2 cm total length groups, respectively. The year is divided into four quarters. HKE age range is 0 to 7 years, with the oldest age treated as a plus group. Recruitment happens in the second and third quarter. The length at recruitment is estimated and mean growth is assumed to follow the von Bertalanffy growth function, with L_{inf}=100 cm and K estimated by the model. DPS age range is 0 to 4 years, the latter used as a plus group. Recruitment takes place in the second and third quarter. Natural mortality was assumed as a vector using the Prodbiom approach (Abella et al. 1997). The datasets used by the models (likelihood components) are listed in Table 2 and include catch data (length structures and landings) for the Italian, Tunisian and Maltese trawlers exploiting the two stocks, as well as catch data for the artisanal vessels exploiting hake with gillnets. In addition, the two models used time series of the MEDITS bottom trawl survey (n km^2 by size class) and were updated for the purposes of this study by adding catch and survey data for 2016, so the forecast period starts in 2017.

Fleet selectivity curves

Gadget in the Strait of Sicily is designed as a single-species tool to model interactions between three main fleets: Italian, Maltese and Tunisian trawlers. Fleets subtract biomass in different ways from the two populations and display differences in the exploitation pattern. In the Strait of Sicily, bottom trawlers target DPS and have HKE as a by-catch (Milisenda et al. 2017).

Native Gadget functions were first used to estimate the selectivity for HKE and DPS of the Italian and Tunisian trawl fleets using the traditional nets without sorting grids. For DPS a classical sigmoidal selectivity function was used (L_{50}=18.92, α=1.16). For HKE a new selectivity function was implemented, considering a reduced trawl catchability of large specimens (Abella et al. 1997, Bartolino et al. 2011). The new function is a double logistic type, which assumes a dome shape but with a constant (at some level) right tail, in order to reproduce the fish escaping from the net, assuming that only a small, constant, percentage of the larger HKE are captured (L_{50}=15.5; R_{50}=35; α. L_{50}=0.7; α. R_{50}=0.7; p=0.1).

Table 2. – Likelihood components, time period covered and their relative contribution to the final total likelihood (SSF: small-scale fishery).

Likelihood component	Period	Relative weight
Hake age-length distributions from Italian trawlers	2005-2016	366.1
Hake age-length distributions from Italian SSF	2005-2016	18.8
Hake length distributions from Italian trawlers	2005-2016	1388.2
Hake length distributions from Italian SSF	2005-2016	16.4
Hake length distributions from Italian survey	2002-2016	452.6
Hake length distributions from Tunisian trawlers	2007-2016	501.7
Hake length distributions from Tunisian SSF	2010-2016	13.2
Rose shrimp length distributions from Italian trawlers	2005-2016	31.6
Rose shrimp length distributions from Italian survey	2002-2016	34.8
Rose shrimp length distributions from Tunisian trawlers	2007-2016	44.4
Hake abundance indices 0-20 cm from survey	2002-2016	23.8
Hake abundance indices 20-30 cm from survey	2002-2016	0.8
Hake abundance indices 30-40 cm from survey	2002-2016	0.5
Hake abundance indices >40 cm from survey	2002-2016	0.1
Rose shrimp abundance indices 0-10 mm from survey	2002-2016	2.9
Rose shrimp abundance indices 10-20 mm from survey	2002-2016	0.4
Rose shrimp abundance indices >20 mm from survey	2002-2016	0.4

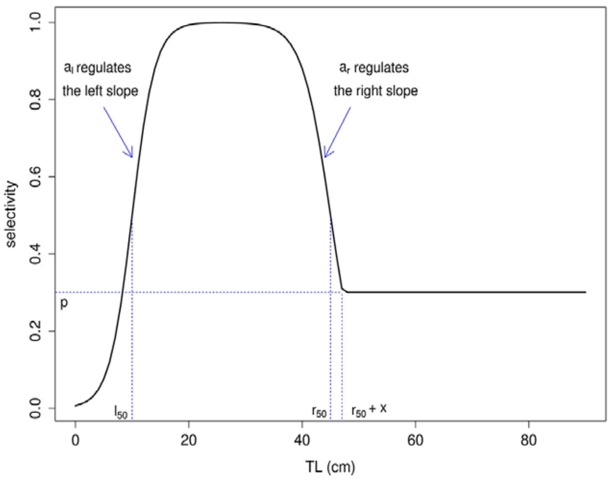

Fig. 3. – Example of the double logistic selectivity curve, with a constant right tail, used to reproduce the selectivity of HKE.

By letting

a_l, a_r, l_{50}, $r_{50} > 0$, $l_{50} < r_{50}$, $0 \le p \le 1$, $L > 0$ and

$$l_{const} = \begin{cases} L - r_{50} - x, & if\ L > r_{50} - x \\ 0, & otherwise \end{cases}$$

where $x = \log((1-p)/p)/a_r$, we define this new selectivity function as

$$S(L;\, a_l,\, a_r,\, l_{50},\, r_{50}\,,\, p) =$$

$$= \frac{1}{[1+\exp(-a_l(L-l_{50}))]*[1+\exp(a_r(L-r_{50}-l_{const}))]}$$

In the above formulation, parameters a_r and r_{50} play the same role in the right tail as the corresponding parameters a_l and l_{50} for the left side, while p indicates the proportion of fish captured after length $r_{50}+x$ (Fig. 3).

Estimation of selectivity curves

During the survey, repeated hauls were carried out without grid (control, *ctrl*) and with grid (*wg*). In the control hauls the number $n^r_{ctrl,L}$ of specimens per length class L retained (r) in the cod-end was recorded. In the hauls with grid both the number $n^r_{wg,L}$ of specimens per length class L retained in the cod-end and the number $n^{eg}_{wg,L}$ of specimens of length class L that escaped from the grid (*eg*) were recorded.

The available data were, however, not sufficient to directly estimate the selectivity of the net with grid, owing to the unknown proportion of specimens that escaped through the cod-end. The parameters to estimate the new selectivity curves were calculated indirectly through the following ad-hoc procedure.

In order to estimate the selectivity of the trawl net as determined by the grid g, the proportion $p^{(r)}_{g,L}$ of specimens of length L retained (r) by the net is needed. This can be calculated from the ratio $n^{(r)}_{g,L}/N_{g,L}$, where $n^{(r)}_{g,L}$ is the number of specimens retained by the net with grid and $N_{g,L}$ is the number of specimens that entered the net. This latter quantity is the sum of the specimens retained (r) by the net, the specimens that escaped from the grid (*eg*) and those that escaped from the cod-end (*ec*): $N_{g,L} = n^{(r)}_{g,L} + n^{(eg)}_{g,L} + n^{(ec)}_{g,L}$.

Since $n^{(ec)}_{g,L}$ is unknown, $N_{g,L}$ cannot be directly obtained from the experimental survey data.

By letting $N_{ctrl,L}$ be the number of specimens of length L that entered the control net (*ctrl*), it can be reasonably assumed that $N_{g,L} = N_{ctrl,L}$. Because *ctrl* was the same net as that used by the Italian trawl fleet, the value of $N_{ctrl,L}$ was estimated as $n^r_{ctrl,L} / P^r_{ctrl,L}$ with $P^r_{ctrl,L}$ obtained from the selectivity curves estimated by Gadget on the 2002-2016 trawl catch data of the Italian fleet. Once $N_{ctrl,L}$ had been obtained, having assumed $N_{g,L} = N_{ctrl,L}$, it was possible to estimate the selectivity of the trawl net with grid from the ratios $n^{(r)}_{g,L}/N_{g,L}$ by using the logistic function for DPS and the modified double logistic for HKE.

This was done externally to Gadget using the R statistical software. The new estimated proportions of specimens retained per length class, the selectivity curve from Gadget and the ad hoc selectivity curve estimated for the net with grid are shown in Figure 4A for DPS and in Figure 6A for HKE.

Selectivity scenarios

Forecast scenarios in Gadget were based on the stock structure, fishing mortality and stock parameters (growth, maturity, etc.) observed during the last year of the hind-cast part of the model (2016). Gadget can be used to run stochastic or deterministic forecasts predicting a future recruitment on which both biomass and catch depend. It fits a lag-1 autoregressive model (AR1) to the fitted recruitment. In particular, AR1 is a linear regression model where the response (recruitment) at time t (year) depends on the recruitment at time t–1.

Four selectivity scenarios were considered, assuming i) recruitment forecast from the AR1 model, and ii) a constant exploitation pattern (catch over the exploitable biomass) set at the 2016 level. In Scenario I (status quo), all the Italian trawlers were assumed to be fishing with the traditional trawl net and the recruitment was forecast by the AR1 model. In the other three scenarios (II, III, IV), all the Italian trawlers were assumed to be fishing with sorting grids mounted on the nets, while the Maltese and Tunisian trawlers were fishing with their traditional nets. The three scenarios differed only in the assumption on recruitment. In Scenario II, it was forecast by the AR1 model. Scenario III assumes an increase of the recruitment at time t+1 that is linearly proportional (100%) to the increase of the spawning stock biomass (SSB). Finally, in Scenario IV recruitment is proportional to a 50% variation of SSB.

Scenarios III and IV incorporate a linear stock-recruitment relationship assuming that any increases in SSB should have a positive effect on recruitment, as observed for other DPS stocks (Colloca et al. 2014).

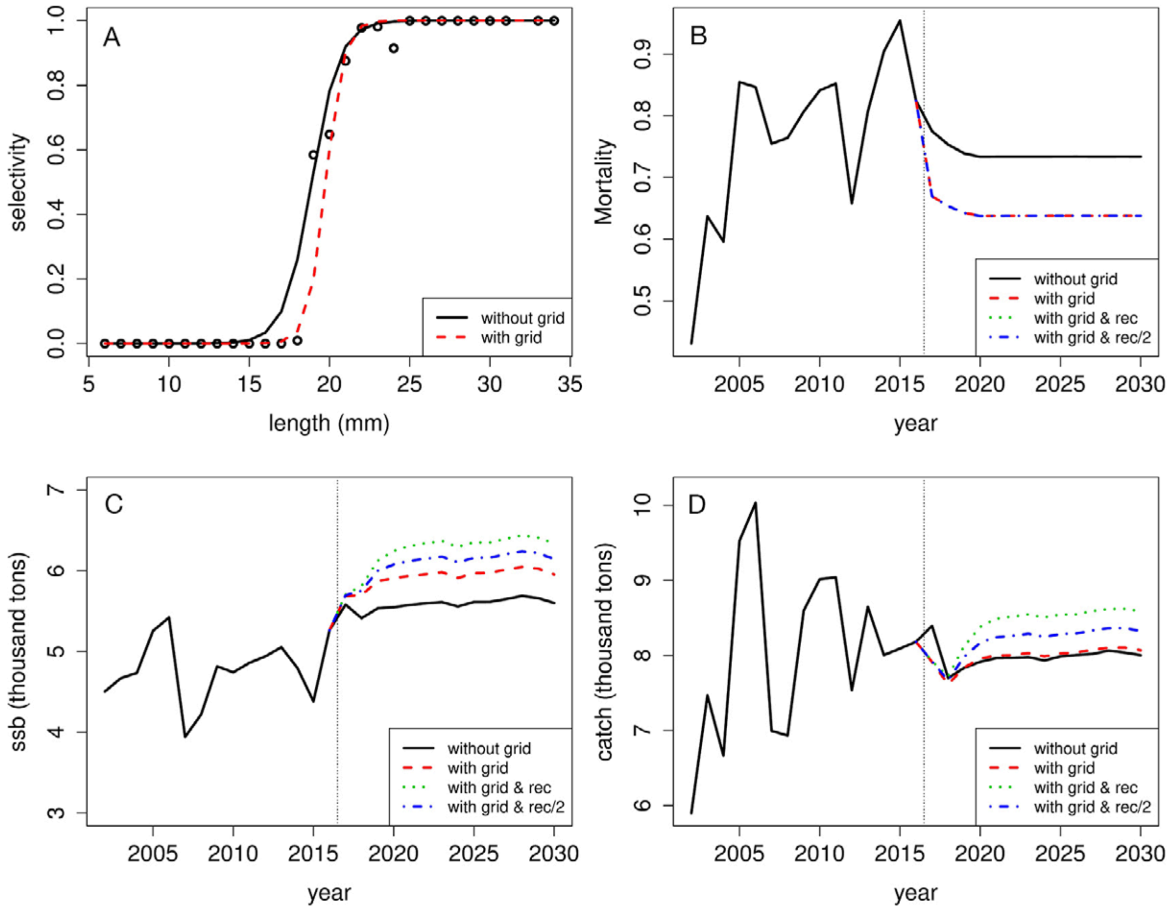

Fig. 4. – Gadget simulations plots of DPS comparing the trawl nets without grid (Scenario I: black solid line) and with grid (Scenario II, red dashed line; Scenario III, green dashed line; Scenario IV, blue dashed line). A, selectivity curves of DPS, circles represent the new proportions of specimens, by length class, retained by the net with grid, forecast up to 2030; B, fishing mortality (F); C, spawning stock biomass (SSB); D, catch.

RESULTS

Deep-water rose shrimp

The use of the sorting grid led to an increase in L_{50} (length at which 50% of the specimens were retained in the cod-end) of about 1 mm: from 18.92 to 19.77 mm of the standard trawl net (Fig. 4A). The grid also increased the steepness of the selectivity curve, reducing to zero the catch of specimens with carapace length (CL) below 18 mm (Fig 4A). Over 20 mm CL, the two nets showed no differences in catchability.

As shown in Figure 4B, the forecast fishing mortality was the same for the three scenarios adopting a grid. Independently of the recruitment simulated, the adoption of the grid led to a decrease in fishing mortality of about 12.5%. The forecast reduction in F occurred in the first two years of simulations and was constant in the remaining years. A similar trend was observed for Scenario I (Table 3).

The SSB was predicted to follow a similar trend for the three grid scenarios, with an abrupt increase across the first three years, particularly in Scenario III (Fig. 4C). The overall average of SSB (from 2016 to 2030) increased by about 5.9%, 11.7% and 8.8% for Scenarios II, III and IV, respectively, compared with Scenario I (Table 3).

The prediction of the catch for the three grid scenarios indicated a reduction in the first two years and an increase in the following years, particularly in the third and fourth year (Fig. 4D). The overall average catch increase was about 5.6% and 2.9% for Scenarios III and IV, respectively, while a negligible difference was recorded for the Scenario II (Table 3).

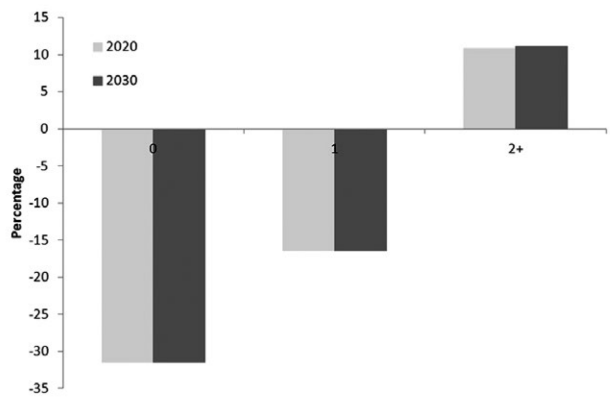

Fig. 5. – Proportional change in age composition of DPS catch in 2020 and 2030 in Scenario II (trawl net with grid and recruitment as in the status quo) when compared with the status quo Scenario I (traditional trawl net).

Table 3. – Summary of the main Gadget outcomes of DPS after survey with forecast from 2017 to 2030: F, SSB and Catch (expressed in metric tons) between trawl nets (Sc. I, Scenario I; Sc. II, Scenario II; Sc. III, Scenario III; Sc. IV, Scenario IV).

Year	F Sc. I	F Sc. II	F Sc. III	F Sc. IV	SSB Sc. I	SSB Sc. II	SSB Sc. III	SSB Sc. IV	Catch Sc. I	Catch Sc. II	Catch Sc. III	Catch Sc. IV
2016	0.82	0.82	0.82	0.82	5266.0	5266.0	5266.0	5266.0	8181.1	8181.1	8181.1	8181.1
2017	0.76	0.66	0.66	0.66	5601.6	5705.0	5723.7	5714.3	8296.6	7817.0	7829.4	7823.2
2018	0.74	0.64	0.64	0.64	5454.6	5740.4	5849.2	5794.8	7669.1	7583.1	7682.5	7632.7
2019	0.73	0.63	0.63	0.63	5579.4	5912.7	6164.3	6038.5	7808.0	7808.9	8088.7	7949.4
2020	0.72	0.63	0.63	0.63	5595.1	5957.4	6288.0	6122.7	7892.3	7928.3	8343.0	8135.7
2021	0.72	0.63	0.63	0.63	5622.5	5982.0	6352.9	6167.5	7940.2	7969.6	8453.7	8211.7
2022	0.72	0.63	0.63	0.63	5644.0	6004.0	6385.9	6195.0	7938.8	7977.2	8482.5	8229.9
2023	0.72	0.63	0.63	0.63	5660.8	6030.2	6416.4	6223.3	7951.9	8007.0	8518.6	8262.8
2024	0.72	0.63	0.63	0.63	5602.6	5955.9	6339.8	6147.9	7908.9	7959.9	8472.8	8216.3
2025	0.72	0.63	0.63	0.63	5660.0	6013.9	6396.0	6204.9	7961.8	8000.0	8510.8	8255.4
2026	0.72	0.63	0.63	0.63	5662.6	6018.8	6397.4	6208.1	7983.3	8011.7	8516.8	8264.2
2027	0.72	0.63	0.63	0.63	5696.2	6062.3	6444.6	6253.4	7996.7	8051.3	8558.3	8304.8
2028	0.72	0.63	0.63	0.63	5733.5	6092.5	6479.7	6286.1	8038.2	8072.5	8584.9	8328.7
2029	0.72	0.63	0.63	0.63	5708.2	6073.1	6457.0	6265.0	8009.8	8081.1	8592.9	8337.0
2030	0.72	0.63	0.63	0.63	5646.8	6001.6	6382.3	6192.0	7982.2	8047.8	8557.7	8302.8

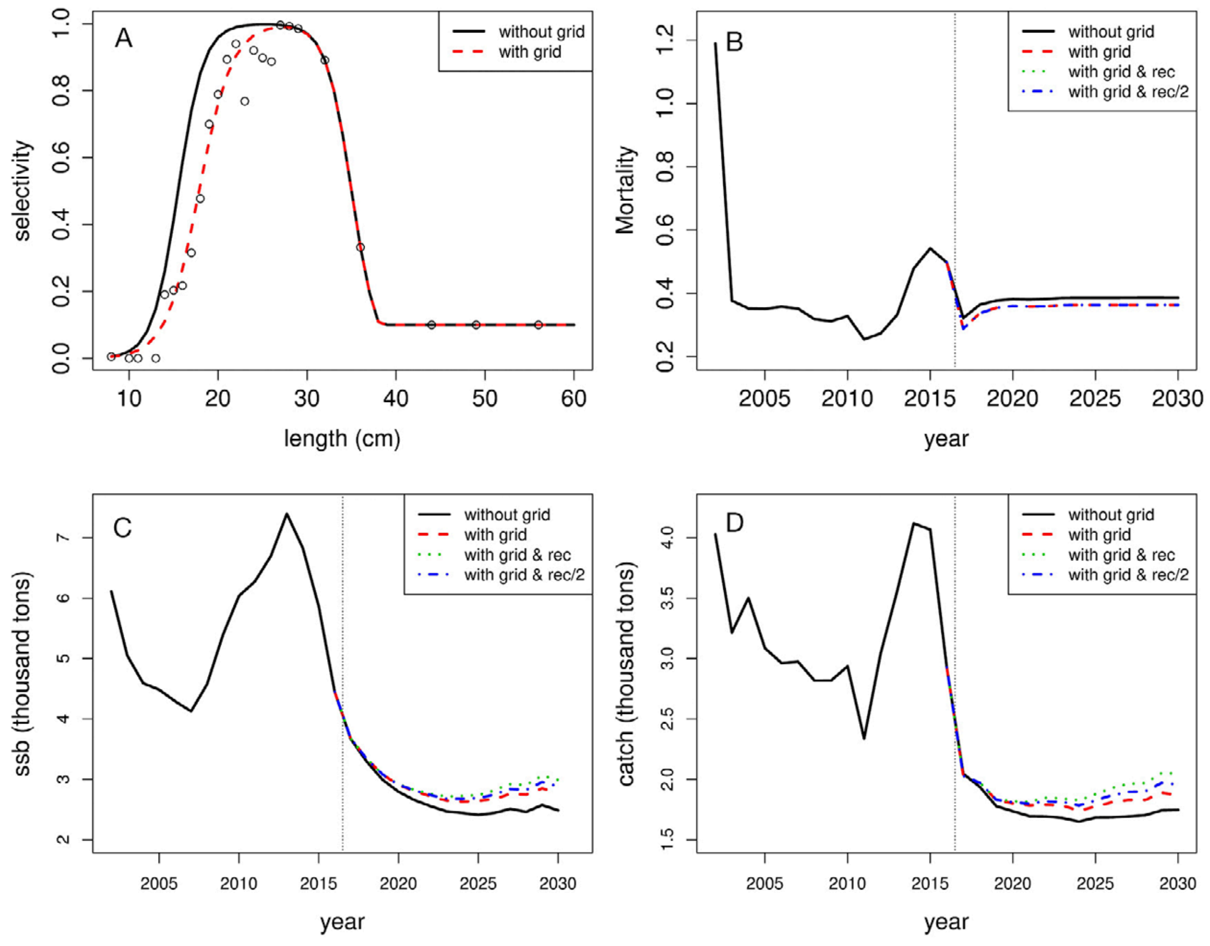

Fig. 6. – Gadget simulations plots of HKE comparing the trawl nets without grid (Scenario I, black solid line) and with grid (Scenario II, red dashed line; Scenario III, green dashed line; Scenario IV, blue dashed line). A, selectivity curves of HKE; circles represent the new proportions of specimens, by length class, retained by the net with grid, forecast up to 2030; B, fishing mortality (F); C, spawning stock biomass (SSB); D, catch.

The effect of the grid on DPS catch at age is shown in Figure 5. Here, the catch at age forecast in 2020 and 2030 was compared between status quo (no grid) and Scenario II. It appeared that the proportional reduction of catch on juveniles was about 31.5% for age 0 and 16.5% for age 1. Starting from age 2 the use of the grid would lead to an increase in catch of about 10.8% in 2020 and 11.1% in 2030.

European hake *Merluccius merluccius*

Selectivity of the trawl net with grid showed an L_{50} of 17.86 cm, approximately 2 cm higher than L_{50} (15.5 cm) estimated for the trawl net without grid (Fig. 6A). The net with the grid displayed an overall escape of all specimens with total length (TL) up to 13 cm, while for specimens up to about 28 cm TL the proportion of

Table 4. – Summary of the main Gadget outcomes of HKE after survey with forecast from 2017 to 2030: F, SSB and Catch (expressed in metric tons) between trawl nets (Sc. I, Scenario I; Sc. II, Scenario II; Sc. III, Scenario III; Sc. IV, Scenario IV).

Year	F Sc. I	F Sc. II	F Sc. III	F Sc. IV	SSB Sc. I	SSB Sc. II	SSB Sc. III	SSB Sc. IV	Catch Sc. I	Catch Sc. II	Catch Sc. III	Catch Sc. IV
2016	0.53	0.53	0.53	0.53	4176.8	4176.8	4176.8	4176.8	2922.9	2922.9	2922.9	2922.9
2017	0.33	0.30	0.30	0.30	3389.4	3397.1	3397.1	3397.1	2021.9	2008.3	2008.3	2008.3
2018	0.37	0.34	0.34	0.34	3008.2	3051.6	3052.0	3051.8	1888.0	1925.7	1926.9	1926.3
2019	0.39	0.36	0.36	0.36	2698.8	2778.3	2781.0	2779.7	1705.4	1758.9	1766.8	1762.8
2020	0.39	0.37	0.37	0.37	2496.5	2600.6	2611.0	2605.8	1650.8	1716.8	1735.0	1725.9
2021	0.40	0.37	0.37	0.37	2359.2	2486.7	2506.0	2496.3	1599.5	1687.4	1717.6	1702.5
2022	0.40	0.38	0.38	0.38	2255.2	2401.9	2439.6	2420.8	1586.4	1695.3	1737.4	1716.4
2023	0.40	0.38	0.38	0.38	2162.3	2331.6	2383.5	2357.5	1576.3	1678.3	1741.1	1709.7
2024	0.40	0.38	0.38	0.38	2125.2	2316.7	2387.5	2352.1	1547.4	1644.2	1729.3	1686.8
2025	0.40	0.38	0.38	0.38	2098.3	2295.8	2387.8	2341.5	1574.8	1677.7	1782.7	1731.2
2026	0.40	0.38	0.38	0.38	2134.4	2344.0	2466.3	2405.8	1575.1	1696.4	1814.3	1755.3
2027	0.40	0.38	0.38	0.38	2180.9	2409.5	2557.0	2483.2	1582.1	1711.8	1847.0	1779.4
2028	0.40	0.38	0.38	0.38	2111.0	2357.0	2504.4	2430.7	1592.6	1706.3	1841.9	1774.1
2029	0.40	0.38	0.38	0.38	2236.0	2473.6	2670.8	2572.2	1618.3	1763.7	1923.3	1844.7
2030	0.40	0.38	0.38	0.38	2139.3	2390.2	2589.4	2489.8	1638.0	1762.1	1931.2	1845.2

specimens retained was lower than in the net without grid (Fig. 6A). The two nets did not differ in selectivity for specimens over 30 cm TL.

The forecast fishing mortality was the same for the three grid scenarios, leading to a reduction of about 5% compared with Scenario I.

The SSB was forecast to decrease from 2017 to 2025. In the last five years of projections, a slight recovery (10.9%-18.4%) was predicted in grid scenarios, while SSB remained stable in Scenario I (Fig. 6B and Table 4).

A similar pattern was also forecast for the catch (Fig. 6C): a reduction until 2024 followed by an increase of between 7.7% (Scenario II) and 16.3% (Scenario III, Table 4).

The effect of the grid on hake catch at age is shown in Figure 7. Here, the catch at age forecast in 2020 and 2030 was compared between status quo (no grid) and Scenario II. It appeared that the proportional reduction of catch on juveniles was about 25% for age 0, 13% for age 1 and 2.5% for age 2. Starting from age 3, the use of grid would lead to a proportional increase in the catch of over 20% from age 5 to age 7+ in 2030.

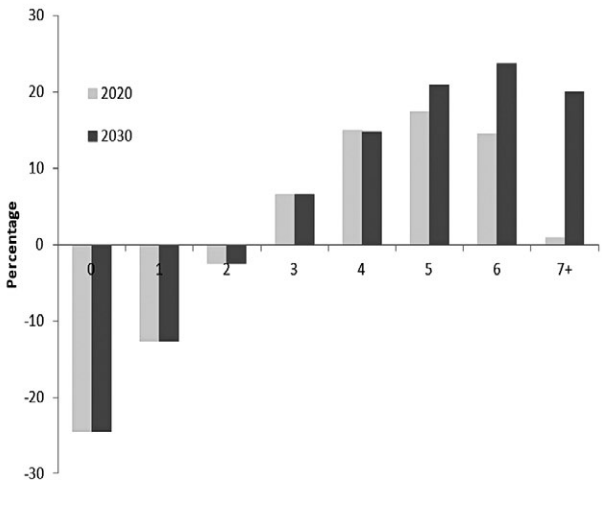

Fig. 7. – Proportional change in age composition of HKE catch in 2020 and 2030 in Scenario II (trawl net with grid and recruitment as in the status quo) when compared with status quo Scenario II (traditional trawl net).

DISCUSSION

In the Mediterranean, the poor selectivity of trawlers is a challenging problem for the reduction of unwanted catches. Studies conducted over the past decade have shown that the selectivity of fishing gear can be improved through the use of innovative systems that enable the capture of certain species and of certain sizes (e.g. Valdemarsen and Suuronen 2003, Hall et al. 2007, Kennelly 2007, Lucchetti 2008). In our study, we used the results of a selectivity experiment carried out in 2015 in the south of Sicily (central Mediterranean Sea) where an ad hoc–designed sorting grid was mounted on a trawl net used by Italian trawlers exploiting DPS. The experiment outputs were explicitly included in length-based stock assessment models (i.e. Gadget) to address the medium-term population effects on two key stocks for trawl fisheries in the Strait of Sicily: deep-water rose shrimp and hake. This was to our knowledge one of the few attempts that have been made in the Mediterranean Sea to quantitatively assess the effects of changing gear selectivity on the productivity of the exploited stocks. Most of the trawl selectivity experiments carried out on multispecies fisheries either in the Mediterranean Sea or in other areas have been limited to analysing the performance selectivity tools and reducing the catch of juveniles (i.e. Sardà et al. 2006, Massuti et al. 2009). A proper evaluation of the effects relative to the goals of these studies is often not available because of a lack of suitable follow-up studies (Suuronen and Sardà 2007).

We have shown that the adoption of sorting grid led to a substantial improvement in selectivity for DPS and HKE. Indeed, the estimated L_{50} for DPS (19.8 mm CL) was close to the MCRS (20 mm CL). For HKE the estimated L_{50} (17.9 cm TL) was noticeably higher than the L_{50} for the trawl net without grid (15.5 cm TL), leading to a consistent reduction in the catch for specimens below the MCRS (20 cm TL). Mediterranean trawl fisheries are largely multi-specific, with several species of fish and shellfish contributing to fisheries landings and profits. Selectivity experiments have highlighted the issue of improving size-selection in a multispecies fishery with a single selection technique (Sardà et al. 2006, Bahamon et al. 2007, Aydın et al. 2008). Clearly, the same mesh size or sorting grid spacing is not suitable for all species, being too large for some species and too small for others, and optimal selection can be achieved for only a few species (Sardà et al. 2006). Nevertheless, even if a precise optimum is not achieved for all species, a general increase in the length at first capture can be obtained for most of the commercial species, offering general benefits in terms of fishery sustainability (Guijarro and Massutí 2006, Bahamon et al. 2007).

In our Gadget simulations, we have shown that the adoption of sorting grids by a consistent proportion (84%) of the trawl fleet exploiting DPS and HKE in the Strait of Sicily is likely to produce long-term positive and immediate effects on SSB and catch of the two stocks. In the case of DPS, SSB would increase by between 6% and 13% by 2030, while the catch in Scenario III would rise proportionally to 7% in comparison with the status quo. The simulated data indicated a relevant effect of the grid in reducing by about 31% and 16% the catch of ages 0 and 1, respectively, while the model simulated a significant effect in the catch of age 2+, with an increase of about 11% in 2030. This prompt reaction of the stock for both SSB and catch seems to be related to the short life cycle of the species, which is able to reach the first maturity during the first year with a length at first maturity in the Strait of Sicily of 20.8-24.0 mm CL and 14.3-19.0 mm CL for females and males, respectively (e.g. Fiorentino et al. 2013). In addition, the adoption of the grid would lead to a reduction of fishing mortality, an important step towards F_{MSY} ranging between 0.83 and 0.93 (Gancitano et al. 2017).

The predicted effect of sorting grids on HKE was basically an inversion of the stock decline trend estimated in the period 2002-2015, which was not immediate as in DPS because it occurred after a few years, leading to a 21% recovery of SSB in Scenario III by 2030. The catch is forecast to follow the same trend of SSB until 2030. The Scenario III would lead to an average increase of up to 10% of the total annual landings of the stock for all the fleets involved in the fishery. The model predictions indicated a relevant effect of the grid in reducing by about 25% and 13% the catch of ages 0 and 1, respectively. The model also simulated a consistent effect on the catch of older HKE (age>5), which increased by more than 20% in 2030. The shifted effect of the grid on hake stock is due to the growth parameters used in the model. According to Vitale et al. (2016), HKE in the Strait of Sicily is assumed to follow a slow growth, reaching the first maturity after the second year of life, with a length at first maturity of 21.5-28 cm TL for males and 31-37 cm TL for females.

As observed for DPS, the adoption of the grid led to an initial reduction in the catch that was compensated in the following years by an increase in total catch. However, unlike DPS, which showed an appreciable reduction of the predicted fishing mortality, HKE showed an overall effect of only a 5% decrease by 2030. This is also the result of the different impact of the Italian trawl fleet on the two stocks. Indeed, in 2016 the annual landing for DPS produced by this fleet was 70% of the total, while for HKE it was 45% (GFCM 2016). Such predicted benefits are therefore likely to be higher in scenarios simulating the whole trawl fleet using sorting grids, particularly for HKE.

The predictions obtained are also the results of the conditions set in the forecast Gadget routine used. In particular, constant harvesting, i.e. the proportion of catch over the available biomass, was assumed, so a variation in the abundance of length/age classes selected by the gear led to a proportional variation of the fishing mortality and catch on those classes. This also implies that the fishing mortality at age remains constant through time, with the only variations expected for the length classes on the left side of the selection curve.

The present study provides a comprehensive understanding of the effects of sorting grids on Mediterranean trawling. Using two important stocks with very different life history traits, deep-water rose shrimps and hake, as case study species, it has demonstrated a clear improvement in the exploitation pattern, with a reduction in the catch of undersized juveniles, an overall reduction in fishing mortality, and an increase in stock biomass and annual landings. These results indicate that sorting grids, if appropriately designed, could be extremely important tools for reducing by-catch of juveniles in Mediterranean trawl mixed fisheries, with clear benefits in terms of sustainability (Massutì et al. 2009, Aydın and Tosunoğlu 2011). Using grids in trawling can therefore contribute substantially to moving towards the goal of the CFP for more "eco-friendly" fisheries in which discards are reduced. In this perspective, the use of sorting grids, if integrated with the protection of the main nursery areas, can be a key step towards minimizing the impact of trawling on juveniles and promoting more selective trawl fisheries in the Mediterranean Sea.

ACKNOWLEDGEMENTS

The data were collected in the framework of the European Commission Horizon 2020 Research and Innovation Programme under Grant Agreement No. 634495 for the project Science, Technology, and Society Initiative to Minimize Unwanted Catches in European Fisheries (MINOUW). The Gadget models used in this study were developed with the financial support of the EU FP7 Programme project MAREFRAME (Grant Agreement No. 613571).

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