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# Bioeconomic impacts of two simple modifications to trawl nets in the NW Mediterranean

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ABSTRACT

A bioeconomic model was built to assess the contribution of more selective trawl nets to the objectives of the European Multi-Annual Plan for demersal fisheries in the Western Mediterranean (WM MAP). The biological submodel was parameterized with age-structured population parameters for the five target stocks in the WM MAP (European hake, red mullet, deep-water rose shrimp, Nephrops and red shrimp) with a sixth stock combining the remaining commercial by catch and following a biomass dynamics model. The trawl fleet was composed of three fleet segments, according to Vessel Length class (VL1218, VL1824, VL2440), practicing two métiers: coastal mixed demersal fishery and deep-water crustacean fishery. The technological solutions analyzed are two simple technical modifications to the otter bottom trawl and based on i) using a panel of meshes turned 90° (T90) in the extension of the trawl net, and ii) inserting a selective grid built from 40 mm square mesh (SM40) netting into the extension of the trawl net. The Results show that, in terms of policy objectives, the reduction in the values of fishing mortality achieved with these selectivity modifications would be insufficient to reach the target fishing mortality at maximum sustainable yield (Fmsy) prescribed in the WM MAP by 2025. However, model results project a substantial recovery of hake and red mullet stock biomass. The recovery of these two important stocks would help improve the evolution of the economic indicators, resulting generally in higher income, profits and salaries in the short (2025) and mid term (2030).

## 1. Introduction

Results of stock assessments over the last decade for the main stocks that sustain Mediterranean fisheries show that 70–90% of the stocks were overexploited and the level of fishing mortality was 2–4 times the fishing mortality that would produce the maximum sustainable yield ($F_{MSY}$), depending on the year of assessment (FAO, 2020). The chronic overexploitation of fisheries resources (Colloca et al., 2013), added to increased economic production costs and market competition with seafood imports results in low economic performance of Mediterranean fishing fleets, which helps explain in part the strong reduction of fishing vessels observed (Maynou, 2020).

With the objective of improving the long-term viability of fisheries, taking into account local specificities, the European Union introduced the concept of regionalization and multi-annual plans in the 2013 reform of the Common Fisheries Policy (EU Reg. 1380/2013). In the case of the Western Mediterranean sea, a Multi-Annual Plan (WM MAP) for demersal fisheries was adopted by the European Parliament (February 2019) and the Council (June 2019) and entered into force on Jan. 1st, 2020 (COM/2018/0115 final – 2018/050 (COD)). Among other things, the WM MAP establishes an important reduction of fishing effort (of 40% over the period 2020–2024), the temporal prohibition of trawling between 50 and 100 m depth in designated areas, as well as promoting the use of more selective fishing gear to reduce fishing mortality. The stated overall objective of the WM MAP is to align the fishing mortality with $F_{MSY}$ for the five main fish stocks in the area: European hake (*Merluccius merluccius*), red mullet (*Mullus barbatus*), Norway lobster (*Nephrops norvegicus*), deep-water rose shrimp (*Parapenaeus longirostris*) and red shrimp (*Aristeus antennatus*).

The new regulations established in the WM MAP add to the traditional management measures applied to Mediterranean fisheries (EU Reg. 1967/2006), which are based on fishing effort control and technical specifications of the fishing gear, but do not limit fisheries output (that is, no limits to catches are set, contrary to other European fisheries) (Medina et al., 2016). In the western Mediterranean otter bottom trawl fleets produce most of the demersal landings (Lleonart and Maynou, 2003). Trawlers practice two main fishing strategies: the mixed demersal fishery on the continental shelf and the deep-water fishery.

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While the mixed demersal fishery targets a large variety of fish, crustaceans and cephalopods, the deep-water fishery targets exclusively the valuable red shrimp. These two fishing strategies are considered as separate métiers in the WM MAP (COM/2018/0115 final – 2018/050 (COD)).

The current regulatory mesh for the codend of trawls operating in EU Mediterranean fisheries is square mesh of 40 mm (SM40, or diamond mesh of 50 mm, DM50, by derogation: EU Reg. 1967/2006). Several studies show that the selectivity of trawls fitted with the regulatory meshes is poor, with significant retention of undersize individuals and juveniles of target and bycatch species (Garcia-de-Vinuesa et al., 2018; Brčić et al., 2018; Bonanomi et al., 2020). These studies, as well as considerations on conservation of marine ecosystems and reduction of fishing mortality of vulnerable fauna, highlight the need to consider additional technical measures that contribute to more selective, lower impact trawl nets (Suuronen et al., 2012).

Improving the selectivity of trawl nets in demersal fisheries may produce important benefits (in biological, ecological and economic terms) in the mid to long term (Demestre et al., 1997; Scott and Sampson, 2011; Colloca et al., 2013; Maynou, 2014). Reducing fishing mortality of juvenile or immature fish would contribute to align exploitation rates with policy objectives (such as fishing at MSY or reduction of unwanted catches). More selective trawls would also help reduce their impact on vulnerable benthic species seabed habitats (de Juan et al., 2020). Despite the expected losses in economic profits in the short term, the adoption of more selective trawl nets can help contribute to rebuild stocks and produce higher revenues, as well as increased labour remuneration (Colloca et al., 2013; Prellezo et al., 2017).

We carried out a bioeconomic analysis with the objective of assessing the effects of adopting two trawl net designs with modifications on the trawl extension, one based on a T90 panel and another based on inserting a selective grid, following the experimental designs and Results of previous studies (Sola and Maynou, 2018a; Vitale et al., 2018a; Maynou et al. (submitted), Garcia-de-Vinuesa et al. (submitted).

## 2. Material and methods

### 2.1. Data sources

Two separate modifications to the standard otter bottom trawl employed for demersal fishing in the Geographical SubArea 6 (GSA06) of Northeast Spain (map, Appendix 1) were trialled in field experiments: i) a panel in the extension piece of the trawl made with 90° turned mesh (T90) before the codend, following the same design and specifications as in Sola and Maynou (2018a), and ii) a selective grid placed in the middle of the extension piece, following design G1-SM40 of Vitale et al. (2018a: Fig. 2). The objectives of the field tests were to determine the selection ogives for hake, red mullet and Norway lobster in the case of the T90 experiments, and only hake and red mullet in the selective grid experiments, see Maynou et al. (submitted) and Garcia-de-Vinuesa et al. (submitted) for details on the experimental procedures and the selection ogives obtained.

The target species of the two trawl fishing métiers practiced in the Western Mediterranean are subject to regular stock assessments by the European Commission Scientific, Technical and Economic Committee for Fisheries (STECF) and the General Fisheries Commission for the Mediterranean (GFCM). We used the biological parameters from recent STECF assessments (STECF, 2018; 2019; 2020) and their assessment Results (number at age, fishing mortality; biological reference points) to parameterize a bioeconomic model. The species assessed in these reports are the target species of the mixed demersal fishery: hake (Merluccius merluccius), red mullet (Mullus barbatus), deep-water rose shrimp (Parapenaeus longirostris), Norway lobster (*Nephrops norvegicus*), and the red shrimp (Aristeus antennatus), which constitute the target species on continental slope fishing grounds. The biological basis of the bioeconomic model is shown in Appendix 2.

The economic parameters for the model were obtained from the Annual Economic Report for EU fisheries (AER, 2020) published by the STECF from fisheries official data (Data Collection Framework) as well as national transversal data available from https://stecf.jrc.ec.europa.eu/. *These official data were complemented with our own observations in the project* CriMa (RTI2018–095770-B-100), for ex-vessel fish sale prices and computing crew salaries, which in Mediterranean fisheries usually follow a share-based model (Guillén et al., 2017). The economic sub-model is parameterized for three trawl fleets, based on the vessel length (VL) classes: fleet 1, vessels 12–18 m LOA (VL1218), fleet2, vessels 18–24 m LOA (VL1824), vessels 24–40 m LOA (VL2440). The parameters the economic submodel are given in Appendix 3.

### 2.2. Model description

The bioeconomic model was built with FLBEIA “FL Bio-Economic Impact Assessment” (http://flbeia.azti.es; http://github.com/flr/FLBEIA). This model has been widely applied to problems of fisheries management simulation in European waters and the model details are available in a number of publications (García et al., 2013, García et al., 2017a, b, c; García et al., 2019, Sánchez et al., 2018). A bioeconomic fisheries model is a mathematical tool designed to investigate the interrelated economic and ecological basis for fisheries (Prellezo et al., 2012). Bioeconomic fisheries models provide a simplified representation of the dynamics of fish stocks, the biological side of the model, and fleets, the (socio)economic factors of fisheries productivity. Bioeconomic fisheries models have advanced notably since the classical Gordon-Schaefer formulation of the 1950’s (Clark, 1990) and in addition to the direct basis of fisheries (fish stocks and fishing fleets) can help analyse the influence of external drivers, such as ecological drivers of fish stock productivity, the impact of alternative management measures (Punt et al., 2016) or changes in the economic parameters (e.g., prices). For the analysis of the impact of selectivity measures in the Western Mediterranean demersal fishery, we built a bioeconomic model with the biological component consisting of age structured population growth models for each of the five main target species, with species-specific stock/recruitment models, plus a biomass surplus model for the accompanying commercial by-catch. The economic component included economic parameters for the three trawl fleet segments. The fleet models were based on fixed effort dynamics, Cobb-Douglas production, fixed species-specific fish prices and fixed capital. The following economic costs of each fleet and/or métier were specified: fuel costs, labour costs, other variable costs, non-variable costs, depreciation of capital and opportunity cost of capital. The model application was built with FLBEIA and the underlying software components of the Fisheries Laboratory in R (FLR, Kell et al., 2007). Technical details are provided in Appendix 1.

### 2.3. Simulation conditions and scenarios

We used a bioeconomic management strategy evaluation (MSE) approach (Punt et al., 2016). MSE can be used to identify a ‘best’ management strategy among a set of candidate strategies. In our case, the primary objective was to compare the performance of two technical solutions to improve trawl selectivity against the *statu quo*. The first technical solution tested was the substitution of the standard 50 mm diamond mesh in the extension of the trawl net for a similar mesh with knots turned 90° (“T90” net), following the design of Sola and Maynou (2018a) and the field tests in Maynou et al. (submitted) and Garcia-de-Vinuesa et al. (submitted). The second modification tested was the insertion of a selective grid made of 40 mm square mesh (SM40) in the extension, following Vitale et al. (2018a) and Maynou et al. (submitted). The stocks analyzed for selectivity with the T90 modification were hake (*Merluccius merluccius*), red mullet (*Mullus barbatus*), and Norway lobster (*Nephrops norvegicus*). The analysis of the selective grid concerned only hake and red mullet.

For each of the five target species, the biological parameters, natural mortality-, weight-, and maturity-at-age were considered constant and equal to the average of the last 3 data years (2017–2019). The economic parameters were projected as constant for the 2019–2030 projection period. The ability of MSE to provide advice to fisheries management depends critically on how well uncertainty is represented (Punt et al., 2016) and in this application we identify uncertainty on the parameterization of the stock-recruitment model for the fishery target species as the main source of uncertainty. Uncertainty was explored by adding a stochastic error term to the SSB/R models of each species j:

$$R_{j,t} = \varphi_j(SSB_{j,t})^* \varepsilon_j$$

where $\varphi$j is the functional form relating recruitment and spawning stock (Beverton and Holt, or Ricker, depending on the species, see Appendix *2*; García et al., 2017c), with $\varepsilon$j derived from the coefficient of variation of the historical recruitment series ($\varepsilon$HKE = 0.17, $\varepsilon$MUT = 0.14, $\varepsilon$NEP = 0.11, $\varepsilon$DPS = 0.25, $\varepsilon$ARA = 0.13), used to draw a value from a Gaussian distribution N ~ (1, $\varepsilon$j) at each iteration. Because the data series of SSBj,t and Rj,t were in all cases short (10–15 years of observations) several S/R models fitted the observations well. The primary model chosen was that with the lowest AIC value.

The model was projected for the period 2019–2030, with 2019 as year 0 (corresponding to the most recent year in the stock assessments) for two scenarios (**s1**: adopting the T90 solution, **s2**: adopting the selective grid solution), compared against the baseline of continuing fishing with the standard net and the current selectivity patterns (**s0:** *statu quo*). The Results of the stochastic simulations were extracted as mean and 95% confidence interval for each indicator variable. For most stocks, the last year in the assessment was 2019, except for deepwater rose shrimp where the series terminated in 2017 and was projected until 2019 (STECF, 2020).

### 2.4. Selectivity ogive

The Results of selectivity field tests typically return the size frequencies of the catches. To examine the effects of the modified fishing gear on changes in fishing mortality by means of bioeconomic models it is then necessary to convert the catch at size into catch at age vectors. The age-length transition matrix was built from the mean length at age and variance of length at age calculated from the size frequencies for the five species in the official data source, combining size frequency histograms of the years 2017–2019 following Hordyk et al. (2014). The probability of individuals of age a being in length class i is:

$$P_{l,a} = \begin{cases} \phi\left(\frac{X^{lo}_{l+1} - X_a}{\sigma_{Xa}}\right) & l = 1 \\ \phi\left(\frac{X^{lo}_{l+1} - X_a}{\sigma_{Xa}}\right) - \phi\left(\frac{X^{lo}_{l} - X_a}{\sigma_{Xa}}\right) & 1 < l < L \\ 1 - \phi\left(\frac{X^{lo}_{l} - X_a}{\sigma_{Xa}}\right) & l = L \end{cases} \quad (1)$$

*where* $\phi$ *is the standard normal cumulative distribution function,* $X^{lo}_l$ *is the upper bound of length class l, and L is the total number of length classes. Xa and σXa are the mean and the standard deviation of the normal component of age-class a. The age-length probability matrix was modified for the experimental fishing gear by multiplying by the expected catch ratio from* Maynou et al. (submitted) and García-de-Vinuesa et al. (submitted)*:*

$$p_{l,a} = P_{l,a} CR_l \quad (2)$$

where CRl is the catch-ratio by length class l.

*The mean length-at-age Xa and its variance σXa2 were computed with the R version of the MIX model (library mixdist v. 0.5-4 in R v. 3.0.2:* http://www.math.mcmaster.ca/peter/mix/mix.html; Macdonald and Green, 1988). The MIX algorithms assume that a size-frequency histogram is the addition of n Gaussian distributions with mean Xa and standard deviation $\sigma$Xa. We used the default algorithm in function mix of the mixdist library, with starting values compatible with the von Bertalanffy parameters used in the stock assessments of the five species (STECF, 2020).

The selectivity ogive by age was computed, for the five species, by adding the proportions in the age-length probability matrix in each age class:

$$S_a = \sum_{l=1}^{L} p_{l,a} \quad (3)$$

This vector was entered as modifier of the "catch.q" slot in FLBEIA, assuming that the properties of each selectivity device was the same for the three fleets (Fig. 1).

### 2.5. Indicators

The performance of the different scenarios tested was summarized with biological and economic indicators. For biological quantities, the indicators are given as thousand individuals (recruitment) or tonnes (biomass). Economic indicators are shown in million Euro or Euro/ton, as appropriate. The fishing mortality indicator shown is Fbar, computed over the ages indicated in the stock assessment Results (STECF, 2020; summarized in Appendix 2).

The primary biological indicators selected were: catch by stock, fishing mortality (Fbar), recruitment, spawning stock biomass. The economic indicators examined, with their definitions were:

- Gross Value: value of landings (landings x prices).
- Operating costs: Landing Fee x Gross value + Fuel cost x Effort + Other variable costs x effort + Fixed costs x Vessel.
- GVA (Gross Value Added) = Gross value - Operating Costs.
- Gross Surplus: Gross Value Added - Labour costs, where Labour costs: share of the landings x Gross value + Fixed labour costs x Crew.
- Profitability: Gross Surplus/Gross Value.

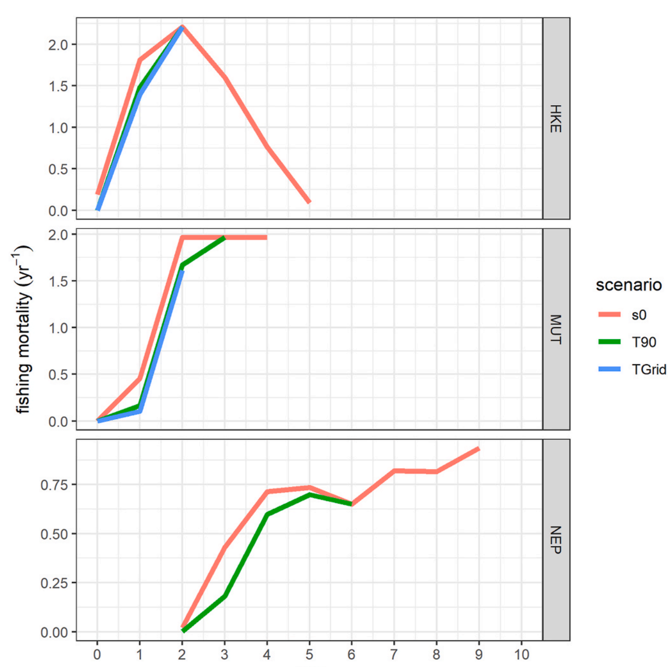


**Fig. 1.** Changes to the fishing mortality vector with the adoption of the extension panel built from 90° turned mesh T90 (green, s1) or the extension panel including a selective grid TGrid (blue, s2) technical solutions, compared to the base case fishing mortality vector (s0). HKE: hake; MUT: red mullet; NEP: Norway lobster. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

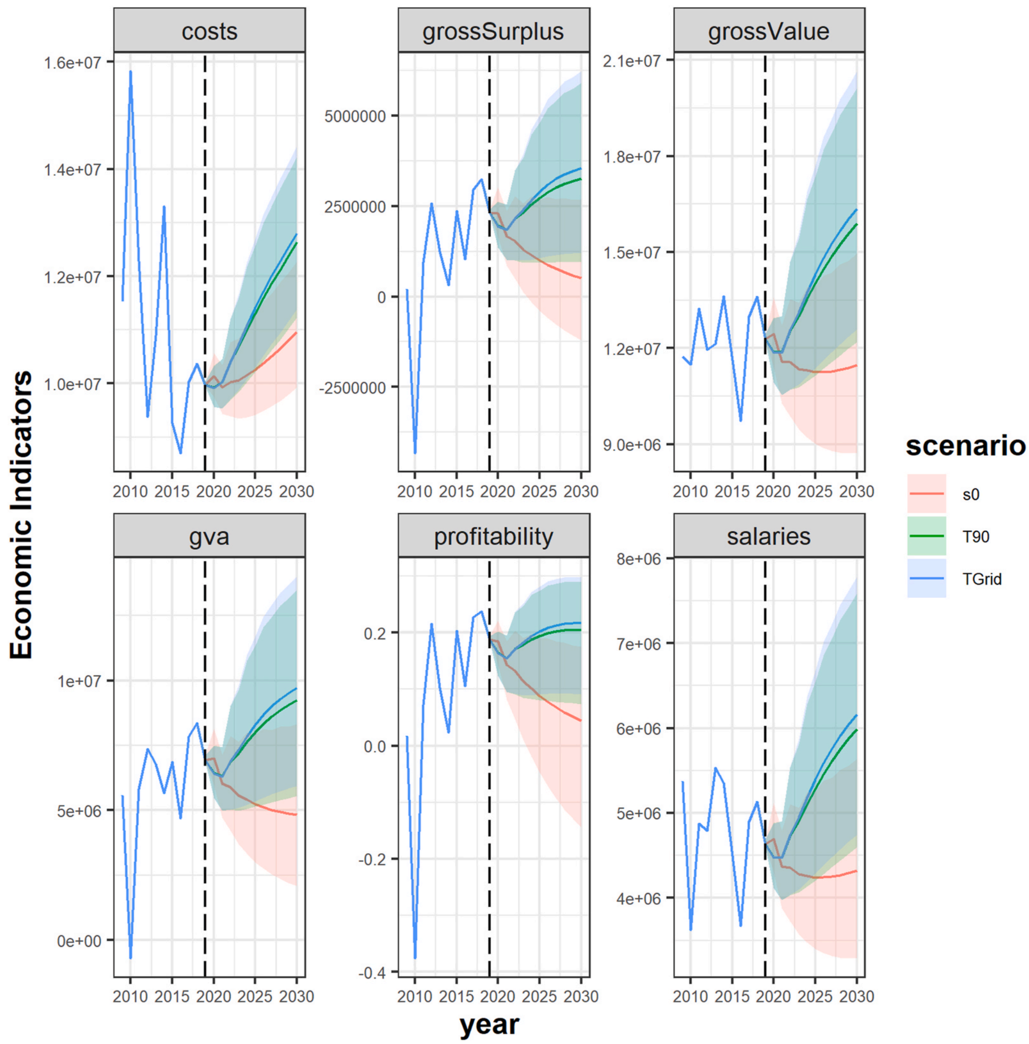


**Fig. 2.** Evolution of economic indicators (in real terms) for Fleet 1 (VL1218) under simulation scenarios **s0** (business as usual), **T90** (s1, improving the selectivity of hake, red mullet and Norway lobster by adopting a T90 panel technical solution) and **TGrid** (s2, improving the selectivity of hake and red mullet by adopting a selective grid technical solution). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

○ Salaries: equivalent to Labour costs.

In addition to the bioeconomic modelling Results, a simple analysis of the differences in catch (in volume and value) was made with the fisheries production data obtained during the field experiments. Naturally, this analysis reflects only the immediate earnings or losses corresponding to the period of the field experiments, while the analysis by means of the bioeconomic model informs at larger temporal scales and aggregated at the level of fleets and allows to examine economic impacts beyond the particular sampling vessels.

## 3. Results

The following tables (Tables 1–4) summarize the main Results of the simulations under scenarios **s0**, s1 (**T90)** and s2 (**TGrid)** for the short term (2025: reference target year in the WM MAP) and the mid-term (2030). The indicators examined are, for each species, catches, biomass, recruitment and fishing mortality and provided in these tables as percentage change from the recent 2016–2018 average.

Table 1 shows that under **s0** the stocks of hake and red shrimp would likely produce ever decreasing catches. The catches of red mullet and deep-water rose shrimp would remain stable over the projection horizon and the catches of Norway lobster would increase by 30% for all periods. Overall, total catches of the OTB fleet would diminish by ca. 10%.

Conversely, under the scenario implementing the **T90** modification to the trawl net, the catches of hake are projected to almost double by 2025. In the case of red mullet a moderate increase of ca. 30% is forecast for 2025. For Norway lobster, an increase of ca. 40% in catches could be expected. In the selective grid scenario, **TGrid**, an increase in catches of hake larger than in the T90 scenario is forecast, while for red mullet the increase in catches would be comparable, if slightly lower. Naturally, the evolution of catches of Norway lobster under the TGrid scenario, and that of deep-water rose shrimp and red shrimp in both alternative scenarios, is not different from the base-case scenario (**s0**) because no changes to selectivity for these stocks were implemented.

Table 2 shows that under the **s0** scenario the biomass of all stocks would decrease (except for Norway lobster), particularly for hake (reduction of ca. 50% by 2025) and red shrimp (reduction by ca. 80%). In contrast, with the **T90** modification the biomass of the hake stock would increase importantly, practically doubling by 2025. The growth in red mullet biomass would be moderate, between 20 and 30%, approximately. The biomass of Norway lobster would increase slightly more under the T90 scenario than in the s0 scenario. The Results of the **TGrid** scenario are very similar, although this scenario would be slightly more favourable to hake and less favourable to red mullet.

Table 3 shows that under **s0** two stocks would likely produce ever decreasing recruitment: hake and red shrimp. Recruitment of red mullet and deep-water rose shrimp would practically remain stable over the

**Table 1**
Changes in **catch** per stock and scenario as % change of the recent average. Short term (2025) and mid-term (2030). Base 100 = average 2016–2018. HKE: hake; MUT: red mullet; NEP: Norway lobster; DPS: Deep-water rose shrimp; ARA: red shrimp. S0: base scenario, no selectivity change; S1 (T90): selectivity device extension panel built from 90° turned mesh; S2 (TGrid): extension panel including a selective grid.

| SCENARIO | STOCK | CATCH (T) 2016–2018 | CATCH 2025 %CHANGE | CATCH 2030 %CHANGE |
|---|---|---|---|---|
| **S0** | HKE | 2071 | 61.06% | 46.87% |
| | MUT | 1189 | 100.86% | 99.99% |
| | NEP | 287 | 130.64% | 132.53% |
| | DPS | 699 | 98.46% | 101.77% |
| | ARA | 856 | 34.81% | 19.26% |
| | all OTB | 10453 | 91.21% | 87.30% |
| **S1 (T90)** | HKE | 2071 | 193.36% | 242.21% |
| | MUT | 1189 | 127.21% | 135.30% |
| | NEP | 287 | 137.11% | 138.29% |
| | DPS | 699 | 98.46% | 101.77% |
| | ARA | 856 | 34.81% | 19.26% |
| | all OTB | 10453 | 120.60% | 130.18% |
| **S2 (TGRID)** | HKE | 2071 | 222.53% | 279.37% |
| | MUT | 1189 | 120.93% | 127.34% |
| | NEP | 287 | 130.64% | 132.53% |
| | DPS | 699 | 98.46% | 101.77% |
| | ARA | 856 | 34.81% | 19.26% |
| | all OTB | 10453 | 106.71% | 106.71% |

**Table 2**
Changes in **spawning stock biomass** per stock and scenario as % change of the recent average. Short term (2025) and mid-term (2030). 1. Base 100 = average 2016–2018. Scenario and stock abbreviations as in Table 1.

| SCENARIO | STOCK | BIOMASS (T) 2016–2018 | BIOMASS 2025 %CHANGE | BIOMASS 2030 %CHANGE |
|---|---|---|---|---|
| **S0** | HKE | 5439 | 53.89% | 41.64% |
| | MUT | 4402 | 87.02% | 86.39% |
| | NEP | 863 | 125.21% | 126.38% |
| | DPS | 2563 | 89.39% | 92.11% |
| | ARA | 5181 | 33.83% | 18.93% |
| | all OTB | 30723 | 83.85% | 79.33% |
| **S1 (T90)** | HKE | 5439 | 183.54% | 223.34% |
| | MUT | 4402 | 123.44% | 129.13% |
| | NEP | 863 | 136.73% | 137.11% |
| | DPS | 2563 | 89.39% | 92.11% |
| | ARA | 5181 | 33.83% | 18.93% |
| | all OTB | 30723 | 112.34% | 117.92% |
| **S2 (TGRID)** | HKE | 5439 | 211.31% | 257.00% |
| | MUT | 4402 | 114.36% | 118.95% |
| | NEP | 863 | 125.21% | 126.38% |
| | DPS | 2563 | 89.39% | 92.11% |
| | ARA | 5181 | 33.83% | 18.93% |
| | all OTB | 30723 | 115.63% | 122.12% |

projection horizon, at slightly lower values than in the base case (2016–2018). The recruitment of Norway lobster would increase by 20% for all periods. Overall, total recruitment of the OTB stocks would diminish by ca. 35–40%. The impact of the fishing gear modifications on recruitment would be relatively low, except for hake with an increase of 50% by 2030 under the T90 scenario and 65% under selective grid scenario.

In terms of fishing mortality (Table 4), projecting the effort observed in 2019 forward would result in a decrease of F for all stocks except red shrimp. This evolution under "business as usual" scenario (s0) is due to the decrease observed in 2019 with respect to the average 2016–2018 in fishing effort on continental shelf stocks and, conversely, the increase in fishing effort directed to the deep water stock (red shrimp). For the three species impacted by the T90 technical modification (hake, red mullet and Norway lobster) additional reductions of ca. 10% in fishing mortality could be expected. The selective grid technical solution (TGrid) would afford 1–2% additional reduction of fishing mortality in the two

**Table 3**
Changes in **recruitment** per stock and scenario as % change of the recent average. Short term (2025) and mid-term (2030). Base 100 = average 2016–2018. Scenario and stock abbreviations as in Table 1.

| SCENARIO | STOCK | REC (000) 2016–2018 | REC (000) 2025 %CHANGE | REC (000) 2030 %CHANGE |
|---|---|---|---|---|
| **S0** | HKE | 121102 | 45.95% | 36.10% |
| | MUT | 494659 | 85.37% | 84.95% |
| | NEP | 42656 | 119.95% | 119.93% |
| | DPS | 705276 | 79.35% | 81.53% |
| | ARA | 671041 | 35.50% | 19.98% |
| | all OTB | 2040444 | 65.30% | 60.27% |
| **S1 (T90)** | HKE | 121102 | 132.34% | 150.55% |
| | MUT | 494659 | 105.19% | 107.51% |
| | NEP | 42656 | 119.47% | 118.70% |
| | DPS | 705276 | 79.35% | 81.53% |
| | ARA | 671041 | 35.50% | 19.98% |
| | all OTB | 2040444 | 75.22% | 72.51% |
| **S2 (TGRID)** | HKE | 121102 | 146.55% | 164.81% |
| | MUT | 494659 | 101.06% | 103.21% |
| | NEP | 42656 | 119.95% | 119.93% |
| | DPS | 705276 | 79.35% | 81.53% |
| | ARA | 671041 | 35.50% | 19.98% |
| | all OTB | 2040444 | 75.07% | 72.34% |

**Table 4**
Changes in **fishing mortality** (Fbar) per stock and scenario as % change of the recent average. Short term (2025) and mid-term (2030). Base 100 = average 2016–2018. Scenario and stock abbreviations as in Table 1.

| SCENARIO | STOCK | F 2016–2018 | F 2025 %CHANGE | F 2030 %CHANGE |
|---|---|---|---|---|
| **S0** | HKE | 1.67 | 91.71% | 91.71% |
| | MUT | 1.17 | 92.50% | 92.50% |
| | NEP | 0.74 | 96.01% | 96.01% |
| | DPS | 0.80 | 96.46% | 96.46% |
| | ARA | 1.00 | 118.81% | 118.81% |
| **S1 (T90)** | HKE | 1.67 | 81.74% | 81.74% |
| | MUT | 1.17 | 78.16% | 78.16% |
| | NEP | 0.74 | 89.94% | 89.94% |
| | DPS | 0.80 | 96.46% | 96.46% |
| | ARA | 1.00 | 118.81% | 118.81% |
| **S2 (TGRID)** | HKE | 1.67 | 79.58% | 79.58% |
| | MUT | 1.17 | 80.66% | 80.66% |
| | NEP | 0.74 | 96.01% | 96.01% |
| | DPS | 0.80 | 96.46% | 96.46% |
| | ARA | 1.00 | 118.81% | 118.81% |

impacted stocks, hake and red mullet.

Figs. 2–4 show the evolution of the economic indicators during the implementation and up to 2030 ("mid-term") of the technical modifications based on the T90 net panel (scenario **T90**) and the selective grid (scenario **TGrid**), against a base scenario **s0** (no technological change) projecting recent average fishing effort. These figures report economic quantities in real terms.

In all three fleets, under scenario **s0**, gross value (equivalent to fisheries income) would tend to decrease in the short to mid-term (i.e. up to 2030), following the decrease in the catches of more valuable stocks hake and red shrimp (cf. Table 1), but on average would take values within the historical (2009–2019) observed range. Costs would rise slightly during the period 2020–2030, but always within the bounds of observed data. Gross surplus (profits) would decrease for all fleets, more clearly for the two largest fleets, whose dependence on the deep water stock (red shrimp) is higher. However, taking into account the confidence intervals produced, the evolution of gross value, costs and gross surplus for the period 2020–2030 is within the variation observed for the historical period 2009–2019. On the other hand, the indicator profitability would tend to decrease and become lower than recent values observed, with non-null probability of becoming negative for fleet 1 (VL1218) after 2025. The indicators GVA and salaries would follow the

 

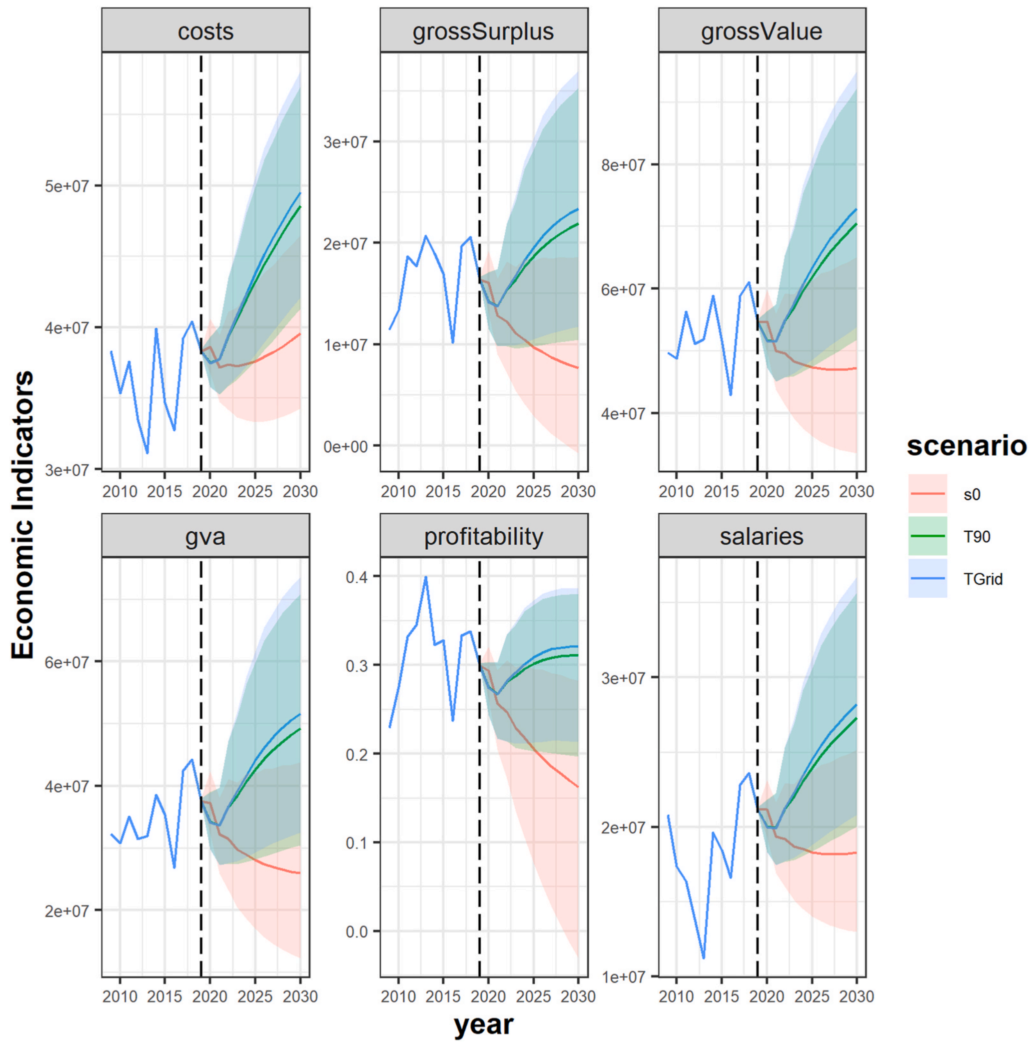


**Fig. 3.** Evolution of economic indicators (in real terms) for Fleet 2 (VL1824) under simulation scenarios **s0** (business as usual), **T90** (s1, improving the selectivity of hake, red mullet and Norway lobster by adopting a T90 panel technical solution) and **TGrid** (s2, improving the selectivity of hake and red mullet by adopting a selective grid technical solution). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

same trends as gross value because salaries here are a constant fraction of gross value (share-based remuneration scheme).

The projection of the six economic indicators under scenarios **T90** and **TGrid** would be very similar (Figs. 2–4), with the Results for **TGrid** slightly more optimistic than for **T90**, probably due to the better selective properties of the selective grid for ages 1 of hake and red mullet. The implementation of any of these two technical solutions would imply losses in gross value in the first to second years immediately after the implementation (i.e. years 2021 and 2022 in these simulations), but within the range of losses forecast for the **s0** scenario. With the quick recovery of the hake and red mullet stocks, all economic indicators would tend to produce higher values by the end of the implementation of the WM MAP. That is, by 2025 all economic average indicators showed higher values than the corresponding indicator under scenario **s0** "business as usual" for all fleets. For some indicators and fleets, the values projected after 2025 would be significantly higher the values obtained historically. For instance, for fleet 1 (Fig. 2), gross value, gross surplus, GVA and salaries are expected to be higher than any observed value in the period 2009–2019 with the adoption of the T90 or the TGrid modifications. Costs would increase, but within the historical range, and profitability would stabilize around 20%, around the upper range of the observed values (Fig. 2).

In the case of fleet 2 (Fig. 3) all indicators, except profitability, would increase beyond the historical observed value. Profitability would remain within the average range of observed values, around 30%. For fleet 3 (Fig. 4) the indicators gross value, costs, GVA and salaries are forecast to reach higher values than historical data, but gross surplus and profitability are not likely to vary beyond the observed ranges. The lower impact on profits of the technological solutions tested on fleet 3 is likely due to the higher reliance of this fleet on the deep water stock (red shrimp), for which no experimental data on selectivity was available.

The Results of the bioeconomic model contrast with the fisheries production data collected during the field experiments for the two sampling vessels (Appendix 4). The immediate loss in total catch was empirically estimated at 20% in volume and 12% in value for the case of the continental shelf demersal fish fishery. In the *Nephrops* fishery, the losses were 14% in volume and 13% in value. In the experiments with the selective grid, although a true control was not available, the catches of the commercial vessel during the days of the selective grid experiments were 12% lower in volume and 14% in value. These catch losses of the three experimental interventions are larger than the losses projected by the bioeconomic models for any of the three fleets for years 1 or 2 of the simulations.

In terms of policy objectives, the values of fishing mortality would be insufficient to reach the target Fmsy (Table 5; Table A2.1) specified in the WM MAP, but would lead to a recovery of hake and red mullet stock biomass (the beneficial effect of T90 on Norway lobster was weak). The recovery of these two important stocks would help improve the

 

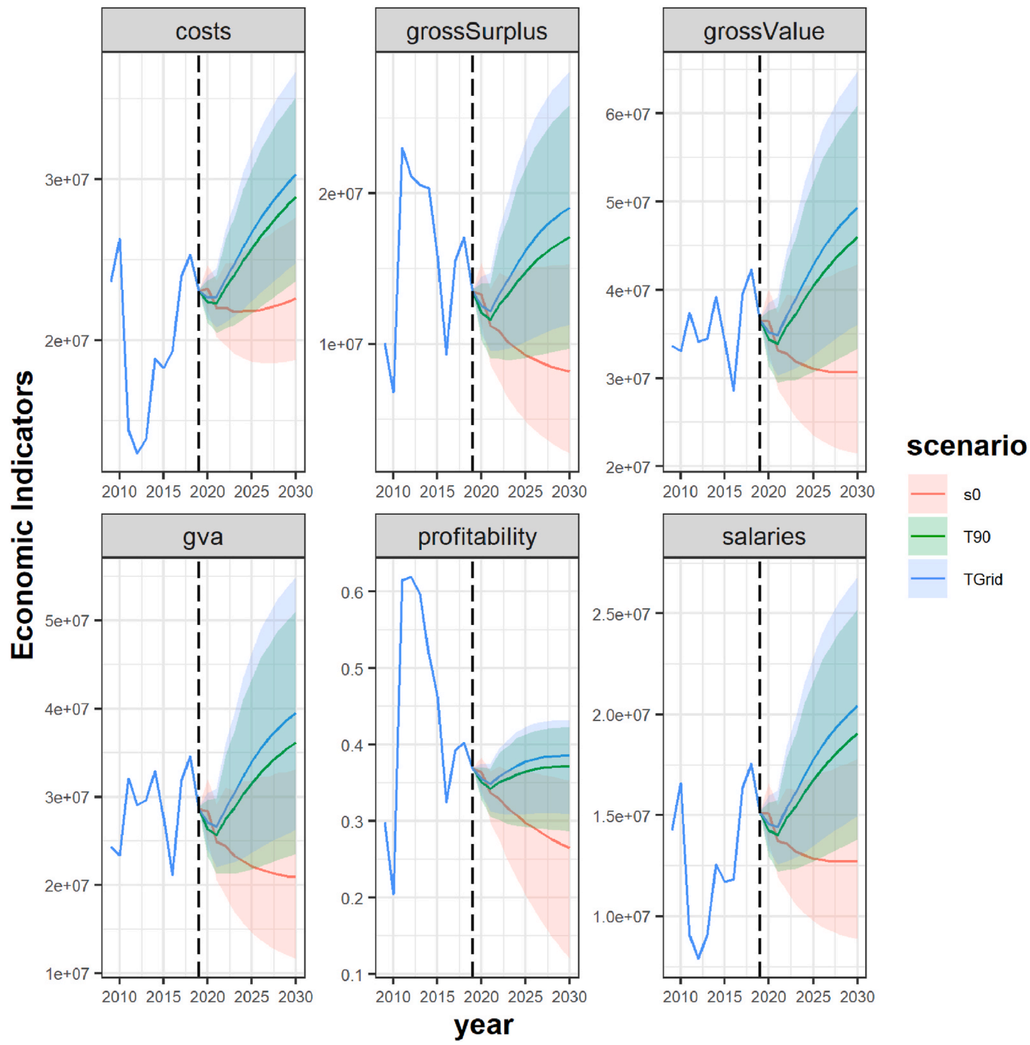


**Fig. 4.** Evolution of economic indicators (in real terms) for Fleet 3 (VL2440) under simulation scenarios **s0** (business as usual), **T90** (s1, improving the selectivity of hake, red mullet and Norway lobster by adopting a T90 panel technical solution) and **TGrid** (s2, improving the selectivity of hake and red mullet by adopting a selective grid technical solution). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 5**
Fishing mortality at MSY ($F_{msy}$) from stock assessment forms (STECF, 2020), Fishing mortality at MSY upper ranges ($F_{upp}$), and projected fishing mortality in 2025 according to scenarios T90 and TGrid. F upper ranges ($F_{upp}$) computed according to the formula: $F_{upp} = 0.007801555 + 1.349401721*F_{msy}$.

| | $F_{msy}$ | $F_{upp}$ | F (average 2016–2018) | F (2025) Scenario T90 | F (2025) Scenario TGrid |
|---|---|---|---|---|---|
| hake | 0.38 | 0.52 | 1.67 | 1.37 | 1.33 |
| red mullet | 0.31 | 0.43 | 1.17 | 0.91 | 0.94 |
| Norway lobster | 0.11 | 0.16 | 0.74 | 0.66 | 0.71 |
| deep-water rose shrimp | 0.21 | 0.29 | 0.80 | 0.77 | 0.77 |
| red shrimp | 0.29 | 0.45 | 1.00 | 1.19 | 1.19 |

evolution of the economic indicators, resulting generally in higher income, profits and salaries, observed in the model projections.

## 4. Discussion

Many proposals to enhance the selectivity of bottom trawls are based on increasing mesh sizes at the codend, to facilitate escapement of undersize individuals and reduce growth overfishing. For instance, Demestre et al. (1997) showed how increasing the mesh size from 40 to 50 mm (diamond) traditional Mediterranean trawls could produce important (67%) increases in yield per recruit for the red mullet (*Mullus surmuletus*). However, while ever increasing cod end meshes can facilitate escapement of undersize individuals of the target species (Sobrino et al., 2000), they lead to important losses of commercial by-catch, which is economically very relevant in mixed species fisheries. Therefore, it is important to examine alternative technological solutions that are selective towards the target species of the trawl fishery, with acceptable levels of losses of valuable bycatch.

Adopting the technological solutions proposed (modification of the trawl extension with a T90 panel or insertion of a selective grid) would result in decreased fishing mortality for younger age classes of hake and red mullet (and possibly other stocks, although experimental data was available only for Norway lobster in the T90 experiments, not for the other stocks). According to the bioeconomic model Results, any of the two technical solutions would produce improved biological and economic indicators by the year 2025, target year of the application of the WM MAP, compared with continuing with *statu quo* fishing selection patterns. A transitional period of lower (private) profits in the first 2 years after the implementation of any of the two technological solutions can be observed for the three trawl fleet segments analyzed, but the values projected by the model during the transitional period are within the confidence intervals of the *statu quo* projection.

In terms of the main policy objective stated in the WM MAP (reaching $F_{msy}$ by Jan. 1, 2025), the adoption of any of the two technical solution would be insufficient, and likely to be less effective than the reduction of fishing effort established in the WM MAP. Maynou (2019) in a theoretical study comparing the reduction of fishing mortality in the younger age classes against an overall reduction of fishing mortality across all classes also concluded that strong effort reductions are more efficient in achieving Fmsy targets than selective measures or protecting nursery areas. However, Results from other applications of bioeconomic simulation models to investigate the effect of increased selectivity show that selectivity can perform better than effort control in biological and economic terms (Prellezo et al., 2017; Sola and Maynou, 2018b; Vitale et al., 2018b). From the perspective of implementation of policies to reduce fishing mortality, more selective fishing gear can be a good option to move towards the Fmsy objective and helps to avoid large reductions in fishing effort, such as the 40% reduction in days-at-sea over the period 2020–2024 established in the WM MAP (*COM/2018/0115 final – 2018/050 (COD)*). Stepputtis et al. (2016) show how clever modifications of trawls can result in very selective gear, that could eventually lead to exploit fish stocks at near optimal size (*Lopt*), which would in turn help rebuild stock biomass and produce higher yields (Colloca et al., 2013).

This simulation study was based on the experimental Results of field tests of the technological solutions shown in Sola and Maynou (2018a), Vitale et al. (2018a), Maynou et al. (submitted) and Garcia-de-Vinuesa et al. (submitted) where only hake, red mullet and Norway lobster were studied for selectivity in the T90 experiments, and only hake and red mullet in the selective grids experiments. The lack of information on the selectivity impact on the important deep water stock (red shrimp) implies that the economic short-term benefits are likely to be overestimated, while the possible biomass recovery of this stock cannot be appreciated in our results. Likewise, the notional stock combining all other species was kept constant throughout the simulation horizon.

Other studies using bioeconomic models for the analysis of the impact of more selective fishing gear (trawl is normally the focus of these studies) reach similar conclusions. For instance, Prellezo et al. (2017), in a simulation study of the effect of increasing mesh size in a trawl fishery in NW Spain, reported small increases in gross revenues and crew compensation (1.5 and 2%, respectively) in the short term. However, Spanish trawl fisheries in the Atlantic ocean are regulated by quotas, not fishing effort, and the simulations allowed for fishing effort increase, i.e. in the model the fisher attempted to compensate the loss of output by increasing the input of production factors. As fishing effort was not restricted, fishing vessels aimed at fulfilling the quota, resulting in reduced efficiency in capital and labour productivity (Prellezo et al., 2017). In Mediterranean fisheries, fishing effort is limited to a number of authorized annual fishing days and catch quotas are not implemented, hence private profits and crew salaries can be expected to increase with increased stock size and constant fishing effort.

Kronbak et al. (2009) made a bioeconomic analysis of implementing four different configurations of selective gear in a trawl fishery operating in Kattegat and Skagerrak waters, which could contribute to rebuild stocks of the main demersal target species. Their Results show that relatively important losses are to be expected in the 1–2 years immediate to the adoption of the more selective fishing gear, because of the larger escapement of the target species in this multi-species fishery, but also because of the up-front cost of adopting the selective fishing gear. In this model the cost was assumed to be met by vessel owners, reducing private profits, while in our simulations the cost of adopting the technical devices are so low (ca. 1000 € per vessel) that we did not take them into account. The results of Kronbak et al. (2009) show also that two of the technical solutions could be expected to continue to generate negative private profits in the short term (approx. 5 years after the implementation of the selective gear) and beyond, while for the other the two solutions producing positive profits, only an increase of ca. 2% was projected in the 10-year simulation period.

A bioeconomic analysis of the multi-fleet, multi-species French fishery in the Bay of Biscay by Raveau et al. (2012) compared the performance of four different experimental modifications to the *Nephrops* trawl net aiming at reducing the catches of undersize Norway lobster and hake. Under the simulation conditions of constant recruitment and constant fishing effort, all technical solutions would result in rebuilding stock biomass, more important for Norway lobster than for hake, while undersize specimens would be strongly reduced with all technical solutions. However, some of the modifications to the trawl net proposed were even too selective and did not allow to increase the fleet landings with the increased stock biomass (in particular, a codend with T90 netting performed poorly). Moreover, when considering the impact of these technical modifications on other fleets (mix trawlers, mixed gillnetters and sole gillnetters) operating in the same area, improving the selectivity of the *Nephrops* trawl would result in economic profits for the other fleets along the projection horizon, and also for *Nephrops* trawlers in the short to mid term (5–10 years). The effect of non-regulated fleets benefitting from stock rebuilding due to improving the selection pattern of trawlers is documented in other studies (Lleonart et al., 2003) and although beneficial for the stock and society in global terms could lead to friction among the vessel owners of different fleet segments.

All these studies show that technological solutions based on modifications of standard trawl nets can contribute to rebuilding of demersal fish stocks by decreasing the fishing mortality of the juvenile fraction of the population. Additionally, they can help align the size at first capture with minimum reference sizes or decrease the problem of unwanted bycatch of small grade fish categories. As such, technical modifications of fishing gear can be complementary to effort reduction programmes aiming at reaching certain fisheries management targets, such as Fmsy within a specified time period. In effect, basing the management of Mediterranean (or other) fisheries solely on effort control without changing the selection pattern does not solve the problem of excessive mortality of immature fish (Colloca et al., 2013). For some fisheries that depend on stocks with clear spatial aggregations (spawning or nursery area), effort limitations can be combined with fisheries restricted areas if improving fisheries selectivity proves to be impractical.

These studies also show economic losses in the first few years immediately after the implementation of the modified fishing gear, which often proves an insurmountable barrier for the widespread adoption of more selective techniques that suppose a trade-off between the short term private gains and the mid-to long-term societal benefits (Raveau et al., 2012). Solutions to incentivise the adoption of more selective fishing gear can be based on penalizing those vessels that do not adopt more selective fishing gear, or which is equivalent, rewarding those fishing units employing more selective technology (Prellezo et al., 2017). In the context of the WM MAP, these penalties or rewards can easily be conceived in terms of deducting/adding fishing days to the allocated effort quota. In addition to direct penalty/reward schemes, the implementation of more selective fishing gears requires that the fishing industry becomes aware of the existence of practical, inexpensive and easy to implement solutions. Strengthening the collaboration between fisheries science and the fishing industry will help develop solutions based on the best available technology (O'Neill et al., 2019).

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Francesc Maynou reports financial support, administrative support, and article publishing charges were provided by Spanish Scientific Research Council.

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## Appendix A. FLBEIA model application the Western Mediterranean demersal multi-annual plan

The geographical scope of the Western Mediterranean demersal Multi-Annual Plan (WM MAP) are the geographical subareas (GSA) of the European Union member states in the North-western Mediterranean (Fig. A1), Spain, France and Italy. The WM MAP applies separately to the western and eastern halves of the area, as *Effort Management Unit*: GSAs 01, 02, 05, 06 and 07 fall under EMU 1, while GSAs 08, 09, 10 and 11 fall under EMU 2.

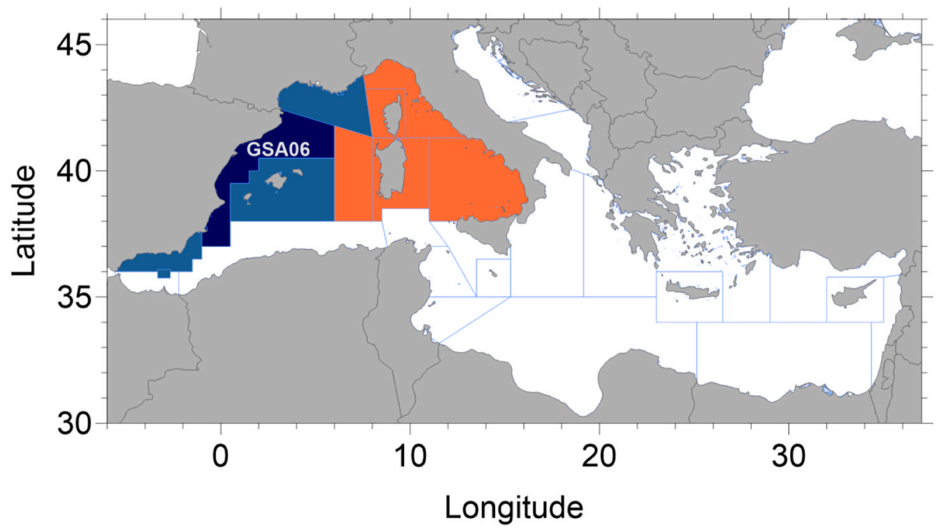


**Fig. A.1.** Mediterranean sea fisheries management units ("GSAs"), established by the General Fisheries Commission for the Mediterranean sea, www.fao.org/gfcm). The GSAs under the Western Mediterranean demersal fisheries Multi-Annual Plan (COM/2018/0115 final – 2018/050 (COD)) are coloured: Effort Management Unit 1 (EMU1) in blue and EMU2 in orange, with the area subject to the application of the FLBEIA, GSA06, highlighted in darker blue.

The specific conditions of the application of the FLBEIA model (García et al., 2017a, b, c) to the WM MAP were:

*Software*

FLBEIA version 1.15.4 run under R3.6.2 (i386, 32-bits), with FLR (Kell et al., 2007) libraries: FLCore 2.6.4, FLash 2.5.11, FLAssess 2.6.3, FLFleet 2.6.1, FLBRP 2.5.4.

FLBEIA model components (cf. FLBEIA manual: García et al., 2017c):

1. Operating model (OM):
   - 1.1. Biological:
     - 1.1.1. Population dynamics:
       - 1.1.1.1. Five target stocks following an age structured population growth (ASPG)
       - 1.1.1.2. One pool of species (commercial bycatch) following a biomass surplus model (BDPG) "stock 6″
       - 1.1.1.3. Spawning Stock Biomass/Recruitment model: Five models, one for each main stock
   - 1.2. Fleet: Three fleets with two métiers each, with the following options (depending on the scenario):
     - 1.2.1. Fixed effort dynamics
     - 1.2.2. Cobb-Douglas production function
     - 1.2.3. Fixed fish price
     - 1.2.4. Fixed capital
   - 1.3. Covariates: a list of fixed covariates, such as: fuel cost, capital cost, salaries (set to 0 in a crew share scheme), internal investment share, fleet capacity (number of vessels), maximum number of fishing days, crew size per vessel, and entry/exit parameters $w_1$ and $w_2$, representing the capital dynamics.
2. Management Procedure Model (MPM):
   - 2.3.1. Observation: No observation for all stocks
   - 2.3.2. Assessment: No assessment for all stocks (i.e. non-adaptive management)
   - 2.3.3. Management advice: fixed advice for all fleets

## Appendix B. Biological basis for the FLBEIA model

Information from age-structured stock assessment was available for the five stocks which are the main target of the trawl fishery and of the WM MAP: HKE, MUT, NEP, DPS and ARA from STECF assessments (STECF, 2020). The outputs of the assessments were directly used to condition the biological component of the FLBEIA simulation model. The analytical stock assessments were based on a4a for all species and the Results (summarized in Table B1) show that the level of exploitation (current fishing mortality $F_{curr}$ over fishing mortality at MSY $F_{msy}$) is 4–6 times the level that should ensure MSY.

**Table B.1**
Summary of stock assessments for the 5 target species in GSA06, from STECF, 2020.

| | Assessment | Advice |
|---|---|---|
| HKE | Method: a4a. Assessment combined GSAs 01, 05, 06 and 07. Data were downscaled here to GSA06 according to landings share.<br>Biomass is low but stable. | Reduce catches by at least 63% to reach $F_{msy}$ in 2020.<br>$F_{msy} = 0.38$<br>$F_{curr} = 1.84$<br>$F_{curr}/F_{msy} = 4.84$ |
| MUT | Method: a4a. Assessment for GSA06.<br>Biomass is low but stable. | Reduce catches by at least 69% to reach $F_{msy}$ in 2020<br>$F_{msy} = 0.31$<br>$F_{curr} = 1.46$<br>$F_{curr}/F_{msy} = 4.71$ |
| NEP | Method: a4a. Assessment for GSA06.<br>Biomass is low but stable. | Reduce catches by at least 71% to reach $F_{msy}$ in 2020<br>$F_{msy} = 0.11$<br>$F_{curr} = 0.71$<br>$F_{curr}/F_{msy} = 6.45$ |
| DPS | Method: a4a (2018). Assessment combined GSAs 01, 05, 06 and 07. Data were downscaled here to GSA06 according to landings share.<br>Biomass is increasing. | Reduce catches by at least 55% to reach $F_{msy}$ in 2020<br>$F_{msy} = 0.21$<br>$F_{curr} = 0.87$<br>$F_{curr}/F_{msy} = 4.14$ |
| ARA | Method: a4a. Assessment combined GSAs 06 and 07. Data were downscaled here to GSA06 according to landings share.<br>Biomass is fluctuating. | Reduce catches by at least 65% to reach $F_{msy}$ in 2020<br>$F_{msy} = 0.33$<br>$F_{curr} = 1.26$<br>$F_{curr}/F_{msy} = 3.82$ |

HKE and DPS were assessed at EMU1 level and the biological data were downscaled for the present study to GSA06 level. ARA was assessed combining GSA06 and GSA07 and the biological data was downscaled here to GSA06. Further, DPS assessment was available until 2017 only and the stock was projected to 2018 using the function fwd in FLR library FLash.

In addition to the main 5 stocks, a 6th stock following a surplus dynamic model was constructed for this application. “Stock 6” combined the landings of all bycatch species, which amount to 55–60% of the demersal fleet catches, depending of the year. The data series of effort of the trawl fleet for the period 2000–2017 was used to derive the required index of CPUE. The parameters of a surplus dynamic model (Schaefer) were obtained with the R program SPiCT (Pedersen and Berg, 2017).

The stock composition resulting from the stock assessments was distributed by fleet segment according to the proportions in the catch. Catches are given in Table B2.

**Table B.2**
Catch (t) by species and fleet segment in GSA06. Data represent averages for the years 2016–2018.

| | VL1218 | VL1824 | VL2440 | Total OTB |
|---|---|---|---|---|
| HKE | 220 | 1145 | 817 | 2182 |
| MUT | 150 | 820 | 350 | 1320 |
| NEP | 29 | 155 | 109 | 293 |
| DPS | 70 | 370 | 250 | 690 |
| ARA | 92 | 460 | 335 | 887 |
| Stock 6 | 1040 | 2910 | 1850 | 5800 |
| Total | 1601 | 5860 | 3711 | 11172 |

*Stock/Recruitment relationships*

For each stock several S/R models were evaluated with function *fmle* of FLR, based on the longest possible data series of spawning stock biomass (SSB) and recruitment (R) available in the stock assessment forms. Note that compared to other European fisheries, series of SSB and R for Mediterranean fisheries are short (typically 10–20 years long). The S/R models evaluated were: Beverton and Holt (“bevholt”), Ricker (“ricker”), Cushing (“cushing”), segmented regression (“segreg”) and their AR1 versions, as well as constant recruitment (“geomean”). Given that the time span of all series was short, the Results of all the models fitted were very similar and the model with lowest AIC was chosen. This component of model uncertainty (e.g. the S/R model and its parameters) is taken as the main source of uncertainty in this report. The S/R model parameters of the models selected are shown in Table B3.

**Table B.3**
Stock / Recruitment parameters for the five main stocks in GSA06. For stock 6, the parameters of a surplus dynamics model are shown.

| | Model | parameters |
|---|---|---|
| HKE | bevholt | a = 330 296 b = 3212 |
| MUT | ricker | a = 206 b = 0.000126 |

(*continued on next page*)

**Table B.3** (*continued*)

| | Model | parameters |
|---|---|---|
| NEP | ricker | a = 185 b = 0.00133 |
| DPS | rickerAR1 | a = 570 b = 0.000151 ρ = 0.598 |
| ARA | rickerAR1 | a = 596 b = 0.000245 ρ = 0.474 |
| Stock 6 | biomass dynamics | r = 2.36 K = 16 803 MSY = 9914 |

## Appendix C. Economic basis for the model

Economic data for FAO Area 37.1 (Spanish Mediterranean) was available until 2016 only in the Annual Economic Report of the EU Fisheries (AER, 2020) and corresponding appendices. These data were carried over to the last three years of the simulation data set, 2017–2019. Fish price data from 2017 to 2019 for all the stocks were obtained from the DG Fisheries of the Autonomous Government of Catalonia (http://agricultura.gencat.cat/ca/ambits/pesca/). The average price for each species was used to condition the model (Table C1), using the same price for all the fleets, métiers, and age groups. The mean price of all non-target species was used to derive a price for the notional Stock 6.

**Table C.1**
Price (€/kg) of main and secondary species in GSA06. Data represent the average for 2017–2019.

| Fish stock | price (€/kg) |
|---|---|
| HKE | 6.53 |
| MUT | 5.06 |
| NEP | 22.20 |
| DPS | 14.93 |
| ARA | 36.50 |
| Stock 6 | 3.99 |

The catches and effort were distributed empirically by fleets and métiers with the proportions shown in Table C2 derived from DCF (tables catch.csv and effort. csv). The two metiers practiced and identified in the table (coastal mixed demersal fisheries: DEMSP and deep water shrimp fisheries: DWSP) correspond to the metiers regulated in the WM MAP. The fleet segments VL1824 and VL2440 produce the largest share of demersal landings. The coastal metier targets mainly HKE, MUT, NEP and DPS, while the deep-water shrimp metier catches mainly ARA, with smaller contributions of HKE and NEP.

**Table C.2**
Technical interaction matrix between species, fleets and their métiers. Métier 1: DEMSP; métier 2: DWSP. The values are proportions produced by each fleet and metier (sum to 1 for each species). Data are averages for 2017–2019.

| | | fleet 1: VL1218 | fleet2: VL1824 | fleet3: VL2440 |
|---|---|---|---|---|
| HKE | metier 1 | 0.0940 | 0.4935 | 0.3525 |
| | metier 2 | 0.0060 | 0.0315 | 0.0225 |
| MUT | metier 1 | 0.1000 | 0.5250 | 0.3750 |
| | metier 2 | – | – | – |
| NEP | metier 1 | 0.0750 | 0.3938 | 0.2813 |
| | metier 2 | 0.0250 | 0.1313 | 0.0938 |
| DPS | metier 1 | 0.1000 | 0.5250 | 0.3750 |
| | metier 2 | – | – | – |
| ARA | metier 1 | – | – | – |
| | metier 2 | 0.1000 | 0.5250 | 0.3750 |
| Stock 6 | metier 1 | 0.0650 | 0.3413 | 0.2438 |
| | metier 2 | 0.0350 | 0.1838 | 0.1313 |

*Costs*

The estimation of costs per fleet (and metier) was based on the methodology of the Annual Economic Report (AER 2020, section 6 “AER Report methodology”), adapted to the model requirements of FLBEIA (García et al., 2017b). In this model, total costs are split into fixed costs and crew wages, by fleet, while variable costs are given by metier. The values taken for the first year of the simulation (2020) are shown in Table C3 and correspond to the average 2017–2019.

**Table C.3**
Average costs per unit of effort (day·vessel), corresponding to average values for 2017–2019.

| | | fleet 1: VL1218 | fleet2: VL1824 | fleet3: VL2440 |
|---|---|---|---|---|
| Variable cost, € per vessel · day | metier 1 | 177 | 280 | 316 |
| | metier 2 | 21 | 51 | 112 |

(*continued on next page*)

**Table C.3** (*continued*)

| | fleet 1: VL1218 | fleet2: VL1824 | fleet3: VL2440 |
|---|---|---|---|
| Fixed cost, € per vessel · day | 31 | 44 | 86 |
| coefficient of Labour cost (crew share) | 0.38 | 0.39 | 0.41 |
| crew size (number) | 3.1 | 4.2 | 5.2 |
| Fuel cost, € per vessel · day | 125 | 264 | 332 |
| Capital costs, € per vessel · day | 2 | 5 | 39 |

## Appendix D. Analysis of commercial production during the experimental sampling

The daily catches commercialized (landings) by the sampling vessel of the continental shelf demersal mixed fishery during the 8 days of the T90 experiments are shown in Table D1. The landings produced by the T90 modified net were, on average, 113.86 kg/day, that is 80% the volume of landings obtained in the same fishery with the control or standard net (142.45 kg/day). In terms of value of landings, the difference was smaller, with average 811.05 €/day obtained with the T90 net, corresponding to 88% of the control net (924.15 €/day). The loss of 20% in volume and 12% in value are comparable to the figures reported in Sola and Maynou (2018a) for similar T90 experiments carried out in 2017, which were 17.5% loss in volume and 18.5% loss in value.

**Table D.1**
Average daily landings by species in volume (kg) and value (€) averaged over the 8 sampling days for the T90 experiment (continental shelf mixed demersal fishery).

| FAO code | scientific name | control net (kg) | T90 net (kg) | Total (kg) | control net (€) | T90 net (€) | Total (€) |
|---|---|---|---|---|---|---|---|
| **ANK** | Lophius budegassa | 20.04 | 13.70 | 33.74 | 176.33 | 125.93 | 302.26 |
| **BRF** | Helicolenus dactylopterus | 5.51 | | 5.51 | 14.55 | | 14.55 |
| **CIL** | Citharus linguatula | 7.26 | 5.30 | 12.56 | 28.39 | 20.82 | 49.21 |
| **CTB** | *Diplodus vulgaris* | | 0.43 | 0.43 | | 1.02 | 1.02 |
| **CTC** | Sepia officinalis | 1.56 | 2.56 | 4.13 | 29.42 | 44.66 | 74.08 |
| **DPS** | Parapenaeus longirostris | 0.29 | 0.53 | 0.81 | 3.57 | 6.57 | 10.14 |
| **EDT** | Eledone moschata | 0.70 | 0.23 | 0.93 | 0.81 | 0.36 | 1.16 |
| **EJE** | Sepia elegans | 3.48 | 3.01 | 6.49 | 57.45 | 49.51 | 106.96 |
| **EOI** | Eledone cirrhosa | 9.53 | 7.81 | 17.34 | 34.46 | 29.32 | 63.78 |
| **GFB** | Phycis blennoides | 8.45 | 6.03 | 14.48 | 17.08 | 12.19 | 29.27 |
| **GUG** | Eutrigla gurnardus | 6.50 | 8.15 | 14.65 | 11.57 | 18.51 | 30.08 |
| **HKE** | Merluccius merluccius | 2.93 | 3.97 | 6.89 | 31.66 | 41.62 | 73.28 |
| **HOM** | Trachurus trachurus | 12.55 | 6.84 | 19.39 | 19.24 | 10.45 | 29.69 |
| **JCR** | Stichopus regalis | 0.93 | 0.64 | 1.56 | 77.88 | 53.70 | 131.58 |
| **JOD** | Zeus faber | 2.68 | 2.11 | 4.79 | 61.41 | 64.00 | 125.40 |
| **LEZ** | Lepidorhombus spp | 4.53 | 3.30 | 7.83 | 59.34 | 45.81 | 105.15 |
| **MON** | Lophius piscatorius | 0.21 | | 0.21 | 1.35 | | 1.35 |
| **MUR** | Mullus surmuletus | 2.77 | 2.57 | 5.34 | 28.82 | 32.86 | 61.69 |
| **MUT** | Mullus barbatus | 29.52 | 27.09 | 56.61 | 165.96 | 169.82 | 335.79 |
| **OCC** | *Octopus vulgaris* | 1.05 | 0.35 | 1.40 | 6.19 | 2.48 | 8.67 |
| **PAC** | Pagellus erythrinus | 0.61 | 0.71 | 1.33 | 1.80 | 0.95 | 2.76 |
| **POD** | Trisopterus minutus | 7.53 | 7.90 | 15.43 | 24.73 | 23.17 | 47.90 |
| **RPG** | Pagrus pagrus | | 0.06 | 0.06 | | 0.43 | 0.43 |
| **RSE** | Scorpaena scrofa | 2.21 | 1.69 | 3.90 | 24.62 | 11.93 | 36.55 |
| **SBA** | *Pagellus acarne* | 1.49 | | 1.49 | 2.24 | | 2.24 |
| **SBG** | *Sparus aurata* | | 0.39 | 0.39 | | 1.91 | 1.91 |
| **SKA** | Raja spp | 4.04 | 3.90 | 7.94 | 8.48 | 12.05 | 20.53 |
| **SOL** | *Solea solea* | | 0.11 | 0.11 | | 3.13 | 3.13 |
| **SQM** | Illex coindetii | 2.76 | 1.71 | 4.48 | 15.65 | 9.82 | 25.47 |
| **SQR** | Loligo vulgaris | 0.23 | 0.13 | 0.35 | 4.30 | 2.58 | 6.87 |
| **UUC** | Uranoscopus scaber | 0.90 | 0.71 | 1.61 | 4.43 | 4.13 | 8.56 |
| **WEG** | Trachinus draco | 2.21 | 1.95 | 4.16 | 12.43 | 11.31 | 23.74 |
| | | 142.45 | 113.86 | 256.30 | 924.15 | 811.05 | 1735.20 |

The daily catches commercialized (landings) by the sampling vessel in the *Nephrops* fishery during the 6 days of the T90 experiments are shown in Table D2. The landings produced by the T90 modified net were 118.53 kg/day, 86% the volume of landings obtained in the same fishery with the control or standard net (137.10 kg/day). In terms of value of landings, the reduction was similar, with 1264.58 €/day obtained with the T90 net, corresponding to 87% of the control net (1451.16 €/day). Thus, losses of 14% in volume and 13% in value can be expected with the T90 net.

**Table D.2**
Average daily landings by species in volume (kg) and value (€) averaged over the 6 sampling days for the T90 experiment (upper slope *Nephrops* fishery).

| FAO code | name | control net (kg) | T90 net (kg) | Total (kg) | control net (€) | T90 net (€) | Total (€) |
|---|---|---|---|---|---|---|---|
| **ANK** | Lophius budegassa | 0.42 | 0.38 | 0.80 | 3.03 | 3.27 | 6.30 |
| **BLI** | Molva dypterygia | | 0.55 | 0.55 | | 2.38 | 2.38 |
| **BRF** | Helicolenus dactylopterus | 0.95 | 1.18 | 2.13 | 0.73 | 2.46 | 3.19 |
| **DIA** | Osteichthyes | 0.65 | 0.18 | 0.83 | 4.58 | 1.15 | 5.73 |
| **DPS** | Parapenaeus longirostris | 18.53 | 14.68 | 33.22 | 443.51 | 350.58 | 794.09 |
| **EOI** | Eledone cirrhosa | 5.45 | 4.90 | 10.35 | 21.47 | 18.10 | 39.57 |
| **GFB** | Phycis blennoides | 39.53 | 33.87 | 73.40 | 87.19 | 86.49 | 173.67 |

(continued on next page)

**Table D.2** (*continued*)

| FAO code | name | control net (kg) | T90 net (kg) | Total (kg) | control net (€) | T90 net (€) | Total (€) |
|---|---|---|---|---|---|---|---|
| **GUG** | Eutrigla gurnardus | 1.95 | 1.23 | 3.18 | 2.31 | 0.62 | 2.93 |
| **HKE** | Merluccius merluccius | 10.80 | 12.83 | 23.63 | 109.27 | 102.03 | 211.30 |
| **LEZ** | Lepidorhombus spp | 3.20 | 2.98 | 6.18 | 35.26 | 34.38 | 69.64 |
| **MON** | Lophius piscatorius | | 3.07 | 3.07 | | 28.90 | 28.90 |
| **NEP** | *Nephrops norvegicus* | 35.75 | 31.08 | 66.83 | 644.22 | 571.72 | 1215.94 |
| **OLV** | Paromola cuvieri | | 0.20 | 0.20 | | 0.42 | 0.42 |
| **RSE** | Scorpaena scrofa | 0.28 | 0.27 | 0.55 | 1.94 | 2.98 | 4.92 |
| **SQE** | Todarodes sagittatus | 2.18 | 1.13 | 3.32 | 15.62 | 7.77 | 23.39 |
| **WHB** | Micromesistius poutassou | 17.40 | 9.98 | 27.38 | 82.03 | 51.34 | 133.37 |
| | | 137.10 | 118.53 | 255.63 | 1451.16 | 1264.58 | 2715.74 |

Regarding the selective grid experiment, in the absence of control net, the catches commercialized during two days before and two days after the experiments by the same vessel are compared in the following table with the actual catches commercialized during the days of the experiment (Table D3). A reduction of 12% in the volume of catches, but an increase of 14% in the value was observed for the selective grid experiments.

**Table D.3**
Average daily landings by species in volume (kg) and value (€) averaged over the 4 sampling days for the selective grid experiment (grid) and from 2 days before and 2 days after (control) (continental shelf mixed demersal fishery).

| kg/day | | control (kg) | grid (kg) | total (kg) | control (€) | grid (€) | total (€) |
|---|---|---|---|---|---|---|---|
| **ANK** | Lophius budegassa | 12.75 | 10.85 | 23.60 | 115.08 | 97.95 | 213.03 |
| **CIL** | Citharus linguatula | 7.38 | 1.65 | 9.03 | 57.46 | 12.84 | 70.30 |
| **COE** | *Conger conger* | 3.05 | | 3.05 | 18.30 | | 18.30 |
| **DPS** | Parapenaeus longirostris | 2.12 | 13.55 | 15.67 | 16.11 | 102.85 | 118.96 |
| **EJE** | Sepia elegans | 7.25 | 21.6 | 28.85 | 131.27 | 391.10 | 522.37 |
| **EOI** | Eledone cirrhosa | 4.95 | | 4.95 | 19.81 | | 19.81 |
| **GFB** | Phycis blennoides | 6.09 | 2.75 | 8.84 | 31.77 | 14.35 | 46.12 |
| **GUG** | Eutrigla gurnardus | 6.07 | 4.5 | 10.57 | 18.56 | 13.77 | 32.33 |
| **HKE** | Merluccius merluccius | 1.54 | 1.25 | 2.79 | 1.92 | 14.75 | 16.67 |
| **HOM** | Trachurus trachurus | 9.98 | 2.3 | 12.28 | 15.35 | 3.54 | 18.89 |
| **IOD** | Liocarcinus depurator | 1.29 | 0.55 | 1.84 | 8.33 | 3.56 | 11.89 |
| **JCR** | Stichopus regalis | 2.18 | 1.85 | 4.03 | 141.93 | 120.50 | 262.43 |
| **JOD** | Zeus faber | 3.69 | 4.10 | 7.79 | 110.75 | 123.00 | 233.75 |
| **LEZ** | Lepidorhombus spp | 3.39 | 4.20 | 7.59 | 2.71 | 3.36 | 6.07 |
| **MON** | Lophius piscatorius | 3.03 | 1.25 | 4.28 | 16.84 | 6.94 | 23.78 |
| **MUR** | Mullus surmuletus | 5.46 | 4.32 | 9.78 | 42.77 | 33.82 | 76.59 |
| **MUT** | Mullus barbatus | 28.42 | 11.31 | 39.73 | 142.43 | 56.68 | 199.11 |
| **PAC** | Pagellus erythrinus | 2.62 | 0.75 | 3.37 | 4.61 | 1.32 | 5.93 |
| **RSE** | Scorpaena scrofa | 2.94 | 1.65 | 4.59 | 27.15 | 15.26 | 42.41 |
| **SBA** | *Pagellus acarne* | 1.05 | 9.27 | 10.32 | 1.58 | 13.91 | 15.48 |
| **SQM** | Illex coindetii | 1.58 | 2.95 | 4.53 | 12.34 | 23.06 | 35.40 |
| **WHB** | Micromesistius poutassou | 0.74 | 3.05 | 3.79 | 5.32 | 21.99 | 27.31 |
| | | 117.56 | 103.70 | 221.26 | 942.38 | 1074.55 | 2016.93 |

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