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"Crash landing" obligation for Mediterranean mixed fisheries: Evaluation of management strategies using bioeconomic modelling in the Aegean Sea

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Summary: Minimizing unwanted catches is a major milestone for achieving sustainable fisheries. In the framework of the Common Fisheries Policy, a landing obligation is being established progressively in European waters (Article 15, EU Regulation 1380/2013). Supplementary management measures have been proposed to support and enhance the effectiveness of this new regime. In this context, the effect of the landing obligation on a demersal mixed fishery (coastal and trawl fleet) in the Aegean Sea (NE Mediterranean Sea) was assessed in terms of both biological and economic sustainability. Our results show that the landing obligation alone does not ensure sustainable fisheries. Management action should be directed to the introduction of additional measures. Evidence suggests that improving selectivity and protecting the nursery grounds are possible solutions to decrease discards and ensure sustainable fisheries in the long term. The landing obligation can have a role in incentivizing the adoption of these management measures that ensure lower fishing mortality on juvenile fish.

Keywords: landing obligation; fisheries management; mixed fisheries; bioeconomic modelling; Aegean Sea; Mediterranean fisheries.

La obligación de descartes: un "aterrizaje forzoso" para las pesquerías mixtas del Mediterráneo. Evaluación de estrategias de gestión mediante un modelo bioeconómico aplicado al mar Egeo

Resumen: Minimizar las capturas no deseadas es un hito importante para lograr pesquerías sostenibles. En el marco de la Política Pesquera Común se está estableciendo progresivamente una obligación de desembarque en aguas europeas (artículo 15, reglamento 1380/2013 de la UE). Se han propuesto medidas de gestión complementarias para apoyar y mejorar la eficacia de este nuevo régimen. En este contexto, se evalúa el efecto de la obligación de desembarque en una pesquería mixta demersal (flota costera y de arrastre) en el mar Egeo (NE mar Mediterráneo), tanto en términos de sostenibilidad biológica como económica. Nuestros resultados muestran que la obligación de desembarque por sí sola no garantiza una pesca sostenible, y que la gestión debería enfocarse hacia la introducción de medidas adicionales. Las evidencias obtenidas sugieren que mejorar la selectividad de las artes de pesca y proteger las áreas de alevinaje son dos soluciones posibles para disminuir los descartes y garantizar una pesca sostenible a largo plazo. La obligación de desembarque puede tener un papel en incentivar la adopción de estas medidas de gestión, que aseguran una menor mortalidad por pesca en peces juveniles.

Palabras clave: obligación de desembarque; ordenación pesquera; pesquerías mixtas; modelos bioeconómicos; mar Egeo; pesquerías del Mediterráneo.

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INTRODUCTION

The practice of discarding unwanted catch back to the sea is highly criticized by stakeholders involved in fisheries governance, which is per se a complex decision making environment, and many attempts have been made worldwide to tackle the problem (Hall and Mainprize 2005, Pérez-Roda et al. 2019). Estimates of discards are 9.1 million t per year for the period 2010-2014 (Pérez-Roda et al. 2019), although high uncertainty in global discard data over time has been detected (Zeller and Pauly 2005). A recent approach based on reconstructed time series has shown a decrease in discard rates due to the likely adoption of more selective gears and the rising market value for fishmeal (Zeller et al. 2018).

The fisheries management regime in European Union countries stems from the Common Fisheries Policy (CFP). From 1 January 2019, a discard ban [Article 15 of EC 1380/2013, the so-called "landing obligation" (LO)] obliges fishers of all fleets to reduce discarding and follow specific management guidelines for catches of species which are subject to minimum conservation reference sizes, as defined in Annex III to Regulation (EC) No. 1967/2006 in the Mediterranean, and to total catch limits generally in Atlantic fisheries. All catches of regulated species must be hauled and retained on board, recorded and landed. The discard bans that have been implemented have not shown positive impacts in all the fisheries in which they have been applied (Condie et al. 2014). Several consequences may arise in European fisheries, including shifts in the ecosystem functioning and alterations to the socioeconomic status of the fishing communities (Guillen et al. 2018).

The Mediterranean area is subject to intense fishing pressure, as 22 countries are fishing in its waters and exploiting the same fishery resources. Mediterranean stocks are at risk from overexploitation, with undersized individuals being under immense pressure (Tsikliras et al. 2015, Vasilakopoulos et al. 2014). Mediterranean discard rates are estimated to range between 13% and 27% (Tsagarakis et al. 2014), but discarding has increased over the last 70 years due to regulatory limitations and changes in market habits that have brought a drop in the commercial value of some species (Damalas et al. 2015). The reasoning behind discarding practices depends on many local parameters that differentiate the composition of catches and landings (Maynou et al. 2018), such as the socioeconomic profile of a fisher and its vessel, which may define the discarding practice followed (Christou et al. 2017).

Having regard to Regulation (EU) No. 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the CFP, the European Commission enacted EU Regulation 2017/86 of 20 October 2016, establishing a discard plan for certain demersal fisheries in the Mediterranean Sea. Under Article 4 of the regulation, a *de minimis* exemption was set for quantities of species which define the fisheries. Discard plans were first introduced for species which define the fisheries in the southeastern Mediterranean [hake (*Merluccius merluccius*), red mullet (*Mullus barbatus*) and deep-water rose shrimp (*Parapenaeus longirostris*)]. These were in force between 2017-2018, when the total landings per vessel in 2014 and 2015 consisted of more than 25% of these species separately or in combination. On 1 January 2019, the European Commission introduced EU Regulation 2018/2036 of 18 October 2018, amending the Delegated Regulation EU 2017/86. Discard management plans are currently applicable to certain demersal fisheries in the southeastern Mediterranean Sea until 31 December 2019, following joint recommendations submitted to the Commission in 2018 by Member States that have a direct management interest in the area (Greece, Cyprus and Malta). The Commission suggests that Member States should commit to increasing the selectivity of the fishing gears to minimize unwanted catches in accordance with the results of current research programmes.

These three species are subject to the LO and constitute the largest catch fraction in terms of volume (Fig. 1), defining the demersal trawl production. These species are closely monitored through the existing national management plans and are subject to stock assessments

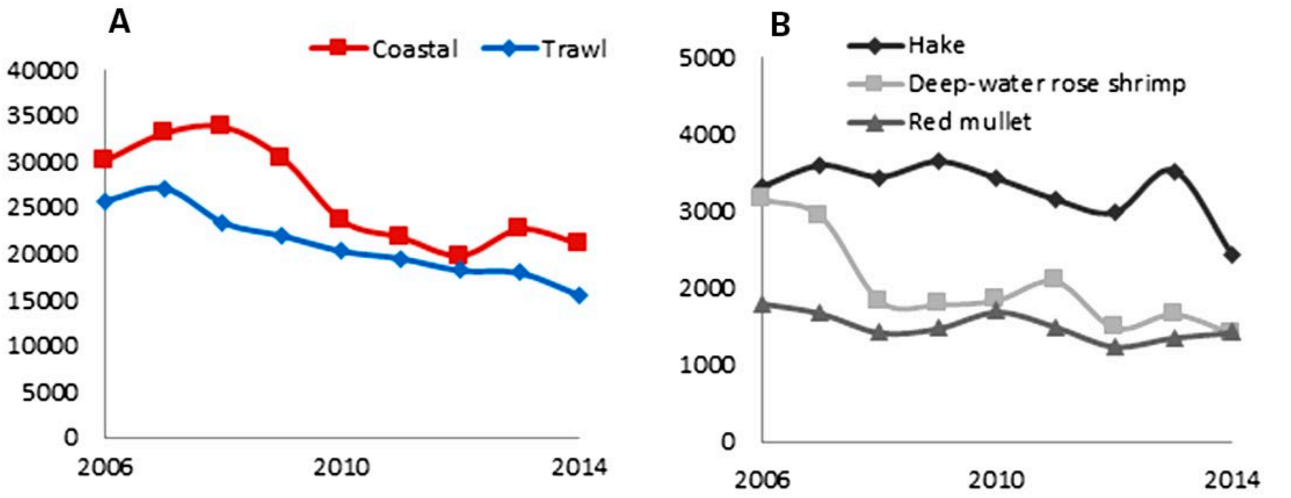

Fig. 1. – Evolution of the quantity of the catch (T) for the two fleets (A) and for the three demersal fish (B) in the Aegean Sea for the years 2006-2014 [data retrieved from the records of Hellenic Statistical Authority (ELSTAT, 2014)].

Table 1. – Discard rates (discards/total catch) of the three species of the demersal fishery, per fleet and gear (OTB, bottom otter trawl; GNS, set gillnets; GTR, trammel nets) for the Aegean Sea for 2014.

Fleet	Gear	Species	Discard rate
Trawls	OTB	*Merluccius merluccius*	0.05
		Mullus barbatus	0.01
		Parapenaeus longirostris	0.06
Coastal	GNS	*Merluccius merluccius*	0.03
		Mullus barbatus	0.01
		Parapenaeus longirostris	0.01
	GTR	*Merluccius merluccius*	0.14
		Mullus barbatus	0.02

by the European Commission Scientific, Technical and Economic Committee for Fisheries (STECF) and the General Fisheries Commission for the Mediterranean (GFCM). Information on the stock status of all three species can be found in the Greek Management Plan (2014) with data from 2009, while for hake and red mullet assessments for the Aegean Sea stocks carried out by the GFCM (2017) have shown that red mullet is in healthy condition and is exploited sustainably, but hake is overfished and the fishing mortality rate (F) is far above MSY levels. The problem of overfishing encountered in the Aegean Sea is closely related to growth overfishing due to the poor selectivity of fishing gears, as elsewhere in the Mediterranean Sea, where a large fraction of the catches of the target species are below their minimum landing size (MLS) and length at first maturity (Tsikliras and Stergiou 2013, Mytilineou et al. 2018).

More than 30 ecological-economic marine fisheries models have been formulated so far to evaluate the multidisciplinary impacts of prospective management measures and to contribute to effective decision making (Nielsen et al. 2017). For the Mediterranean Sea there is an extensive literature on bioeconomic modelling (Guillen et al. 2012, Rossetto et al. 2015, Maynou 2014), while for the Greek fisheries there are a limited number of studies on the demersal fisheries of the Aegean Sea (Merino et al. 2007, Maravelias et al. 2014, Tserpes et al. 2016) and on small pelagic species (Maravelias et al. 2014, Politikos et al. 2012, 2013).

The present case study refers to the Aegean Sea fisheries that exploit demersal stocks. Table 1 presents the discard rates at fleet and gear level for 2014. The approach followed herein analyses the possible supporting measures (legal, technical, market-based or effort-based) that can be applied in order to facilitate the rebuilding of demersal stocks and provide forecasts on the economic viability of the fishing industry for the next 20 years using a bioeconomic simulation model (Mediterranean FIsheries Simulation TOol-MEFISTO, Maynou et al. 2017). Here we study the possible socio-economic and biological effects of alternative management measures in order to propose sustainable solutions for the fishery and resolve any issues that may arise due to the implementation of the new regime.

MATERIALS AND METHODS

Data mining

For the biological component of the model, all target or main stocks were included in the analysis, as they are exploited by both trawl and coastal vessels, excluding that of deep-water rose shrimp which is captured solely by trawlers. Other fleets (purse and boat seiners) operating in the area were not included in the analysis as they do not target these species. Market prices of the main and secondary species were also obtained from the Data Collection Framework, and stock assessment data for the main species in the form of catch at age were obtained from the literature (see Tserpes et al. 2016, compiling individual stock assessment forms from STECF and/or GFCM) and were the latest available (Table 2). We used landings estimates in weight and value that are available from the records of Hellenic Statistical Authority (ELSTAT 2014).

Fishing fleet data were obtained by questionnaires in 2015 under the Data Collection Framework and the MINOUW project (MINOUW 2015, Christou et al. 2017), with 2014 as the reference year.

Three broad categories of costs were considered:

1. Variable costs, which include i) daily costs resulting from the fishing activity, which are a function of effort (fuel, ice and other operational expenses); ii) labour costs, which are a function of catch (daily wages); and iii) commercial/trade costs, which are a function of catch (commercialization, transportation and packaging expenses).

2. Fixed costs accumulated from flexible costs such as vessel and gear repair and maintenance costs, and compulsory costs such as insurance, legal and banking expenses. Fishing licences and other unavoidable port

Table 2. – Input (biological and economic) parameters for the scenarios tested. a, b, total length-weight relationship [$W = aL^b$] constant; L_∞, k and t_0, Von Bertalanffy growth function parameters; L_{50}, length at 50% capture; L_{to95}, length from 50% to 95% retention; a_1, b_1, c, Ricker model [$R=a_1SSB_{t-k}e^{-b1SSBt-c}e^{\varepsilon}$] parameters (age of recruitment).

Parameters	Hake	Red mullet	Pink shrimp
a	0.0033	0.00316	0.0029
b	3.23	3.25	2.483
L_∞	104	30	30
K	0.12	0.199	0.74
t_0	–0.01	–1.53	–0.5
N cohorts	6	6	4
a_1	0.12	0.6	1.012
b_1	1E-09	1E-09	5E-10
c	1	1	1
L_{50}	12.5	8.75	9.25
L_{to95}	3.5	2.5	2.5
Average price for the trawl fleet (€/ kg)	11	12.5	6
Average price for the coastal fleet (€/ kg)	15	16	-

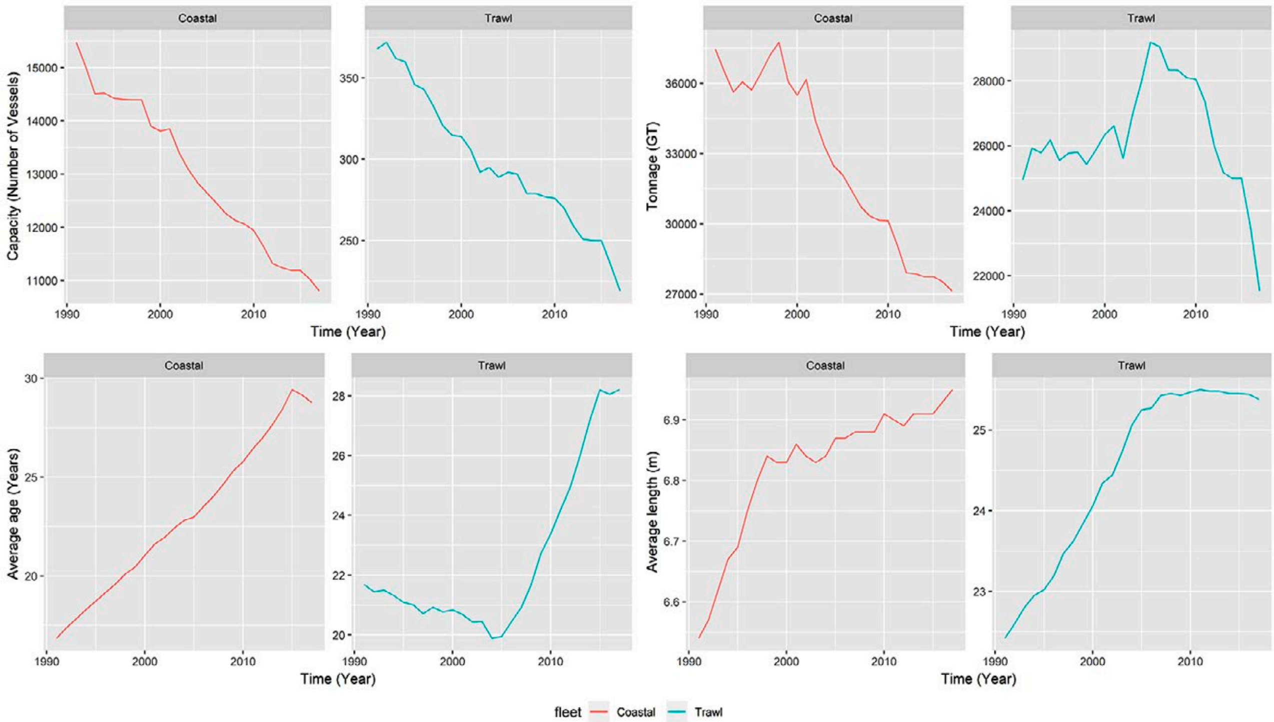

Fig. 2. – Trawl (blue) and coastal (red) fleet evolution over the years 1991-2017. For each fleet the capacity, total tonnage, average age and average length are presented for the two demersal fleets that operate in the Aegean Sea [data retrieved from IMAS-Fish database (Kavadas et al. 2013)].

costs (electricity, mooring and water supply) were also included in the model.

3. Long term costs derived from financial and opportunity costs. The real interest rate for Greece in 2014 was used as a proxy for opportunity costs and was estimated from the equation (STECF 2016):

$$r = [(1 + i)/ (1 + \pi)] -1$$

where π is the inflation rate and i is the nominal interest rate.

In addition, the following five factors were considered:

4. Initial capital and capital investment of the vessels.

5. Technical characteristics at vessel level, e.g. capacity (number of vessels, gross tonnage and engine power) and year of vessel construction.

6. Annual fishing effort at fleet and vessel level (mean value of fishing days and hours per day).

7. Employment and insurance data.

8. The average price paid by the Fisheries Administration for decommissioning vessels, based on vessel age and gross tonnage as if the vessels were exiting the fishery in 2014 (Regulation (EC) No. 1198/2006, Article 51, paragraph 1).

The economic data were disaggregated at the vessel level for the trawl fleet. The capacity and tonnage of both fleets that define the demersal fishery in the Aegean Sea has been declining in the last few decades (Fig. 2). Where incomplete data existed, to simulate the whole trawl fleet of the Aegean Sea, we used the R package *mice* (R Core Development Team, 2017) to impute incomplete multivariate data by chained equations. The default method for completing the gaps in more than one variable for numerical data is predictive mean matching, and we conducted 1000 multiple imputations. For the coastal fleet a nominal large vessel was considered in the analysis to simulate the activity of the whole fleet.

Management strategies and simulation conditions

The alternative management scenarios established herein were based on current knowledge of the legal constraints, the socioeconomic state of the fleet and the options that fisheries managers will have to consider in the near future. The performance of selected biological indicators (fishing mortality, landings and spawning stock biomass) and economic indicators (net profits and gross value added) was examined against the current exploitation strategy. The eight scenarios examined herein are:

1. *Business as usual (The baseline/status quo scenario)*. The current fishing pattern of the Aegean Sea is described by 250 trawlers fishing for 7.5 months in the area with spatiotemporal restrictions and *no changes in discarding practices*. In this scenario, unwanted catches, i.e. undersized individuals of the target species, are simulated to be discarded in low numbers or sold “as usual” on the black market (neither enter into the estimation of F or generate income/cost that is recorded in the official statistics). The current management plan, first implemented in 2014, bans fishing activities from June to September each year and additionally introduces a ban from 24 to 31 December and from 24 to 31 May each year. A total of 10000 coastal vessels were taken into account, although 35% of them were inac-

tive in 2014 (Kavadas et al. 2013). These vessels use polyvalent passive gears and operate all year around. It was assumed that selectivity and catchability were considered constant from 2014 onwards. Fishing effort from trawlers was simulated to decrease by 2% per year as the general trend detected from the records of capacity for the Greek fleet (Fig. 2). The coastal fleet shows a larger decrease in numbers, although the relative decrease is very low (~0.5% per year) in comparison with the total number of coastal vessels (Fig. 2). Also, the profits obtained from fishing were assumed to be destined to sumptuary consumption and not to increasing fishing effort or capital over the years of the simulation period (i.e. no internal investment).

2. *Implement a discard ban*. Producers are obliged to face a cost of disposing of undersized fish of three target species subject to the LO, and this represents a penalty for generating discards estimated at 0.50 €/kg (cf. Sartor et al. 2016).

3. *Implement a discard ban and impose a 10% reduction in fishing effort*. In combination with the discard ban, additional temporal closures will be set in order to simulate reductions in effort by reducing days at sea to address the excessive fishing effort problem. This will be simulated with a 10% decrease in the number of days devoted to this fishery by both fleets following GFCM recommendations (Resolution GFCM/33/2009/1 "On the Management of demersal fisheries in the GFCM Area").

4. *Implement a discard ban and changes in selectivity*. In order to reduce discards, we suggest changes in gear technology in addition to the introduction of a discard ban. This is an imaginary perfect fishing gear that fulfils the MLS for hake. Changes are made to the gear selectivity, assuming the introduction of a selection device to reduce juvenile by-catch by excluding undersized hake and therefore other undersized targeted species (simulated by a knife edge ogive at length = 20 cm for hake, see Maynou et al. 2017).

5. *Implement a discard ban and reduce fishing mortality* of species at age 0 to zero to simulate a closure of nurseries to trawling and hence increase the length at first capture to one year (simulated by a logistic ogive defined by L_{50}, L_{to95} of the three species) (Table 2).

6. In addition to the discard ban, *provide incentives for compliance* to motivate fishers to comply with the discard ban. To implement the discard ban, all fish subject to the LO (below MLS) should be brought to land. An increase in the market price for compliant fishers was simulated by providing them with a discard-free product certification [assuming that consumers were ready to pay a premium price of 15% more based on results from the willingness to pay scenario for hake, based on Onofri et al. (2018)]. The costs of discard-free certification were not included in the model.

7. *Implement a discard ban and provide subsidies* to support the marketing of alternative species (annual subsidy of 2500 €/vessel).

8. *Implement a discard ban and legally sell the fraction of former discarded fish for purposes other than direct human consumption* at an estimated price of 0.20 €/kg (Sartor et al. 2016).

The simulations were carried out over a projection horizon of 20 years from 2014 onwards (year 0) using 1000 iterations. Ricker's model was used to generate recruits. The first four years were used for model initialization, based on the biological cycle of the species studied, and the scenarios were introduced in 2019 (year 5). The results of the stochastic simulations are presented as the mean and 95% confidence interval for each indicator. The % change was calculated to compare the baseline scenario of the different scenarios implemented at different times to reveal tendencies. In this model, perfect compliance was assumed under the LO (Scenarios 2-8), i.e. all regulated fish are either landed to be destroyed at a cost paid by the producer or channelled to the markets for non-human consumption.

Model description

The bioeconomic analysis was carried out using the MEFISTO 4.0 bioeconomic simulation model (Maynou et al. 2017). It is a multispecific, multigear and multifleet bioeconomic model that incorporates the dynamic state of living resources along with the economic conditions that govern the Mediterranean fisheries (Maravelias et al. 2014). The model used is the same as the one described by Maynou (2014) but also includes a formulation of the production of unwanted catches and the option of including a market for former discards. The conceptual framework that this model was built on involves a stock, a market and a fisherman module:

1. The stock module simulates the dynamics of one or more target fishery stocks whose age-structured dynamics are completely explicit, and the secondary/commercial by-catch, whose dynamics are not known but their contribution to total revenues is important in Mediterranean fisheries, and their catch is computed as a function of the catches of each main species. The input to the stock module is the fishing effort and the catchability (as exerted from the fishers' module), whose product constitutes the fishing mortality (F) applied to the stock. The output of the stock module is the catch that feeds into the market module. Note that the biological module does not include ecological interactions among species, only technical interactions (Maynou et al. 2017).

2. The market module converts the catch of main and secondary species into money with a price function. The price function includes the base price, the average fish size and the fish offer. In our study all fish is sold fresh and the prices used are ex-vessel prices (€/kg).

3. The fishers' module simulates the economic behaviour of the fishing firm. It assumes that fishers follow standard economic theory and seek to maximize profits. The input data are the revenues resulting from the market module and its output is the effort and the catchability, over which the fishers have certain control through their capital (although in our study, catchability was assumed constant and effort control was exogenous, as no internal investment was simulated).

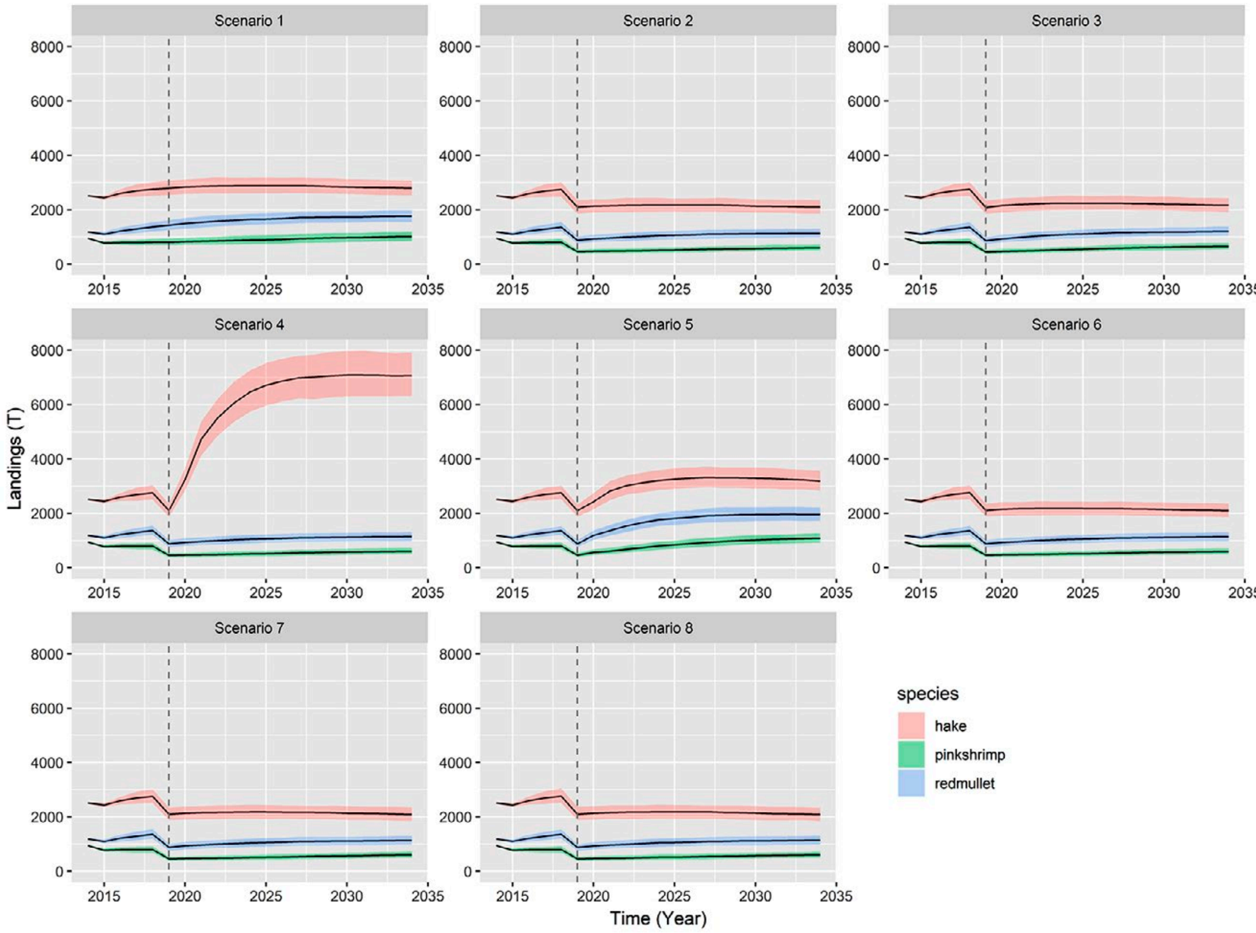

Fig. 3. – Landings estimates for the three species under the eight simulated scenarios. Black solid lines indicate the mean estimates, and the upper and lower limits of each ribbon indicate the 0.05 and 0.95 quantiles.

The parameters of the fishers' module are organized at two levels, fleet and vessel, allowing the characteristics of each vessel to be particularized. More information on the model and the equations used can be found in Maynou et al. (2017).

RESULTS

Biological indicators

Under the baseline scenario, landings show a stable increasing trend for all species, except for a slight decrease for hake landings after 2030. For all scenarios that simulate a discard ban (Scenarios 2-8), landings decrease after 2019 due to the fact that unwanted catches of the target species are brought to land but would not enter the official landings fraction (Fig. 3). However, for scenarios 4 and 5 landings return to the 2014 levels in the long term: hake landings increase by 14.2% in the short term, while a tremendous increase is evident in the long term (Scenario 4) and a small short-term decrease and an average increase of 10% is expected in the long term for all three species (Scenario 5).

Under the business as usual scenario, F increases for hake by 8.2% in the long term, while for the other species F decreases by approximately 20% in 2019 and by 5.7% for red mullet and by 10.7% for deep-water rose shrimp in the long term. In general, F shows the same pattern in all scenarios and changes only in Scenarios 3-5, i.e. after applying effort reduction and selectivity improvement. An introduction of a discard ban by itself is not going to bring a decrease in F, because under the current application there is no endogenous adaptation of catchability or effort that would relate an economic result (earnings or losses due to the LO) with variations in F (Scenario 2). Under Scenario 3, this indicator shows a decreasing trend that is stable after 2020 for all species. For Scenario 4, the F for hake decreases significantly (by 27%) after 2020 and stabilizes at 0.5 in 2034. In contrast to hake, under the same management measure the fishing mortality for red mullet and deep-water rose shrimp shows a very small decrease of 0.5% and 0.7%, respectively, in comparison with 2014 levels. When year age 0 of all species is protected (Scenario 5), the fishing mortality decreases by 8% for all species in the short and long term.

For all scenarios (except 3, 4 and 5), the hake spawning stock biomass (SSB) is stabilized to the 2014 levels at the end of the simulation period, while the SSB of the other species increases by 35.3% for red mullet and by 9.7% for deep-water rose shrimp in the short term and by 94% for red mullet and by

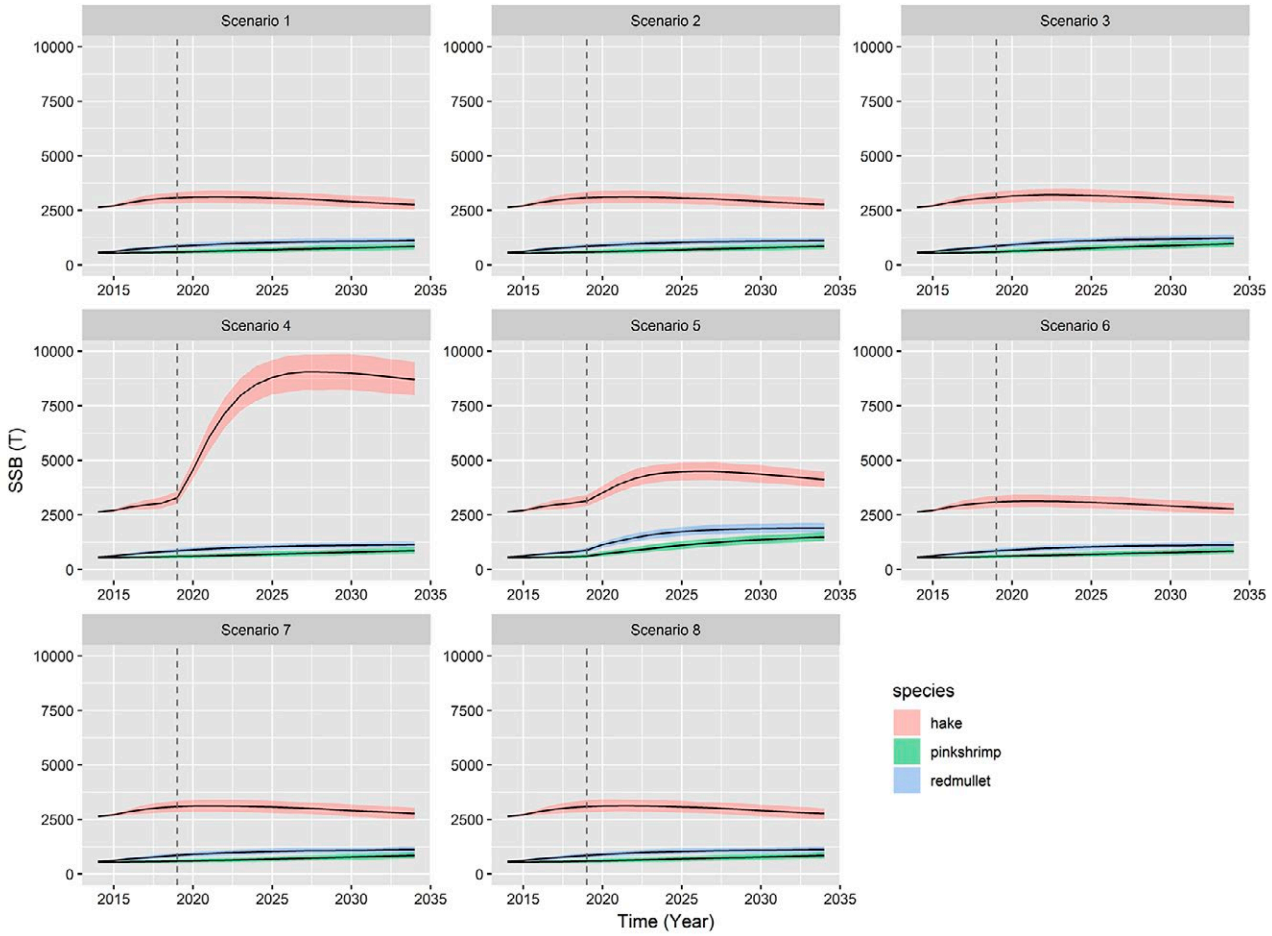

Fig. 4. – Spawning stock biomass estimates for the three species under the eight simulated scenarios. Black solid lines indicate the mean estimates, and the upper and lower limits of each ribbon represent the 0.05 and 0.95 quantiles.

Time	Species	Landings	% variation	F	% variation	SSB	% variation
2014	hake	2514.60		0.634		2641.72	
2020		2834.85		0.620		3105.36	
2034		2788.89		0.675		2766.16	
2014	red mullet	1187.08		0.929		581.90	
2020		1491.32		0.777		900.03	
2034		1758.43		0.736		1129.65	
2014	pink shrimp	948.73		0.860		552.92	
2020		828.09		0.690		612.43	
2034		1016.92		0.623		851.13	

Fig. 5. – Biological indicators of performance of the three target species. Comparison of the baseline values (2014) of three biological indicators (Landings, F, SSB) with the values after the implementation of the management measures (% variation, each column bar is the % difference of the baseline scenario and scenario tested for the respective year), under scenarios 2-8 in 2020 and 2034. Red and green column bars indicate negative and positive trends, respectively. F, fishing mortality; SSB, spawning stock biomass.

53.9% for deep-water rose shrimp in the long term. Scenario 3 would lead to significantly higher hake SSB levels than scenario 1 (business as usual), with just a slight increase of 3.77% in the long term. Scenario 5 would result in moderate increases in 2020 for all three species and significantly higher increases of 48% to 76% in 2034. For SSB the nursery closure has the largest positive impact on all three species in both the short and long term (Scenario 5) in comparison with the introduction of a selective improvement measure (Scenario 4), which results in a small but stable increase in SSB for all species, except hake, which shows a very large increase of 47% in the short term which is stabilized by 2025 at 8706.75 t, offering considerable hope for the future of this species, the most vulnerable of the three (Figs 4 and 5).

Time	Fleet	Net profits	% variation	GVA	% variation
2014	Trawl	9.85		19.00	
2020		12.39		22.18	
2034		12.99		22.64	
2014	Coastal	129.26		278.40	
2020		167.82		355.53	
2034		173.97		367.83	

Fig. 6. – Economic indicators of the trawl and coastal fleet. Comparison of the baseline values (2014) for two economic indicators (net profits, GVA) with the values after the implementation of the management measures (% variation, each column bar is the % difference of the baseline scenario and the scenario tested for the respective year) under scenarios 2-8 in 2020 and 2034. Red and green column bars indicate negative and positive trends, respectively. GVA, gross value added. Values are in million euros.

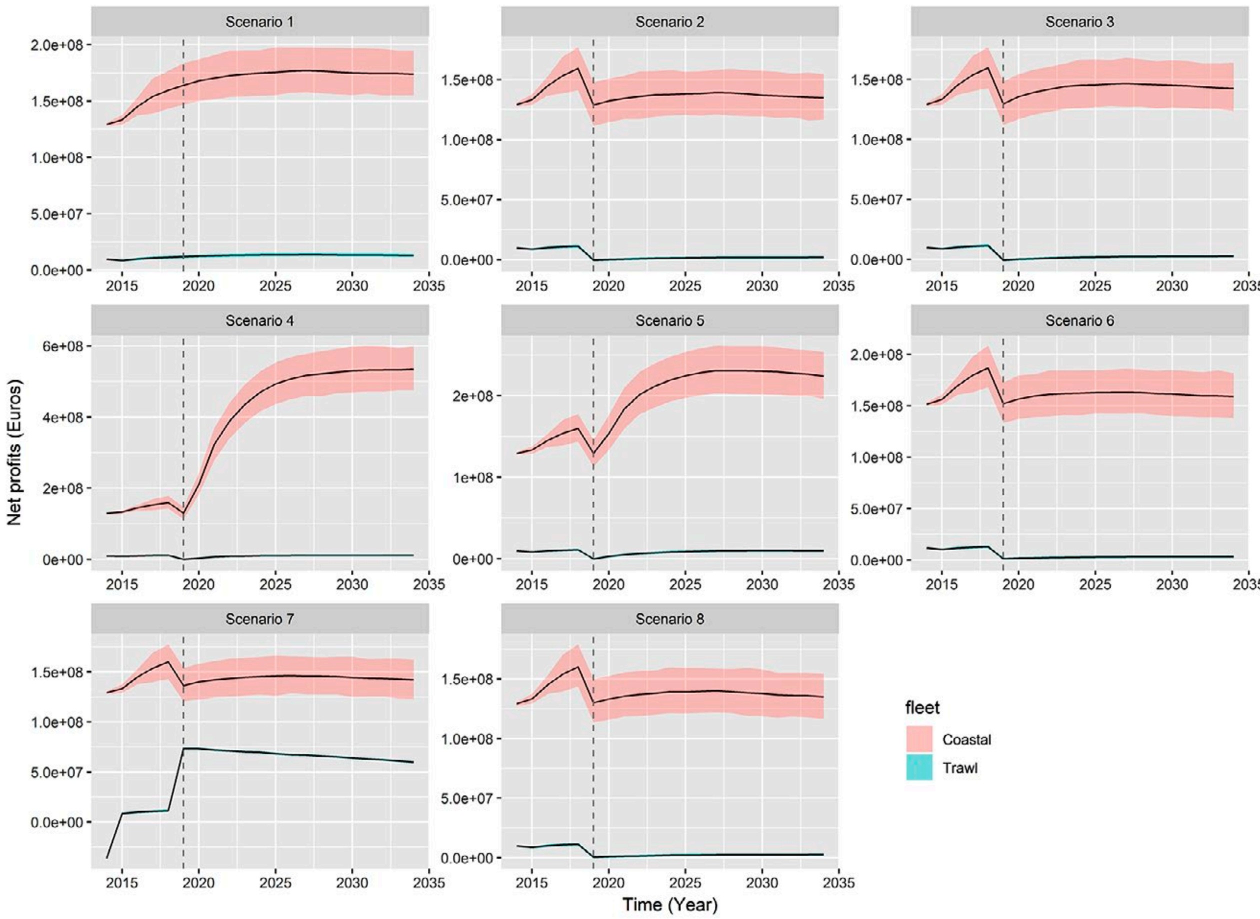

Fig. 7. – Net profits for the trawl (blue) and coastal (red) fleet under the eight simulated scenarios. Black solid lines indicate the mean estimates and the upper and lower limits of each ribbon represent the 0.05 and 0.95 quantiles.

Economic indicators

In economic terms, Figures 6, 7 and 8 reveal that only under the baseline scenario are no short-term losses observed. All other scenarios show a negative trend for net profits, except that of provision of subsidies, which boosts the performance of the trawl fleet due to a short-term income from subsidies (Fig. 6). The coastal fleet largely benefits from a selectivity improvement measure (Scenario 4), which increases net profits and gross value added (GVA) by ~25% in the short term and by 400 and 800 M €, respectively, in the long term. The same applies for nursery closure (Scenario 5), which causes an increase in net profits of €98 K for trawlers and €95 M for the coastal fleet in the long term. If former discards were used commercially (Scenario 8), the economic indicators reveal that this would likely bring a slight improvement in profits in comparison with introducing a discard ban alone, but in general a negative effect will be evident in the economic performance of both fleets, especially for trawlers (Figs 7 and 8).

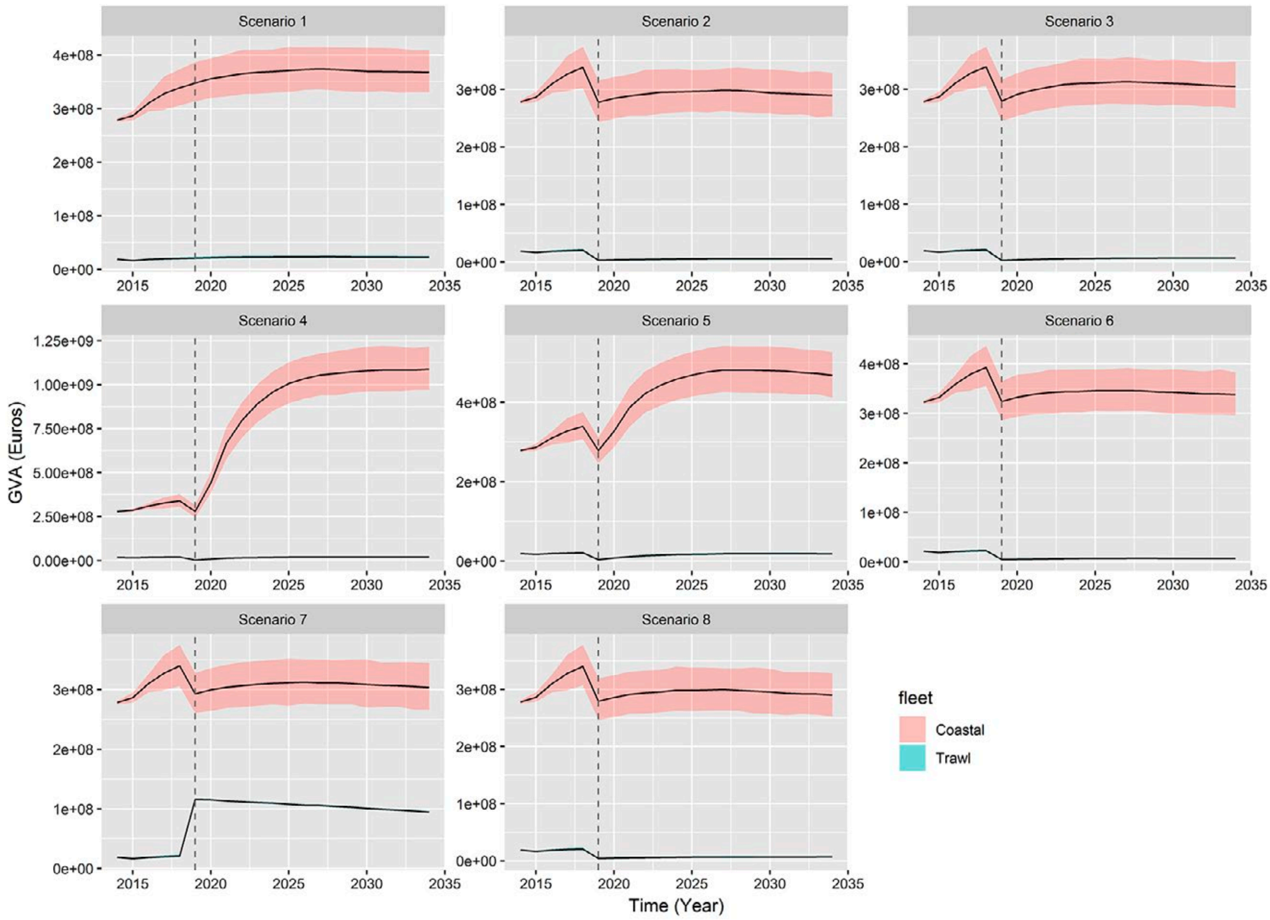

Fig. 8. – Gross value added (GVA) for the trawl (blue) and coastal (red) fleet under the eight simulated scenarios. Black solid lines indicate the mean estimates and the upper and lower limits of each ribbon represent the 0.05 and 0.95 quantiles.

DISCUSSION

Under the status quo, the viability of the fishing industry in the Aegean Sea is threatened. According to our simulations, given the current management conditions, the three target stocks should generate a small increase in income in the long term. Nevertheless, in the last few decades the fleet has decreased to a great extent (Fig. 2), key stocks are overexploited, and the fishery is not considered sustainable, like other Mediterranean fisheries that are under an "alarming decline" (Froese et al. 2018, Vasilakopoulos et al. 2014). Projections under the baseline scenario have shown that SSB of hake is the only one that demonstrates a steadily decreasing trend. Hake is the most vulnerable species, according to the GFCM assessment (GFCM 2017). The stock is currently overexploited (Biomasscurrent/BMSY is 0.85) and overfished (Fcurrent/ FMSY is 1.17). The same assessment for red mullet indicates that the stock is in healthy condition, as biomass is above MSY levels and fishing mortality is below the FMSY (GFCM 2017). Exploitation patterns need to change if all stocks are to be fully utilized at sustainable levels and the profitability of the Greek fleets is to be secured.

In general, the trawl fleet records higher income per vessel but coastal vessels are numerically larger and thus contribute more to the economy of Greece in terms of both GVA and employment. Moreover, our results show that, when implemented in isolation, the discard ban will generate few economic incentives for fishers to operate more selectively. In our simulation, the lack of endogenous effort adaptation or a constant catchability assumption mean that any earnings or losses from the former discards brought to land do not enter the economy. Given the volumes of discards estimated for the target species of the Aegean demersal fishery, the economic impacts are expected to be low and will not incentivize major operational changes. Therefore, the discard ban in isolation will not result in stock rebuilding or improvement of the socioeconomic state of fisheries, but rather to a decrease in landings and long-term economic losses. The sale of former discards will bring small additional profits but will not compensate losses due to the landing of target species or sorting and handling costs (a "crash landing" obligation). Sola and Maynou (2018) produced similar figures but the Spanish fleet was shown to bounce back in the long term despite the significant losses of revenue in the short term. In fact, anything beyond the short to medium term depends on the initial conditions introduced in the model (e.g. uncertainty in the SSB/R relationship, internal investment, capital depreciation, discount rate and original F/FMSY ratio for each species).

Additional management measures should be considered in order to ensure a smooth implementation of the CFP. The current study has visualized the output of eight possible scenarios in order to enable comparisons of management strategies. The fishing mortality will not decrease until technical measures are applied in different forms, such as effort reduction and selectivity improvement, with the latter offering a greater benefit to stocks. The projections agree with those of Tserpes et al. (2016), who also pointed out the importance of decreasing effort in the Aegean fleet for stock rebuilding. Subsidies may result in higher profits for the trawl fleet, but their effect is highly controversial because they provide incentives for overcapitalizing the fleet (Sumaila et al. 2010). GVA was exceptionally high in the selectivity scenario (scenario 4) for protecting juvenile hake. By protecting the nurseries of target species and decreasing the fishing mortality at safe biological limits, this could result in sustainable production patterns. Measures to support the fishing communities need to be implemented to support the sector, which already faces serious problems due to the ongoing national economic recession and the ageing population.

Recent policy imperatives have focused on resolving sustainability issues, in particular on eliminating or reducing discards caused by fisheries harvest patterns and poor selectivity of fishing gears. By implementing a discard ban in mixed fisheries, evidence has shown that it is essential to examine the conditions under which discards are generated in order for them to be decreased (Condie et al. 2014). These policy imperatives can be put into practice thanks to the provision of solid scientific advice. Mixed fisheries management is now focused on simultaneously meeting conservation targets for multiple species and fleets by understanding the dynamics of individual fishers and fleets (Tidd et al. 2012). Implementing any management measure in multi-species fisheries is a difficult task (Alzorriz et al. 2018). European mixed fisheries are called to manage challenging situations: to enforce the minimization of undersized individuals for Mediterranean fisheries and to avoid losing opportunities in exploiting other species because of the lack of quota availability for certain (choke) species, a complex phenomenon that could arise frequently for Atlantic fisheries under the LO (Sánchez-Lizaso et al. 2018, Spedicato et al. 2018). The ecosystem approach to fisheries management can lead to effectively managed fishing activities. The new policy could improve the current state of fisheries resources in Greece by encouraging avoidance of unwanted catches, but only when combined with other technical measures. The results of this study show that it will be challenging, but not impossible under F reduction actions (as seen in Maynou 2014), to meet the CFP objectives regarding stock sustainability, i.e. to achieve maximum sustainable yield by 2020 for all stocks.

The market and regulatory constraints are the main reasons for discarding in Hellenic waters, but other reasons are also detrimental, including the low commercial value of the landings, fishing practices, mishandling on board, etc. (Tzanatos et al. 2007, Gonçalves et al. 2007, Christou et al. 2017). Therefore, under the LO, supporting measures should be established to discourage the marketing of undersized fish, monitor the fish supply and distribution chain by fostering traceability of fisheries resources from vessels to consumers, and increase stakeholders' awareness through education seminars (Maynou et al. 2018). In general, the multispecific nature of Mediterranean demersal fisheries makes it difficult to reduce discards as policies are difficult to implement when there is a lack of clear *métiers* and high spatiotemporal variation in discard composition (Maina et al. 2018). Other studies have shown that if effort or quota restrictions are combined with a discard ban, this will result in additional costs and a short-term fall in income but will generate economic incentives to avoid unwanted catches (Condie et al. 2013). When a discard ban was implemented in a mixed fishery in the eastern English Channel, fishers' behaviour changed to fully utilizing the cod quota or reallocating effort to areas and weeks in which cod catch was low (Batsleer et al. 2013). The CFP could create incentives to improve the harvest patterns (Prellezo et al. 2016) by enabling exemptions specific to each fishery and providing a regionalization of advice. Also, gear modifications could improve selectivity and enhance sustainability (Sola and Maynou 2018) and spatiotemporal closures could assist the rebuilding of fisheries through an increase in the SSB of targeted stocks (Russo et al. 2017). Measures proposed for solving the discards problem in Europe vary in form and application status (Sigurðardóttir et al. 2015). By improving the gear selectivity, the unwanted catches generated will be reduced at the point where they are generated, resulting in the impoverishment of the illegal market of undersized individuals.

Significant data issues arose in the writing of this manuscript because the implementation of the Greek National Fisheries Data Collection Programme has faced some difficulties in the last ten years ("data poor mixed fishery" Sgardeli et al. 2019). Things that were not taken into account in our analysis are the additional handling and disposal costs of former discards brought to land and any investments that the fishers must leverage in order to comply, but these are expected to be low (Maynou et al. 2018). Moreover, when a nursery closure is simulated, the length frequency data used to generate L_{50} and L_{to95} estimates for the target species derived were not spatially explicit. Another aspect that could be investigated is a selectivity scenario using the mesh panels or grids that have been successfully applied elsewhere. Mytilineou et al. (2018) completed research on the selectivity of trawl fisheries in the Aegean Sea using different codend mesh sizes under a national research program, showing the importance of the 40 mm square and 50 mm diamond mesh currently used by the Greek fleet in comparison with the previous gear (40 mm diamond), which had fewer escapees and more discards, but none of them achieved a value of L_{50} close to the MLS. The willingness to pay scenario was based on a survey held in two other European countries, Spain and Italy (Onofri et al. 2018), where consumers assessed the value of the reserve price for a more sustainable fishery, but the consumption patterns and consumer choices may be very different for the Greek case. In fact, in Greece and in other Mediterranean countries, there is a strong local black market for undersized fish (Damalas and Vassilopoulou 2013) and for this reason discards appear to be low. Short-term incentives are important for increasing compliance (Pascoe 1997) and ensuring the implementation of the LO. Compliance levels among fisheries are highly uncertain and variable among areas in Europe (de Vos et al. 2016, Guillen et al. 2018).

To overcome the discard problem, a participatory approach needs to be followed to connect all available evidence (Maravelias et al. 2018). Given the peculiarities of European fisheries, appropriate management action is important to address any issues at local levels (Spedicato et al. 2018). The active involvement of stakeholders could increase legitimacy and reveal the main reasons for discarding in order to find relevant and effective solutions at local levels. Future work could be aimed at testing different mechanisms and incentives for increasing compliance towards a smooth implementation of the CFP. To this end, the managers should carefully examine all available ways to support the rebuilding of stocks and the adaptation of fisheries-dependent communities under the new regime by encouraging the adoption of more selective gears and techniques through the funding opportunities offered by the European Maritime and Fisheries Fund. It is still critical to resolve data deficiencies and investigate the potential consequences of supplementary measures introduced under the CFP. An improved application of fisheries management will be enabled through an evidence-based and adaptive policy.

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