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Policy management of the Italian small pelagic fishery in the Adriatic Sea: A dynamic maximum economic yield approach

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ABSTRACT

The sustainability of most Mediterranean fisheries is heavily compromised, suggesting the need for an effective policy response to preserve both profitability of fleets and fish stocks in the long run. This study focuses on the Italian small pelagic fleet in the Adriatic Sea. More specifically, we focus on anchovies and sardines' stocks, which account for most of the total catches in the area in terms of landed weight. We build an optimization model aimed at estimating the discounted Maximum Economic Yield (MEY) of this fishery under selected policy scenarios ranging from effort limitations to total allowable catch (TAC) management. The model allows us to compare the bioeconomic performances of the fishery over a time span of 10 years. The results outline a trade-off between biological and economic policy targets, as well as an efficiency gap among fishing gears. This gap ultimately leads to an uneven distribution of economic benefits under restrictive policy scenarios.

1. Introduction

The European Union (EU) manages most of its stocks under the European Common Fisheries Policy (CFP), which regulates fishing activities and aims to achieve sustainability in the long run mainly through the maximum sustainable yield (MSY) approach. However, despite these efforts, the well-being of most of the EU stocks is heavily compromised and the management of EU fisheries has been less efficient overall than that in other countries, such as Australia, New Zealand, and Iceland, mostly due to the heterogeneity of interests and the economic and political backgrounds of its member states (Marchal et al., 2016).

Northern EU stocks appear to be harvested safely, while, in the Mediterranean Sea, >80% of fish stocks are exploited beyond their safe biological limits (Froese et al., 2018). These distinctions may be driven by different key factors. First, the CFP was originally established in 1983 to address fishing in the Northern Seas. In 1994 it was only marginally extended to include technical measures for the Mediterranean Seas. The delay and the protracted pace at which Mediterranean fisheries have been regulated may have contributed to a lack of effectiveness of such policies (Lado, 2016). Second, the Mediterranean Sea is bordered by many different EU and non-EU countries with diverse economic and political backgrounds resulting in different levels of prioritization of fisheries management in their political agendas. Third, the Mediterranean fisheries are multispecific (see Carpi et al., 2017). Such differences are reflected in the management approaches adopted in the two areas. Output control measures have been a key policy instrument in the Northern EU seas, where most species are subject to total allowable catch (TAC) limits. In the Mediterranean area, this approach has often been dismissed because of the heterogeneity of fishing gears and target species. Instead, a series of input control measures have been applied, limiting the fishing effort and/or capacity or defining technical measures and minimal conservation reference sizes. For these reasons, fisheries management in the Mediterranean area has always been a highly debated topic, especially when it comes to defining binding rules for different stakeholders and countries. The implementation of such measures has been further hindered by a generalized low level of enforcement and misreporting, leading to inadequate or defective information which affected the quality and reliability of stock assessments and scientific advice (Lado, 2016).

This paper evaluates the economic impact of a set of policies implemented in the Mediterranean Sea while focusing on the Adriatic Sea small pelagic fishery, particularly targeting the anchovy (*Engraulis*

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encrasicolus) and sardine (*Sardina pilchardus*) stocks. Research on small pelagics' management in the Adriatic area is crucial because harvests of anchovies and sardines combined have come to account for 60% of the total catches in the Adriatic Sea by weight in the last five years. Such catches are mostly imputable to Italy and Croatia as Slovenia harvests a negligible quantity of these two species (FAO, 2018, 2020). However, while both anchovy and sardine stocks have been well monitored in the past decades from a biological perspective, with new assessments available every year, the economic conditions of the fishing fleet have not been explored at the same rate.

We estimate the dynamic Maximum Economic Yield (MEY) for the Italian small pelagic fishery under different policy scenarios through an optimization model. The past and current recommendations of the General Fisheries Commission for the Mediterranean (GFCM) will be used to set realistic policy objectives. We will explore the absence of policy restrictions, effort limitations and two quota scenarios, differentiating between mixed and separate[1] TAC policies.

Among the few studies that have investigated the Adriatic small pelagic fishery management (Silvestri and Maynou, 2009; Spedicato et al., 2016; SAC, 2018), one of them focuses on (static) profit maximization (Mulazzani and Malorgio, 2013). Both prior and recent research lack a dedicated focus on dynamic profit maximization as a management strategy.

Our paper aims to address this research gap concerning how small pelagic fisheries management impacts the fishery from an economic standpoint. We focus on evaluating how current and prospective policies may influence the profitability of the fishing fleet. We contribute to the literature by (i) presenting, for the first time, an estimation of the dynamic MEY of this fishery; (ii) improving our understanding of the economic dimensions of the small pelagic fishery in the Adriatic Sea; (iii) comparing policy scenarios aimed at both restricting fishing effort and implementing quotas while allowing for varying degrees of efficiency at the gear level in an economic efficiency perspective. The results of this work could be used to understand if and how policy objectives compatible with biological sustainability can ensure the economic efficiency of the Italian small pelagic fishing fleet.

We acknowledge the need for an integrated management approach aimed at securing the sustainability of the marine ecosystems in the long run as suggested by the ecosystem-based fishery management (EBFM) approach. However, the lack of direction concerning the practical implementation of EBFM has frequently led to the omission of this approach from the policy debate and interventions (Link et al., 2017). Previous evidence (Froese et al., 2008) has demonstrated how the benefits derived from the EBFM approach could exceed those expected when utilizing the MSY approach, and that defining MEY as a management objective produces effects that are consistent with the foundations of the EBFM framework (Caputi et al., 2018). MEY has also been mentioned among a potential set of indicators deemed feasible to quantify the policy impact of the EBFM approach (Kim and Zhang, 2011). Despite the constraints posed by data limitations on our biological theoretical framework, we believe that our multi-species and multi-gear approach constitutes an advancement compared to the standard single-species management approach, given the intertwined nature of anchovy and sardine fishing in the area. Further limitations of this studies are discussed in the conclusion section.

The rest of the paper is structured as follows. Section 1.1 includes the literature review. The case study description and the methodology are presented in Section 2, while Section 3 reports the model results and discussion. Conclusions, policy implications and empirical limitations are discussed in Section 4.

[1] With the mixed quota, both species are subject to the same TAC at the same time. With the separate quotas, every species is subject to its own TAC limit.

1.1. Related literature

The static MEY was originally defined by Gordon (1954) as a reference point where the net economic benefits of the fleets (profits) are maximized when the discount rate is equal to 0. The discount rate indicates how much fishermen value the future monetary benefits compared with the current ones. The static MEY can therefore be used to determine the amount of effort required by the fishing fleet to maximize profits, i.e., the difference between revenues and total costs. The optimal level of fishing effort thus obtained is lower than that required by MSY and the so-called bioeconomic equilibrium, which is instead defined as the point where the economic rent is dissipated (hence when revenues equal total costs). As a result, a lower fishing effort associated with MEY corresponds to a higher level of stock biomass. However, the inclusion of discount rates in dynamic optimization models is crucial to consider the fishing activity as an economic choice regarding the amount of fish that should be harvested at a given time and the amount that should be preserved. In dynamic optimization models, a non-zero discount rate is typically incorporated resulting in an optimal biomass (effort) level lower (higher) than its static counterpart. The distinction between these two reference points becomes more pronounced with increasing discount rates (Clark, 1976; Hoshino et al., 2018). A fixed exogenous discount rate has been identified as one of the main limitations of the MEY, (Cuilleret et al., 2022), along with the omission of external factors such as technological progress, consumer benefits and externalities (see Squires and Vestergaard, 2016). In this regard, non-constant discount factors have also been investigated (Da-Rocha et al., 2016).

Many empirical studies have estimated the MEY for different stocks and proved that it can be effective in favoring both the biological sustainability of fish stocks and the economic sustainability of the fishery in the long run. MEY has been officially implemented as a management reference point in Australian fisheries (Kompas et al., 2010; Grafton et al., 2011). However, the CFP pursues the achievement of the maximum sustainable yield (MSY) instead, which is the level at which harvests can be maximized while preserving the stock in the long run. The debate on whether MEY or MSY should be applied has been ongoing for decades. Holma et al. (2019) outline that the CFP vaguely requires harvested stocks to be 'above MSY' levels without effectively specifying such levels, and that the MEY could be a suitable policy alternative to achieve such target. Indeed, there is extended evidence on how achieving the MEY entails achieving a higher value of profits for the fleet (Chu et al., 2022) compared to the business-as-usual scenarios (Guillen et al., 2013), which is why MEY could be a valid alternative to pursue the current CFP goals. Recent work (Diop et al., 2018; Lagarde et al., 2018; Cuilleret et al., 2022) has shown that the MEY can be a relevant strategy to deal with climate change as an adaptation strategy. In the EU context, dynamic profit maximization strategies have been used to quantify pelagic fisheries' economic response to real or hypothetical management policies over time, mostly referring to North Atlantic fish stocks. Ekerhovd and Steinshamn (2016) developed a multispecies model of the North-East Atlantic pelagic complex, where species growth depends on a common environmental carrying capacity parameter. They built a surplus production model optimized from a sole owner perspective. Salenius (2018) modeled a multispecies and multi-fleet fishery system considering the same North Atlantic fishery and three exploiters (Norway, Iceland, and the EU), deepening our knowledge of transboundary fish stocks and their management under a profit maximization strategy in cooperative and noncooperative scenarios.

The empirical research work on the economic management of small pelagics in the Adriatic Sea is limited. Silvestri and Maynou (2009) described the long-term behavior of the small pelagic fishery under different management scenarios, such as fuel price decreases/increases and fishing day limitations/extensions, using a simulation tool, accounting for the uneven impact of the policy scenarios on different fleet segments. Mulazzani and Malorgio (2013) studied the Adriatic small pelagic fishery through a steady-state optimization model and game theory. They built a two-fleet and two-species model to set different scenarios for Italy and Croatia. This is the only study to have considered a profit maximization strategy in the case study area. Few recent bioeconomic assessments from the GFCM and Scientific, Technical, and Economic Commission for Fisheries (STECF) simulate the biological and economic effects of some selected management scenarios to support the policy decision-making process (e.g., Spedicato et al., 2016; SAC, 2018). None of the most recent studies has focused on profit maximization as a feasible policy target.

2. Material and methods

2.1. Case study description

We will focus on the northern and central areas of the Adriatic Sea, which belongs to the major FAO fishing area 37 (Mediterranean and Black Sea). The study area is included in Geographical Sub-Areas[2] (GSA) 17 and 18. The Adriatic Sea is over 800 km long and 150–200 km wide. It can be divided into northern, central, and southern areas with progressively increasing depth, the northern area being the shallowest and the southern being the deepest. In the last decades, anthropogenic activities and urbanization have led to an increasing level of pollution in this basin, especially in its northern area, where contaminants are less dispersed because of the lower depth of marine waters (Danovaro and Boero, 2019). The fishing activity in the Adriatic Sea has been one of the main economic drivers of the region on both sides of the basin, with Italy and Croatia being the largest exploiters. Small pelagic fish, such as anchovies and sardines, are the main species targeted by both countries (FAO, 2020).

In Italy, small pelagics are highly targeted at the overall national level, even though they are not the most relevant species in terms of harvested value as they are less profitable than other types of fish (BMTI, 2020). On the Italian coastal side of the Adriatic, anchovies have historically been the main harvested species by weight until 2013, when the first GFCM recommendation entered into force. Since then, the difference between anchovies and sardines' harvests has almost disappeared. However, anchovies are still considered the preferred species and have a significantly higher value, while the price discrepancy between the two species in the Croatian markets is less pronounced.[3] These differences are mainly driven by the final destination of the harvested fish: in Italy, fish is mainly sold fresh for local consumption, while, in Croatia, it is processed by the food industry or used in tuna farms (STECF, 2018).

There is a pronounced disparity in the landings' composition and quantities between Italy and Croatia: while Italy seems to target both species almost equally especially in most recent years, Croatia is exploiting the sardines' stocks in substantially higher quantities. Fig. 1 shows the time series of landings in both countries.

Both species are currently considered overfished (SAC, 2022). It is often acknowledged that small pelagic biomass (i.e., the quantity of fish available expressed in live weight units) levels depend heavily on the environmental and climatic conditions of the marine ecosystem and on the availability of nutrients, which lead fish stocks to fluctuate considerably over time for natural reasons. In this context, climate variables that negatively affect stock growth are often emphasized by fishing activities: stock recovery (reduction) can be slowed (accelerated) and hindered (supported) by high fishing mortality (Checkley et al., 2017).

The short life span of small pelagic specimens, coupled with cyclical trends of abundance and scarcity due to environmental factors, has led to their stocks to collapse on more than one occasion and in various locations (Petitgas et al., 2010). In the Bay of Biscay, anchovies collapsed between 2005 and 2009 leading to the full closure of the fishery until 2010 challenging the profitability of the Spanish and French fleets. This event led to the subsequent establishment of long-term management plans based on scientific advice from the STECF, aimed at implementing policies based on TACs (Uriarte et al., 2023). In the Adriatic Sea, TACs have been only recently enforced, and small pelagic species have undergone through a management process based on input control measures such as effort and capacity limitations, albeit with little success.

Starting in 2013, the GFCM defined a series of recommendations aimed at regulating fishing activity by using input control measures such as the reduction of fishing days and fleet capacity. The first recommendations were aimed at regulating the fishery only in the northern and central areas of the Adriatic Sea, where most of the fleets operate, but their enforcement was subsequently extended to the southern area. The yearly fishing day limit was set to a maximum of 180 days per vessel (GFCM/42/2018/8). Within this range, no >144 days could be spent targeting either sardines or anchovies. In 2016, the GFCM established a maximum catch limit (GFCM/40/2016/3) based on the 2014 level. This limit was never strictly enforced, considering how harvests achieved extremely high levels in 2014 (Carpi et al., 2017). In 2021, the GFCM opted for a shift toward output control measures in an attempt to mitigate overfishing (GFCM/44/2021/20). A long-term management plan was set to be established during the 2024–2029 or the 2025–2029 period. Meanwhile, transitional quota measures for 2022 and 2023 were defined as it follows by the EU council regulations 2022/110 and 2023/195: limits for Italy and Croatia were respectively set at 35,394 and 56,304 t in 2022, and at 32,941 and 51,735 t in 2023. The transitional quota measures have recently been extended for another year (GFCM/46/2023/5): EU Regulation 2024/259 redefined the maximum level of allowable small pelagic catches at 30,672 t for Italy and 47,139 t for Croatia. The actual quota limits are supposed to represent the maximum amount of small pelagics allowed for both sardines and anchovies, but single species quotas may be established in the coming years. A long-term management plan is now under discussion and expected to be enforced starting in 2025, pending a satisfactory benchmark assessment of the small pelagic stocks. Past, present, and potential future policies will be used in our empirical framework to assess their economic consequences.

2.2. Data description

This work uses economic data collected under EU Regulation (EC) No. 199/2008, later abrogated by EU Regulation No. 2017/1004, which established a common framework for the gathering, management, and use of data in the fisheries sector. Every member state of the European Union is required to collect and report data on the fishing sector on an annual basis. We consider economic data from both GSA 17 and GSA 18. Selected variables are the number of vessels, production (catches) and its value by species, overall revenues, costs, fuel consumption, employment, and fishing time (measured in fishing days and often referred to as fishing effort). We compute variable costs as the sum of the expenses for all the factors of production, which vary with the number of fishing days, as suggested by Maiorano et al. (2019). Fixed costs are given by the sum of expenses not related to fishing days, such as maintenance, repair, and capital costs. Revenues refer exclusively to the quantity of fish landed (in tonnes) and do not include any subsidy or revenues from non-fishing activities as they are considered negligible for most of the Italian fisheries (Maiorano et al., 2019).

Revenues and catch data can be tracked down to the single harvested species, whereas costs are aggregated and refer to specific fishing gears. Previous studies (e.g., Salenius, 2018) have attributed the costs of harvesting each species to their relative percentage of total catches. We

[2] See Res. GFCM/33/2009/2 on the establishment of geographical subareas in the General Fisheries Commission for the Mediterranean (GFCM) area of application.

[3] STECF (2018) provides the average prices of sardines and anchovies in both countries in 2015: anchovies prices were 1.64 €/kg in Italy and 0.85 €/kg in Croatia, while sardines' prices were 0.78 €/kg in Italy and 0.38 €/kg in Croatia.

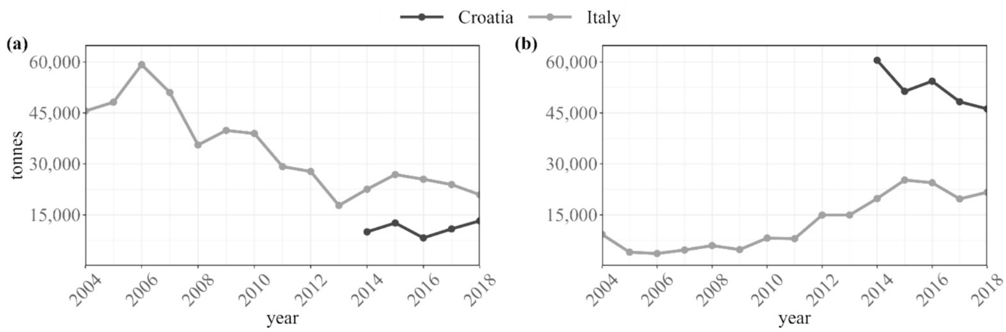

Fig. 1. Anchovies (a) and sardines (b) landings. Source: STECF.

make a slightly different assumption by distributing costs according to the relative percentage of small pelagic species' landed value in the total revenues. While both purse seines and mid-water pelagic pair trawls are primarily used for small pelagic fishing, they also account for a marginal portion of higher-value landings such as tuna or cattlefish (Maiorano et al., 2019), which may contribute to more profitable outcomes. Distributing costs based on catch value allow us to exclude the harvesting costs for other, more profitable targets not considered in our model due to their marginal harvested quantity. This assumption is needed to deal with the small portion of non-sardine and non-anchovy landings of the small pelagic fleet.

As for the biological data, we rely on sardines' and anchovies' biomass values from the MEDIAS (MEDiterranean International Acoustic Survey) project, which has developed a specific data collection protocol on the stock abundance of the mentioned species by using acoustic surveys as sampling methods. MEDIAS acoustic biological data included in this analysis refer to the western side of the Adriatic; therefore, they are a measure of stock abundance on the Italian side. Fig. 2 shows the time series of biomass levels for both species.

On the Italian side of the Adriatic Sea, small pelagic fishing is carried out using two fishing gears: purse seines (PSs) and mid-water pelagic pair trawls (TMs). PSs are designed to attract schools of fish to the same spot and surround them before pulling in the nets. TMs are mid-water trawls dragged by two vessels at the same time (Maiorano et al., 2019). The nets and mesh sizes for both gears are defined by European Regulation EEC No. 1967/2006 as well as the minimum allowed length of catches (11 cm for sardines and 9 cm for anchovies). From 2004 to 2018, the number of vessels operating in GSA 17 and GSA 18 has significantly decreased. In 2018, the Italian small pelagic fishing fleet was mainly composed of TM vessels.

2.3. Model description

In this work, we build an optimization model to estimate the dynamic MEY of the Adriatic small pelagic fishing system (Italian side). Our optimization model accounts for the interaction between the biological and the economic complex of the fishery at the aggregated level.

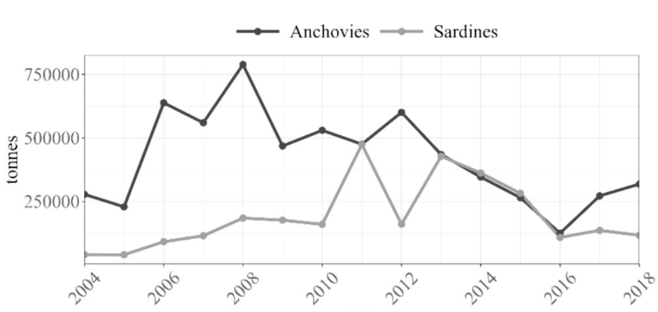

Fig. 2. Anchovies and sardines' biomass. Source: GFCM.

More specifically, our analysis considers two species (sardines and anchovies) which we assume to have no interdependency. Several hypotheses have been proposed to explain the potential interdependence between sardines and anchovies, considering biological and environmental influences (Takasuka et al., 2008; Irigoien and de Roos, 2011). However, landing data from various countries have confirmed that the most supported hypothesis for explaining the observed dependence between these species is associated with environmental factors such as temperature and availability of nutrients. These factors are more likely to influence the prevalence of one species over the other, in contrast to the hypothesized interspecific competition, which has so far received limited support (Hosack et al., 2013). Two different fishing gears (PS and TM) will be included separately in the analysis to account for possible differences in their efficiency. The main objective of this study is to analyze the trend of discounted profits of the Italian small pelagic fishing fleet as the management policies vary. We are particularly interested in comparing the effect of effort limitation policies with quota implementation. A complete description of the selected policies will be provided in the following paragraphs.

We test and compare the logistic and the Ricker (1954) functional form to simulate the discrete population growth for sardines and anchovies. As the Ricker equation better fits the empirical biological data for both species, we use Eq. (1) to describe the species growth over time.

$$B_{i,t+1} = B_{i,t}e^{r_i\left(1-\frac{B_{i,t}}{K_i}\right)} - \sum_{j=1}^{2} h_{i,j,t} \tag{1}$$

where B_{it} stands for the biomass of species $i = 1, 2$ (where 1 indicates anchovies and 2 indicates sardines) at time $t = 1, \ldots, (T-1)$ (where $T = 10$), j stands for the fishing technique (1 indicates purse seine vessels and 2 indicates mid-water pelagic pair trawls), r_i is the species intrinsic growth rate of the stock, and K_i is its carrying capacity, which is the highest possible quantity of fish (by weight) that can live within a specific environment. The term $h_{i,j,t}$ indicates the harvests of species i by gear j at time t. Eq. (1) states that, if the quantity harvested is higher than the natural growth of the stock each year, the stock will decrease in the following year and vice versa. To estimate the parameters from the Ricker functional form, we linearize it and subsequently use ordinary least squares (OLS). A complete recap of the estimated biological parameters is provided in Table 3.

The harvested amount of each species is modeled by using a Cobb–Douglas production function considering biomass B_i and fishing days E_j as inputs, as has often been undertaken in previous studies (e.g., Salenius, 2018):

$$h_{i,j,t} = q_{i,j} B_{i,t}^{a_{i,j}} E_{j,t}^{b_{i,j}} \tag{2}$$

where $q_{i,j}$ is the catchability coefficient and $a_{i,j}$ and $b_{i,j}$ are the catch elasticities with respect to the stock size and the fishing days. The catchability indicates the efficiency of the fleet. The separate calibration of harvest data by species and gears allows for distinct catchability coefficients, thereby accounting for disparities in the efficiency of the fleets. Harvest parameters are calibrated by minimizing the normalized root mean square error (NRMSE) between real (y) and calibrated ($\hat{y}$) data at time $t = 1, \dots, T$. The NRMSE is defined as follows:

$$NRMSE = \frac{RMSE}{y_{max} - y_{min}}, \text{ where } RMSE = \sqrt{\sum_{t=1}^{T} \frac{(\hat{y}_t - y_t)^2}{T}} \tag{3}$$

Elasticity parameters are restricted to values between 0 and 1 to account for the hyperstability of small pelagic stocks and decreasing returns to scale (Cruz-Rivera et al., 2019).

As for the dynamics of the fleet, we assume that the variation of the number of vessels using a specific fishing gear j at time $t = 1, \dots, (T-1)$ is related to their overall profitability at time $t-1$:

$$n_{j,t+1} - n_{j,t} = \varphi_j \frac{\pi_{j,t}}{(1+\delta)^{t-1}} \tag{4}$$

In this case, φ_j is the fleet dynamics parameter for gear j and $\pi_{j,t-1}$ is the overall amount of profits in any previous year. δ represents the discount rate applied to future profits every year. Eq. (4) allows for a change in the number of vessels every year, accounting for new entries (exits) to (from) the fishery when it is more (no longer) profitable. Parameters φ_j are calibrated using NRMSE calibration process on past profits. We have not included any constraint to describe the amount of time and investments needed to increase the fleet size. We therefore assume that an increase in the number of vessels happens at no cost at any time.

The base optimization problem aims to maximize the sum of PS and TM discounted net benefits (profits) $\pi_{j,t}$ over a time horizon $T = 10$ years.

Profits $\pi_{j,t}$ for gear j at time t are defined in Eq. (7) as the difference between revenues $R_{i,j,t}$ and costs $(V_{j,t}, C_{j,t}, F_j)$.

$$\pi_{j,t} = \sum_{i=1}^{2} R_{i,j,t} - V_{j,t} - C_{j,t} - F_j \tag{5}$$

More specifically, revenues are defined as the product between the ex-vessel fish price and the harvested quantities $R_{i,j,t} = p_{i,j}\, h_{i,j,t}$, while $V_{j,t}$, $C_{j,t}$, and F_j represent variable, crew, and fixed costs, respectively. Fishing effort $E_{j,t}$, which intervenes in the revenues and variable costs components as detailed in Eq. (6) and Eq. (7). The number of vessels $n_{j,t}$ intervenes in the fixed cost component as outlined by Eq. (8).

We include prices as exogenous parameters. The unit prices for both species (€/ton) are computed as the mean among price values during the most recent available five-year period, 2014–2018. Computing the mean for the overall period 2004–2018 does not satisfy the need to estimate the effects of selected policies starting from the current fishing conditions. We consider the average ex-vessel prices and not the average final consumption prices. The prices for sardines and anchovies are assessed separately. Moreover, we compute separate prices for the two fishing gears as they may affect the physical selling conditions of landings differently.

The cost parameters are all calibrated through the OLS method. We use the Newey–West estimators (Newey and West, 1987) to correct for heteroskedasticity and autocorrelation. The variable costs V_{jt} are defined as a linear function of fishing days E_{jt} at time t. The unitary variable cost per day (€/day) per gear j is calibrated according to the following relationship:

$$V_{j,t} = v_j E_{j,t} \tag{6}$$

We remove the intercept from the model as zero fishing days also imply zero variable costs. The crew costs C_{jt} are defined as a fraction of the net revenue $R_{ij,t}$ with respect to the variable costs:

$$C_{j,t} = c_j \left(\sum_{i=1}^{2} R_{i,j,t} - V_{j,t} \right) \tag{7}$$

Here c_j defines the share of the net revenues that is allocated to crew members for gear j.

The aggregated fixed costs F_j are computed according to the number of active vessels in a given year as follows:

$$F_{j,t} = f_j n_{j,t} \tag{8}$$

where f_j is the fixed cost per vessel specific to every fishing gear and $n_{j,t}$ is the number of vessels using gear j at time t.

A summary of the estimated economic parameters is provided in Table 2. Additional results regarding parameters' estimation are reported in Appendices A, B, and C.

The maximization problem can be expressed as follows:

$$max \sum_{t=1}^{T} \sum_{j=1}^{2} \frac{\pi_{j,t}}{(1+\delta)^{t-1}} = \sum_{t=1}^{T} \sum_{j=1}^{2} \frac{(1-c_j)\left(\sum_{i=1}^{2} p_{i,j} q_{i,j} B_{i,t}^{a_{ij}} E_{j,t}^{b_{ij}} - v_j E_{j,t}\right) - f_j n_{j,t}}{(1+\delta)^{t-1}} \tag{9}$$

The decision variables are biomass ($B_{i,t}$), effort ($E_{j,t}$) and the number of vessels ($n_{j,t}$). E. (9) is subject to Eq. (1), Eq. (4), and the following constraints:

$$E_{j,t} \le d n_{j,t} \tag{10}$$

$$B_{i,t}, E_{j,t}, n_{j,t} \ge 0 \forall i, j, t \tag{11}$$

Additional policy-specific constraints are defined in paragraph 2.4. Profits $\pi_{j,t}$ are discounted by a fixed rate δ every year. The discount rate defines how much fishermen value future profits versus current profits. The higher the discount rate, the lower the value of future net benefits. We set the discount rate at a 5% fixed rate, similar to the approach used in previous studies (Ekerhovd and Steinshamn, 2016; Salenius, 2018) on fisheries management. We maximize the joint net benefits from both gears instead of the profits for every gear separately as the main goal is to determine the MEY for the Italian small pelagic fleet as a whole entity.

Eq. (10) represents a structural limit for the fishing fleet. It does not allow the yearly fishing days per vessel d to extend beyond 365 (in the no-policy scenario) and 180 (under policy management). Finally, we set non-negativity constraints for the biomasses, fishing days, and number of vessels in Eq. (11).

Along with the optimization results, we provide a graphical comparison with the 'status quo' values calculated as the average of the variables of interest (fishing days, number of vessels, biomass) during the period 2014–2018. Results are also presented in terms of the current revenue/break-even revenue (CR/BER) ratio. The CR/BER is estimated to compare the economic statuses of the two fleets by using a profitability indicator. It is commonly used by policymakers for EU fisheries (Spedicato et al., 2016; SAC, 2018) as it provides a clean way of indicating how close the revenues in a given year t are to the revenues necessary to achieve the break-even point. A CR/BER value >1 indicates good profitability, a ratio less than one indicates unprofitability, and a negative ratio indicates that the revenues are not sufficient to cover the variable costs. The CR/BER is computed as the ratio between revenues in the year t ($R_{j,t}$) and the break-even-revenue ($BER_{j,t}$), defined as follows:

$$BER_{j,t} = \frac{F_{j,t}}{1 - \left[\left(V_{j,t} + C_{j,t} \right) / R_{j,t} \right]} \tag{12}$$

We use a traffic light approach (Spedicato et al., 2016; Maiorano et al., 2019) to report the CR/BER results in Table 6.

2.4. Policy scenarios

EU authorities have provided a framework for member states to define their national management plans for small pelagics and other stocks. Italy and, later, Croatia and Slovenia have therefore individually adapted their legal frameworks to Council Regulation (EC) No. 1967/2006 for sustainable fishery exploitation, which established minimum sizes of both species and fishing gears. An attempt to develop a broader EU management plan for small pelagic species was started in 2017 by the European Commission, but the proposal was dismissed in 2020 due to irreconcilability between the decision makers and the other interested parties, which led the policy debate to a dead end. Meanwhile, the GFCM has managed small pelagic stocks at the international level since 2013 (Carpi et al., 2017). The GFCM has defined a series of recommendations to ensure that the exploitation levels of small pelagic stocks in the Adriatic Sea stay within reasonable limits, but, despite their efforts, these measures have not been completely successful, requiring more substantial policy efforts. Starting in 2022, the GFCM has therefore established TAC limits to manage both species in the Adriatic Sea.

Table 1 recaps the main policy scenarios that will be compared in this study. Every policy scenario is designed to reflect previous or current GFCM policy recommendations.

2.4.1. Dynamic MEY

In the dynamic MEY scenario, we impose no constraints on the number of days and vessels that can operate in the fishery. In other words, the small pelagic fleet could expand its capacity if deemed profitable. Note that this is a purely descriptive scenario as in contrast with the current management policy. However, it provides an intuition of the fishery's performance in the absence of regulation.

2.4.2. Dynamic MEY – Stock conservation

To complement the pure dynamic MEY analysis, we replicate the fishing conditions outlined in section 2.4.1 with the addition of a hypothetical *stock conservation constraint*. This restriction intervenes in every year of the optimization process and sets the minimum net biomass level at least equal to a pre-determined percentage level of its starting point. Under this scenario, we aim to mitigate stock depletions. As both species are currently considered overfished (SAC, 2022), a90% threshold ($\overline{\alpha} = 0.9$) is enforced. The constraint is expressed as it follows for $t = 1, \ldots, 9$:

$$B_{i,t+1} \geq \overline{\alpha} B_{i,1} \tag{13}$$

Table 1
Policy scenarios.

Scenario	Description
Dynamic MEY (MEY)	Fishing can occur for a maximum of 365 days per year per vessel
Dynamic MEY – 'Stock conservation'	Dynamic MEY with a 'stock conservation' constraint
Effort limitation (EL)	Fishing can occur for a maximum of 180 days per year per vessel
Mixed quota (MQ)	Overall quota for small pelagic species (30,672 t)
Separate quotas (SQ)	Separate quotas for anchovies (15,074 t) and sardines (15,598 t)

2.4.3. Effort limitation

The effort limitation scenario is based on the policy recommendations before 2021, which defined a maximum limit of fishing days for small pelagic fishing. The maximum number of days for both fishing gears - the d parameter in Eq. (10) - is set to 180 days per year.

2.4.4. Mixed quota

The mixed-quota scenario is based on the current GFCM recommendation, which defines a total allowable catch limit by country. We only use the Italian quota value as our model only depicts the Italian coastal side of the fishery. The recommendation keeps the previous fishing effort limitations in place, and that will also be reflected in our model. When defining the quota scenario, we include an additional constraint in our specification:

$$\sum_{i=1}^{2} \sum_{j=1}^{2} h_{i,j,t} \leq TAC \tag{14}$$

where i, j, and t are the species, gear, and time subscripts, h represents the quantity harvested, and TAC is the constant established quota limit enforced every year. Note that we only need one constraint to simulate this scenario as the limit is comprehensive for both species. Among the results, we provide the values of the Lagrange multipliers (Nocedal and Wright, 1999; Boyd and Vandenberghe, 2004). The Lagrange multipliers indicate the extent to which a constraint is binding for the problem. In other words, they express the marginal variation of the value of the objective function if the constraint is relaxed by one unit.

2.4.5. Separate quotas

In the case of separate quotas, we define two constraints to account for sardines and anchovies harvest limits. The two constraints are:

$$\sum_{j=1}^{2} h_{i,j,t} \leq TAC_i \tag{15}$$

The mixed-quota value is taken from the existing policy but, as separate quotas have not been implemented yet, we need to assume quota limits by species. We compute the percentage reduction in the overall amount of catches in 2018 due to the new quota limit (27.98%) and apply that same percentage reduction to harvests by species (in 2018) to define the separate TAC values. See Table 1 for detailed TAC limits. Lagrange multipliers' values on both constraints are provided for this scenario.

2.4.6. Additional measures

In addition to the effort limitations and quotas, all the GFCM recommendations mention constraints on fleet capacity increases in terms of the number of vessels, gross tonnage, and power. While gross tonnage and power are not key variables in our analysis, our model directly accounts for the dynamics of the fleet over time, intended as a change in the number of vessels. We cap the maximum vessel value when implementing every policy to make our design consistent with the existing regulatory framework as per eq. (16) and (17). The maximum vessel limit is established by the GFCM (GFCM/44/2021/20) at the 2014 level, with 36 purse seines ($n_{1,t}$) and 130 mid-water pelagic pair trawls ($n_{2,t}$) for a total maximum limit of 166 vessels.

$$n_{1,t} \leq 36 \tag{16}$$

$$n_{2,t} \leq 130 \tag{17}$$

3. Results and discussion

3.1. Calibration results

Table 2 reports the values of all the calibrated economic parameters. The estimated prices per ton provide a clear idea of the profitability of

Table 2
Economic parameters.

Symbol	Definition	PS	TM	Units
$i = 1, 2$	Subscript (species)			–
$j = 1, 2$	Subscript (gear)			–
T	Time horizon	10		years
δ	Discount rate	5%		
$p_{i,j}$	Unitary price of fish			€/ton
	Anchovies	1528	1562	
	Sardines	871	661	
v_j		644	802	€/day
c_j		0.46	0.42	–
f_j	Fixed costs per vessel	87,300	75,374	€/vessel
q_j	Catchability			days^{-1}
	Anchovies	0.05	0.30	
	Sardines	0.19	0.99	
$a_{i,j}$	Biomass elasticity			–
	Anchovies	0.32	0.12	
	Sardines	3.8E-7	0.43	
$b_{i,j}$	Effort elasticity			–
	Anchovies	0.92	0.99	
	Sardines	0.99	0.42	
φ_j	Fleet dynamics	1.0E-7	1.0E-7	€$^{-1}$

the two species. Regardless of the fishing gear, anchovies have a much higher price than sardines as they are considered the most valuable species. We do not see a marked difference in prices for anchovies between the two techniques. However, when considering sardines, we note that PSs account for a higher average ex-vessel price. This is presumably due to PS-harvested specimens being in better physical condition and of a greater size (Mulazzani, 2011). These data suggest that anchovies are more likely to sell on the market irrespective of their physical conditions. Given their lesser value, sardines may experience a more pronounced impact on their final value due to variations in their physical condition and size.

The unitary variable costs per day are in the same order of magnitude but greater for TM vessels. This difference reflects the higher fuel consumption of the trawling fishing techniques, which increases the fuel expenditure of mid-water trawls (Maiorano et al., 2019) and consequently affects their total variable cost amounts.

The shares of net revenues compensating for labor are quite similar for the two gears, with purse seine crew members earning an overall slightly larger share of the net landed value than pelagic trawlers' staff. The fixed costs per vessel are also in the same order of magnitude, with PS fixed costs being higher than TM ones.

The catchability coefficient varies between the two different species and gears. Both TM and PS vessels exhibit a greater catchability for sardines. In the case of PS vessels, the disparity between sardines and anchovies is more pronounced, and could potentially hinder their profitability, being anchovies the most valuable species.

The biomass elasticity coefficients are low (< 1) and sometimes close to 0 for all species and gears, indicating that harvested quantities are less than proportionally affected by biomass levels, consistently with previous insights from other pelagic fisheries (Mulazzani, 2011; Mulazzani et al., 2015; Salenius, 2018). This non-linear relationship between stock size and catches is attributable to the schooling behavior, which results in the harvesting process being almost detached from stock abundance. As a result, shoal proximity may ensure a successful harvest even when biomass levels are low or concerning. This occurrence is usually referred to as hyperstability and has been documented in small pelagic fish stocks (Pope, 2009).

Table 3
Biological parameters.

Symbol	Definition	Anchovies	Sardines	Units
$i = 1, 2$	Subscript (species)			–
r_i	Growth rate	0.50	0.66	–
K_i	Carrying capacity	437,041.3	222,434.8	ton

Table 4
Payoff (net present value) per fishing gear (mln €) in different scenarios.

Scenario	PS	TM	Total
Dynamic MEY	54.1	226.7	280.8
Dynamic MEY – Stock conservation	56.9	173.1	230.0
Effort limitation	23.4	93.3	116.7
Mixed quota	24.4	29.9	54.3
Separate quotas	−6.3	29.1	22.8

The effort elasticity values are close to 1 due to the limitations imposed on the calibration process of the harvest function. Any value greater (smaller) than 1 would indicate that harvests are more (less) than proportionally affected by the increase in fishing days. The sardines' coefficient for the TM gear is notably smaller than one, suggesting that the TM fishing activity is predominantly targeted toward anchovies.

The entry/exit coefficient determines the change in the number of vessels according to the previous year's profits. No particular differences are detected between PS and TM vessels.

More details on the parameter estimation and the significance of the economic coefficients are reported in Appendix B and C.

From Table 3, we note that the sardines' intrinsic growth rate is greater than that of anchovies. However, the carrying capacity of the two species is significantly lower for sardines. This reflects anchovies being present in greater quantities than sardines on the Italian coastal side of the Adriatic during the years 2004–2012.

Additional information on the parameter estimation and the significance of the growth coefficients is available in Appendix A.

3.2. Optimization results

Here we report and comment on the results of the optimization problem by comparing the five different scenarios. Table 4 summarizes the results by showing the net present benefits. The benefits are reported by gear and for the Italian small pelagic fishery as a whole.

By comparing the values in the last column of Table 4, we can see the overall economic effect of different policy management approaches on the fishery. The presented scenarios are quite different in terms of how the aggregated benefits are allocated between the two fishing gears. The pursuit of the dynamic MEY leads to the highest aggregated net present benefits over time. This is not surprising, as no policy are implemented in this scenario. Imposing a stock conservation constraint to preserve biomass levels within the dynamic MEY optimization process reduces the amount of net present benefits over time with a greater emphasis on TM vessels, which appeared to benefit the most from a no-policy approach. This disparity between the two fishing gears is preserved in most of the policy scenarios, with PS vessels always ending up earning the lowest amount of net present benefits. Such differences are mainly due to the diverse size of the two sub-fleets as most Italian vessels targeting small pelagics in the Adriatic area are TMs. For this reason, more detailed economic results, such as the trend of the net present value of profits over time, will be provided at the individual vessel level. Table 4 also shows how, at the aggregate level, there is only a small difference between the effort limitation approach (up to 180 fishing days) and the current mixed quota approach for PS vessels. Similarly, there would be almost no difference between the current mixed quotas and the separated ones for TM vessels. These two results seem to highlight how in multi-specific and multi-gear fisheries, specific policy arrangements aimed at limiting either fishing inputs or outputs may have a different impact on distinct gears, sometimes defeating the purpose of reducing their fishing pressure.

Table 5
Biomass levels in different scenarios (by species).

	Anchovies			Sardines		
	(a)	(b)	(c)	(d)	(e)	(f)
	Biomass (thousand tonnes)	Final biomass as % change of the starting level	Final biomass as % change of carrying capacity	Biomass (thousand tonnes)	Final biomass as % change of the starting level	Final biomass as % change of carrying capacity
All scenarios (starting point)	318	–	–	117	–	–
Carrying capacity	437	–	–	222	–	–
Dynamic MEY (final point)	219	−31.0	−49.7	191	+63.1	−14.0
Stock conservation (final point)	286	−10.0	−34.4	195	+66.9	−12.0
Effort limitation (final point)	356	+11.9	−18.4	201	+71.7	−9.5
Mixed quota (final point)	391	+22.8	−10.5	206	+76.3	−7.0
Separate quotas (final point)	404	+27.0	−7.4	207	+77.0	−6.7

Table 5 reports the stock levels of anchovies and sardines at their starting point and in the final year of every scenario. The starting point is always set using the 2018 data.[4] Neither the anchovy nor the sardine stock achieves the carrying capacity level, as suggested by columns (c) and (f). However, the policy management scenarios are more supportive of the stocks growth over time than the dynamic MEY conditions, particularly for anchovies, which biomass would decrease with respect to the 2018 level in both the dynamic MEY and the stock conservation constraint scenarios. Both species would benefit from some kind of policy implementation, even if the environmental benefits of such policy interventions are particularly evident in the case of the sardine stock, which reports lower biomass levels at the optimization starting point. The separate-quotas scenario could be considered the most conservative one in terms of the biological welfare of the stocks as it leads to the highest stock abundance. On the contrary, the effort limitation scenario is the most prone to higher levels of exploitation among all the presented policies.

These results are reiterated by Fig. 3 which offers a graphical representation of the biomass levels throughout the whole optimization period. The separate quotas are indeed the option that allows for better conservation over time of the biomass of both species, reaching the highest values among all the selected scenarios in the shortest amount of time. This beneficial effect is clearly visible for anchovies, as they tend to be the most targeted species when the enforced policies are less restrictive in terms of species and harvested quantities, given their greater ex-vessel price. As a result, anchovies are benefitting the most by any of the policy constraint considered in this analysis. Fig. 3 also shows that policy management is effective from a biological perspective as, in the dynamic MEY scenario, both stocks achieve lower or even decreasing (in the case of anchovies) biomass levels. On the contrary, under any policy scenario, both stocks steadily increase until the end of the optimization period.

The yearly discounted profits per vessel are reported in Fig. 4, while the yearly fishing days per vessel are represented in Fig. 5. Under the no-policy (dynamic MEY) scenario, there is not much difference between the profits individually achieved by PS and TM vessels. This confirms that the disparity in aggregate profits is indeed due to the difference in the total number of vessels per gear type. When the stock conservation constraint is imposed, TM vessels are the ones subjected to a greater decrease in individual profits (fishing days) over time. This reduction may be explained by considering the TM harvest parameters, as they are allowing for a greater degree of efficiency of this specific gear. Consequently, when the stock conservation constraint is enforced, TMs are forced to reduce their fishing days (and consequently their profits) to secure the selected minimum biomass levels. A similar issue rises under the policy scenarios. As each scenario corresponds to a progressively more restrictive policy, TMs discounted net profits[5] will decrease by a greater extent each time a new policy is implemented. The change from input to output limitation measures (from effort limitation to mixed quotas) marks the highest profit decrease for TM vessels below the Status Quo level, while the further implementation of separated quotas does not have the same impact (TMs profits achieved under separated quotas almost completely overlap the ones achieved under the mixed quota). On the other hand, PSs vessels see no fishing day (and discounted profits) reduction when moving from an effort limitation management framework to the mixed quota. However, the economic benefits between TMs and PSs are unevenly distributed under the separated quotas policy implementation, with PSs vessels experiencing an average loss throughout the whole optimization period. PS vessels deal with higher costs and a lower catchability in harvesting the most profitable species (anchovies), which becomes a disadvantage when TACs are lower. Within a time span of 10 years, such vessels will either be inactive or harvesting a greater amount of non-small pelagic species. Some of the PS vessels are involved in much more valuable harvesting processes that are not included in this study (such as tuna fishing), which could enable them to remain active, but the historically decreasing number of active PS vessels over the last 15 years suggests more articulated reasons behind the shrinking size of this sub-fleet. On the contrary, TM vessels would continue to operate under every policy scenario with different economic performances.

The number of vessels (Fig. 6) is also affected by the selected policies. The PS sub-fleet's starting condition is already below the status quo level due to the reductions in active vessels experienced in preceding years. It struggles to expand from that point throughout the entire optimization period. Conversely, the number of active TM vessels constantly expands during the optimization time frame. In the dynamic MEY scenarios (with and without the stock conservation constraint), this expansion goes beyond the status quo value suggests that the size of the fleet is a crucial factor in the management process and that the existing constraints on fleet capacity are crucial to ensure the sustainability of the fishery.

[4] Our optimal search is not global, which means that we could end up in a local optimum. However, the starting guess point of every optimization scenario is set using the 2018 data point; hence, our results may show the second-best optimal value given the initial state of our model.

[5] Here we specifically refer to the individual vessel-level profits. Refer to Table 4 for the aggregated overall net present value of benefits.

Table 6
CR/BER performance in different scenarios.

	Dynamic MEY		Stock conservation		Effort limitation		Mixed quotas		Separate quotas	
Year	PS	TM	PS	TM	PS	TM	PS	TM	PS	TM
1	>1	>1	>1	>1	>1	>1	>1	>1	>1	>1
2	>1	>1	>1	>1	>1	>1	>1	>1	<1	>1
3	>1	>1	>1	>1	>1	>1	>1	>1	<1	>1
4	>1	>1	>1	>1	>1	>1	>1	>1	<1	>1
5	>1	>1	>1	>1	>1	>1	>1	>1	<1	>1
6	>1	>1	>1	>1	>1	>1	>1	>1	<1	>1
7	>1	>1	>1	>1	>1	>1	>1	>1	<1	>1
8	>1	>1	>1	>1	>1	>1	>1	>1	<1	>1
9	>1	>1	>1	>1	>1	>1	>1	>1	<1	>1
10	>1	>1	>1	>1	>1	>1	>1	>1	<1	>1

Table 7
Lagrange multipliers in selected scenarios.

	Mixed quota	Separate quotas	
Year		Anchovies	Sardines
1	504.46	621.62	4.79E−11
2	483.02	606.64	5.39E-11
3	462.50	588.28	5.89E-11
4	443.12	567.56	6.18E-11
5	424.71	545.79	6.32E-11
6	407.09	523.91	6.37E-11
7	390.20	502.46	6.38E-11
8	374.09	481.78	6.39E-11
9	358.85	462.14	6.39E-11
10	344.60	444.07	6.40E-11

The CR/BER results summarize our previously stated findings. TM vessels would remain profitable across all periods and in every possible scenario, while PS vessels would suffer the economic consequences of the more restrictive policies and would struggle to remain profitable under the separated quotas.

Finally, we check the Lagrange multipliers of our solutions. We report the results for the two quota scenarios in Table 7.

The Lagrange multipliers for the quota constraints express how much the net present value of the overall benefits increases as the TACs increase by one tonne. It is interesting to observe the difference in magnitude between the Lagrange multipliers for sardines and those for anchovies in the case of separate TACs. Anchovies show a very high multiplier when compared with sardines. The quota constraint for anchovies therefore exerts a greater impact on the Italian fishing system. Consequently, limiting anchovy fishing through separate quotas can affect the overall profits far more than any limitation imposed on sardines. On the contrary, the mixed quota's multipliers are smaller implying that fishers would be granted a slightly higher degree of flexibility in managing the catch composition of the harvested species.

4. Summary and conclusions

Our study investigates how the profitability and sustainability of the Italian small pelagic fishery in the Adriatic Sea are affected by a different mix of policy comparisons. We build an optimization model to provide an estimate of the dynamic MEY over a 10-year time span. By assessing the policy scenarios using a dynamic MEY approach, we also offer a new management perspective as the main target reference points chosen by the CFP and the GFCM for small pelagic fisheries management in the Adriatic Sea have always been biological targets, such as the maximum sustainable yield (MSY) (Schaefer, 1954) and/or Patterson's exploitation rate.[6] We highlight the difference between effort limitation policies and total allowable catch limits for the fishery, accounting for two distinct fishing techniques. When considering the policy scenarios, we show that the overall profitability is enhanced by the effort limitation policy and majorly hindered by the separate-quotas scenario. Intuitively, the two mentioned policy options also lead to different percentage biomass increases, indicating that separate quotas would be more effective in preserving the fish stocks over time. This result highlights the contrast between conflicting biological and economic policy targets and reinforces Hilborn (2007) concept of how the failure of one policy objective can be the success of another. Following our results, we acknowledge the presence of a trade-off between the biological and the economic policy objectives in the small pelagic Adriatic fishery: among the selected policy scenarios, the effort limitation is the one leading to greater profitability, while the separate quota scenario grants higher biomass levels. In terms of exploited species, anchovies remain the most targeted as they have a higher ex-vessel price and are therefore more profitable. The impact of every policy is much more evident for anchovies than for sardines, which would be overall less affected. In assessing the effectiveness of different types of policy management measures for the selected fishery, we pay careful attention to the distribution of the economic benefits among the small pelagic fishery. Our modeling framework allows us to decompose the economic effects of the policies between two fishing gears. Indeed, we highlight how maximizing the overall profits of the fishery differently affects PSs and TMs vessels in each policy scenario. For PS vessels, more restrictive policies (separated quotas) are associated with concerning levels of long-run profitability. Our results are broadly in line with the historically decreasing number of active Italian PS vessels in the past years. We note that the efficiency gap between the two fishing techniques may therefore lead to an unequitable distribution of the economic benefits within the fishery.

The main limitation of our study is data driven. The data for the Italian fleet refer to the period 2004–2018. Unfortunately, Croatian data are not available within the same period as Croatia joined the EU later, in 2013. For this reason, our work focuses exclusively on the Italian coastal side of the fishery. We acknowledge that an additional effort to include Croatia in our model is still needed and encourage further steps and research in that direction. Moreover, data at the individual vessel

[6] The exploitation rate E is defined as the ratio between the number of individuals caught and the total number of individuals dead. At $E = 0.4$, there is a 50% probability of a stock decline/increase. $E = 0.4$ can be considered as a sort of equilibrium point for pelagic stocks (Patterson, 1992).

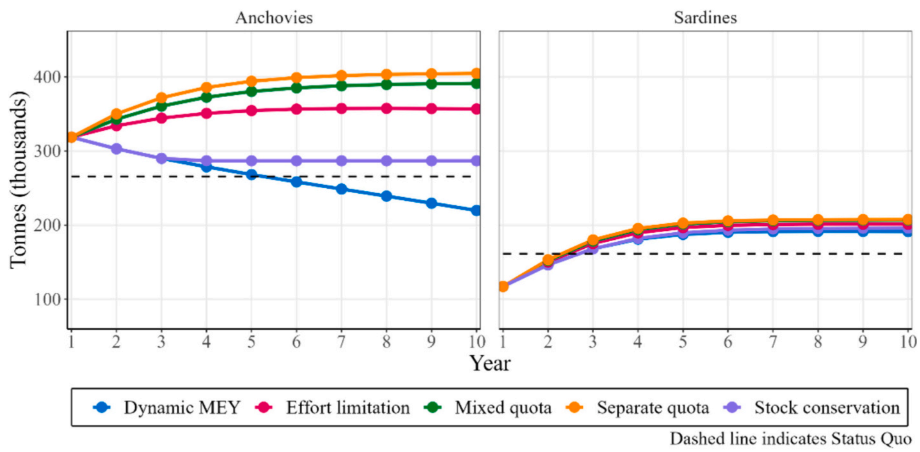

Fig. 3. Biomass levels (thousand tonnes).

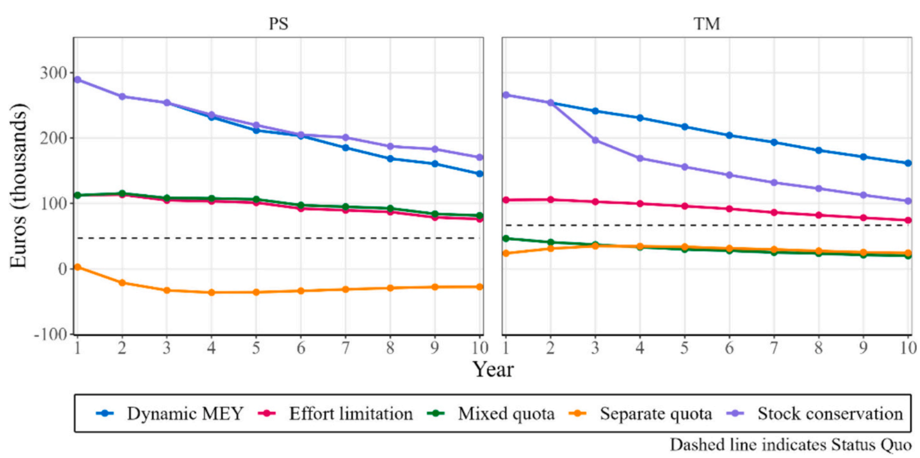

Fig. 4. Profit levels (thousand euros per vessel).

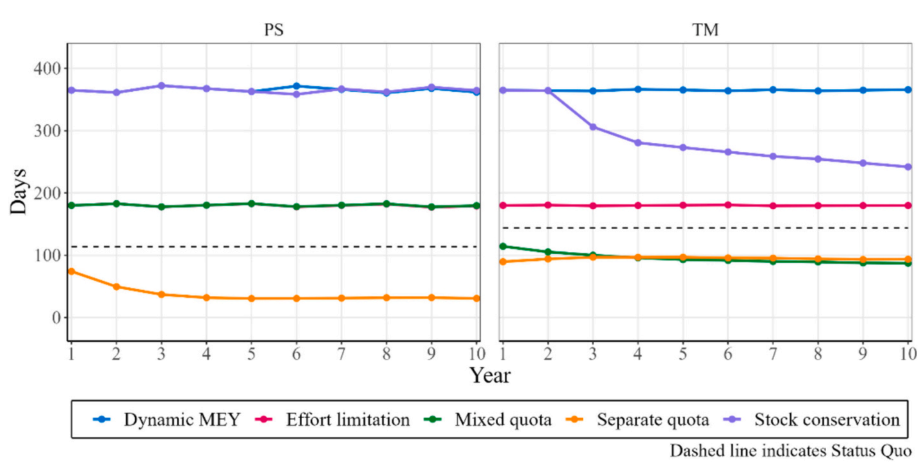

Fig. 5. Effort levels (fishing days per vessel).

level are not provided by our main sources. Therefore, our analysis is performed at the aggregated level – i.e., from the sole owner perspective.

Further research on this topic should be aimed at addressing the main limitations that we encountered. Expanding the range of this study toward the Balkan area, including the Croatian small pelagic fishery, is essential to provide a comprehensive analysis of the impact of quota management and to improve our knowledge of the implementation difficulties of stock conservation policies involving different countries. In light of the considerations and requirements posed by the EBFM approach, our perspective on net economic benefits needs to be complemented with further research emphasizing the biology of the small pelagic fishery with greater detail. The biological framework could be expanded to improve the fitting of the growth function, and possibly to account for the marine environmental conditions, which could enhance

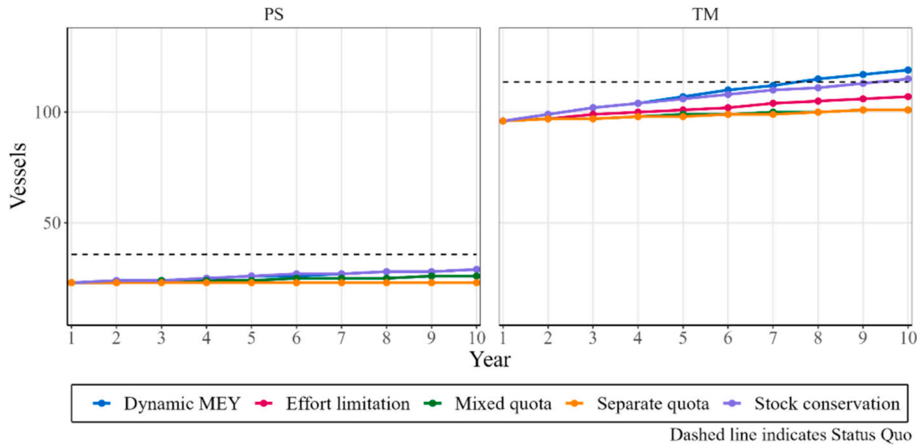

Fig. 6. Yearly number of vessels.

or hinder the stock growth over time (Checkley et al., 2017). Our results suggest that specific policy measures to increase the efficiency of the fishing fleet should be further discussed. If TACs remain the preferred management option, implementing an ad hoc set of transferable quotas could potentially reward the efficiency of the fishing fleet and lead to its profitability. Additional investigations into the impact of such quotas should therefore be properly addressed in future studies.

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CRediT authorship contribution statement

F. Natali: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **G. Toraldo:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis. **F. Giannino:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis. **G. Cicia:** Writing – review & editing, Validation, Supervision, Methodology. **G. Branca:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Estimation of growth parameters

Table A.1
Newey–West estimation results Ricker (biological parameters).

Parameters	Anchovies	Sardines
a	0.50*	0.66***
	(0.26)	(0.20)
b	-1.2E-6***	−3.0E-6***
	(3.6E-7)	(5.7E-7)

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table A.2
Newey–West estimation results logistic (biological parameters).

Parameters	Anchovies	Sardines
a	0.60	0.92*
	(0.37)	(0.51)
b	−1.2E-6**	−3.1E-6**
	(5.3E-7)	(1.2E-6)

Standard errors in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.1
Note: The growth rate is $r = a$, and the carrying capacity is $K = -a/b$.

Appendix B. Estimation of economic parameters

Table B.1
Newey–West estimation results (economic parameters).

	Variable costs		Crew costs		Fixed costs	
Param.	PS	TM	PS	TM	PS	TM
Cons			−2.4E5 (2.1E5)	7.9E5 (9.7E5)		
v_j	644*** (86)	802*** (33)				
c_j			0.46*** (0.01)	0.42*** (0.04)		
f_j					8.7E4*** (6.9E3)	7.5E4*** (2.6E3)

Appendix C. Estimation of harvest and fleet dynamics parameters

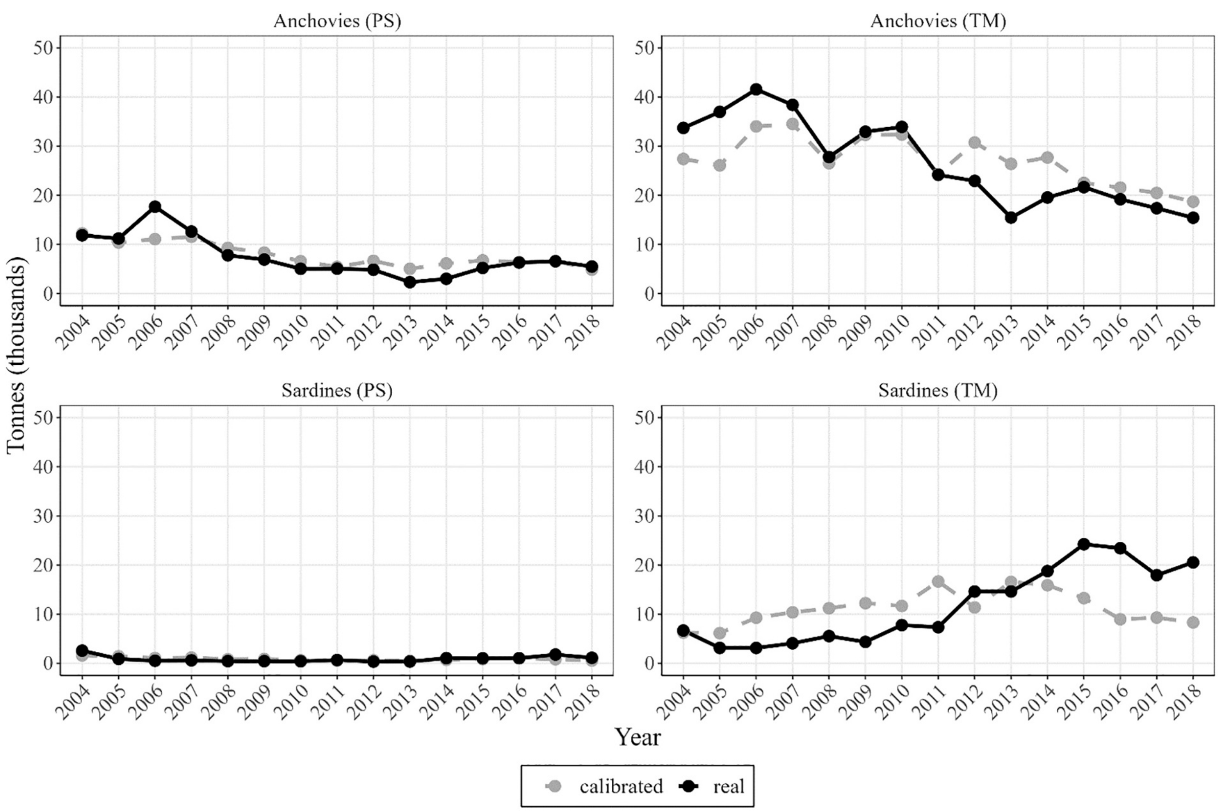

Fig. C.1. Harvest calibration vs real data by species and gear.
Estimation method: minimized NRMSE.

Table C.1
Minimized NRMSE - harvests.

NRMSE	PS	TM
ANE	0.15	0.22
PIL	0.23	0.36

Table C.2
Minimized NRMSE - dynamics.

NRMSE	PS	TM
	0.37	0.36

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