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The economic policy of sustainable production and consumption: case studies on fishery resources from the Mediterranean Sea

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Contents

Abstract (English version)

Fish stocks' overexploitation raises concerns regarding their long-term availability. The well-being of most Mediterranean fisheries is heavily compromised, indicating the need for an effective policy response to preserve fish stocks in the long run. The aim of this thesis is to assess the effectiveness of current fishing management policies in the Mediterranean area and compare them with alternative strategies to promote sustainability. The research encompasses three different case studies at the national or regional level, covering a wide range of topics. These include sustainable fresh fish consumption, the economic implications of alternative fisheries management measures, and policy scenarios for managing transboundary resources. The selected topics are:

(i) consumer preferences for discarded species, by mean of a discrete choice experiment aimed at estimating the willingness to pay for discarded species at the national level;

(ii) the economic implications of alternative policy measures in the Adriatic Sea by mean of a dynamic optimization model to assess the maximum economic yield of the Italian small pelagic fishery, and

(iii) policy scenarios for managing transboundary resources between Italy and Croatia, using static optimization methodologies within a game theory framework.

The Mediterranean basin is a suitable location for this research, given its history of overexploitation, the shared use of marine resources by multiple countries, and the high incidence of fish consumption in the diets of most Mediterranean countries. The results of this work provide valuable insights into the complex issue of balancing economic benefits and environmental sustainability in the context of Mediterranean fisheries management.

Abstract (Italian version)

Lo sfruttamento delle risorse ittiche è un fenomeno di vasta portata che solleva preoccupazioni in merito alla loro sostenibilità nel lungo termine. Il benessere della maggior parte delle risorse ittiche nel Mediterraneo è fortemente compromesso e indica la necessità di politiche volte a preservare gli stock nel tempo. L'obiettivo di questa tesi è analizzare le politiche di gestione già in vigore o di prossima implementazione comparandole quando possibile con strategie alternative volte a promuovere la sostenibilità dell'attività di pesca. La ricerca si occupa dell'analisi di tre casi studio e affronta una serie di tematiche quali il consumo sostenibile di prodotti ittici, le implicazioni economiche derivanti dalle politiche di gestione, e la gestione di stock transfrontalieri sfruttati da diversi paesi. Più precisamente, gli argomenti trattati sono:

(i) le preferenze dei consumatori per le specie di scarto, attraverso un esperimento di scelta volto alla stima della disponibilità a pagare per tali specie a livello nazionale;

(ii) le implicazioni economiche di politiche di gestione alternative in mare Adriatico mediante la definizione di un modello di ottimizzazione per stimare il massimo rendimento economico della flotta italiana coinvolta nella pesca di piccoli pelagici, e

(iii) lo studio di scenari volti ad analizzare l'efficacia delle politiche implementate per gestire gli stock transfrontalieri tra l'Italia e la Croazia utilizzando un modello di ottimizzazione statico inserito in un contesto di teoria dei giochi.

Il mar Mediterraneo è una zona di pesca adatta ad affrontare certe tematiche vista la sua lunga storia di sfruttamento, la vasta presenza di stock transfrontalieri e l'alta incidenza del consumo di prodotti ittici nella dieta della maggior parte dei paesi afferenti. I risultati di questa tesi forniscono una conoscenza approfondita sulla complessa questione del bilanciamento tra benefici economici e sostenibilità ambientale nel contesto della gestione delle risorse ittiche nel Mediterraneo.

Introduction

In economic theory, fish and other natural resources are classified as common pool resources or common goods. These goods are generally considered to be non-excludable, meaning that nobody can be prevented from using them unless specific management measures are in place, and they are also rivalrous in consumption, meaning that once the resource has been used or consumed, it is not available for other users to do the same (Ostrom et al., 1994). The debate surrounding the management of common pool resources has been ongoing for decades. Hardin (1968) identified the lack of well-defined property rights as a critical issue that inevitably leads to overexploitation, also known as the "tragedy of the commons." In his view, either governmental coercion (referred to as "the Leviathan") or the assignment of individual property rights could have prevented the depletion of resources. Another perspective was offered by Ostrom (1994), who argued that people may often organize themselves to protect and effectively manage natural resources.

Nowadays, fish stocks' overexploitation is widespread and raises concerns regarding their availability in the long run (Ostrom, 2008). To prevent the extinction of marine species in an open-access condition and to ensure sustainable fishing over time, some management policies can be enforced (Hilborn et al., 2003) including input, output, or technical regulations (e.g., effort limitation measures, total allowable catch limits or mesh/nets/specimen size). The idea behind the output control measures is that, once the output limit has been reached, fishing activities must cease for the rest of the season. Input control measures are usually aimed at reducing the fishing effort, that is the level and amount of factors of production. Finally, technical measures define specific criteria of regulation such as age and length of targeted specimen or size and dimension of fishing gears (Spagnolo, 2006). Output regulations such as Total Allowable Catches (TAC) are more widespread in the Northern European Seas and they are not widely applied in the Mediterranean area (Carpi et al., 2017) except for the Mediterranean bluefin tuna (Mulazzani, 2011; Lucchetti et al., 2014), while input regulations and technical measures are commonly used in the rest of the Mediterranean fisheries (Mulazzani, 2011; Carpi et al., 2017). This is mainly due to the high multi-specificity of Mediterranean fisheries, which has often required an input limitation approach along with technical measures (Lucchetti et al., 2014).

This study examines the sustainable consumption and management of fish resources in the Mediterranean region. It explores the relationship between management options and sustainability in the Mediterranean Sea from various perspectives, including the economic impacts of different policy options and the role of sustainable fish consumption in promoting the sustainability of the fish value chain when or where traditional management approaches are insufficient.

Fishing in the Mediterranean Seas has historically played a crucial role in the cultural, social, and economic development of coastal areas since prehistoric times (Cortés-Sánchez et al., 2011), and has represented a source of food, income, and economic development over the past decades (FAO, 2022). However, although many scientific experts have been highlighting the serious state of overexploitation of Mediterranean stocks, the management policies implemented so far have failed to unequivocally address this condition (Colloca et al., 2011). In the Mediterranean area, most fish stocks are exploited beyond their safe biological limits (Froese et al., 2018). Therefore, the careful management of access to and exploitation of the Mediterranean resources is the key to ensuring the protection of the marine environment over time and immediate actions must be pursued to avoid the depletion of Mediterranean stocks. Moreover, many countries bordering the Mediterranean Sea are fervent consumers of fish products (EUMOFA, 2022) and have incorporated them into their traditional diet increasing the chance to reap their long-term health benefits (Chen et al., 2022).

This thesis is divided into three sections specifically focusing on the Mediterranean area to explore different policy solutions and ensure the sustainable growth of fish stocks over time. It encompasses topics such as sustainable fresh fish consumption, the economic implications of alternative fisheries management measures, and policy scenarios to deal with the management of transboundary resources. In doing so, it identifies and analyzes multiple case studies at the national or regional level, all of them located in the Mediterranean Sea.

The focal point of all chapters is to provide an in-depth study of issues related to fisheries management. The Mediterranean basin is an ideal area to work on these topics given its past and current levels of overexploitation, the extended and simultaneous exploitation of shared marine resources exerted by multiple countries, and the high incidence of fish consumption in most Mediterranean countries' diets. Additionally, the Mediterranean area has been at the center of several policy debates: the European Common Fishery Policy (CFP) and its following revisions have been the main regulatory framework for most of the European fisheries. However, the CFP has faced multiple criticism in the past decade as it was deemed to be more suited to manage the

North Sea stocks and was not implementing appropriate measures to deal with Mediterranean fisheries and their characteristics (Drouineau et al., 2023; Carpi et al., 2017).

The overall scope of this thesis is to understand the effectiveness of the current management policies in the Mediterranean area and to compare them with alternatives aimed at maximizing economic profit and minimizing the environmental impacts of the fishing activity. In doing so, the shortcomings of the ongoing management measures are analyzed, and other potential policy solutions are explored. Case-studies are identified to fill specific gaps in the scientific literature. The first chapter explores a rarely explored topic on consumer preferences for discarded species at the national level (Italy). The second chapter focuses on small pelagic stocks in the Adriatic Sea, particularly on the Italian fleet. Management policies are assessed using a dynamic optimization model to provide the first estimate of the dynamic maximum economic yield of the Italian small pelagic fishery. The third chapter also focuses on the Adriatic small pelagic stocks but examines the management issue from a multi-player perspective assessing the optimal management option in the case of transboundary resources between Italy and Croatia. The last two sections specifically aim to provide updated economic estimates and assessments on the current and potential management policies in the Adriatic Sea, while the first section delves into innovative management practices or alternatives to make Mediterranean fisheries more sustainable. A thorough description of the content of each chapter is provided in the following paragraphs.

The selected case studies and topics are analyzed using a variety of mathematical and econometric models as considered more appropriate. Choice experiment design and subsequent mixed and latent class logit models are used to estimate Italian consumers' willingness to pay for discarded species. Dynamic constrained optimization is the preferred method to estimate the maximum economic yield of the Italian small pelagic fishery over ten years. Static constrained and unconstrained optimization models is used to assess the optimal effort levels at the Nash equilibrium between Italy and Croatia. Econometric models such as Ordinarily Least Squares are used to estimate the exogenous parameters when necessary.

The first chapter focuses on sustainable seafood consumption as a potential opportunity to deal with discards in the fish value chain. Discarding is defined as the accidental catch of non-targeted species which are thrown back into the sea, and it is known for having negative consequences on the marine environment (Bellido et al., 2011) but also from an economic perspective, as it generates an unnecessary waste of products that could be sold onto the market. The European Union has defined regulations and guidelines to manage the discarding process without being completely effective, as it may be due to a demand-driven issue (van Putten et al., 2019). The empirical approach used in this work is therefore aimed at estimating the willingness to pay for discarded seafood for Italian consumers, filling the gap in the research literature on the demand for such products. Respondents were also analyzed to identify groups of consumers with homogeneous preferences toward the discarded species using appropriate latent class models.

The second chapter determines the economic impact of multiple policy measures on sardines (*Sardina pilchardus*) and anchovies' (*Engraulis encrasicolus*) fishing in the Adriatic Sea on the Italian fleet. Sardines and anchovies combined almost account for 60% of the total catches in the Adriatic area and are therefore the most relevant fishery by live weight (FAO, 2018). The management of the above-mentioned stocks is highly debated and has recently shifted from a complete input-control approach to an output-based one, establishing total allowable catch limits. Only a few studies have estimated the economic impact of such policies and none of the existing assessments has evaluated them from a dynamic perspective. This section is therefore devoted to the specification and empirical application of an optimization model to quantify the dynamic maximum economic yield of the Italian small pelagic fleet accounting for the different efficiency levels of the fishing gears involved in the harvesting practices. Because of initial data limitations and computational needs, the economic impact of such policies on the Croatian fleet is not estimated in this section.

The third and last chapter adds further investigations on the Adriatic small pelagic fishery including the Croatian perspective along with the Italian one. This allows for a greater understanding of the management of transboundary stocks that are exploited by fleets of different countries (Bailey et al., 2010). The main objective of this section is to use a game theory framework to define the fishing activity of a country as a strategic response to the fishing activity of its direct competitor and estimate the maximum economic yield with and without the imposition of a total allowable catch limit constraint. This approach allows for a direct comparison of the current and optimal effort levels of both countries. In addition, it provides an evaluation of the current policy targets from an economic efficiency perspective, distinguishing between the optimal effort level that should be targeted by both countries.

Chapters 2 and 3 provide complementary perspectives on the Adriatic case study. While chapter 3 offers a static and long-term understanding of the Maximum Economic Yield (MEY), chapter 2 explores the dynamic response of the Italian fleet under different policy scenarios across a time span of 10 years. Both chapters are crucial for deepening our understanding of the economic impact of fishing policies in the area.

The conclusive section of the thesis summarizes and connects the results obtained in each chapter, the policy implications derived from the main results, and discusses the empirical limitations as well as future challenges and opportunities for further research.

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1. There are plenty more (sustainable) fish in the sea: A discrete choice experiment on discarded species in Italy

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Abstract

Overfishing is a widespread environmental issue that needs to be resolved to secure sustainable fishing practices over time. An additional and much less-discussed threat to sustainable fishing is represented by discards, that is, the accidentally caught species that are thrown back into the sea given their low market relevance. Fishermen often decide to discard some species mainly depending on their low market value. Therefore, supply-side regulations can only be partially effective in taking care of discarding practices given that they are mainly due to demand-side issues. One possible solution could involve the purchase of discarded species, provided that consumers are willing to change their habitual consumption patterns. In this paper, a discrete choice experiment is conducted to investigate whether consumers would be willing to pay for discarded species. The data are analyzed using a mixed logit model and a latent-class logit model. The results indicate that consumers tend to prefer the most commercialized species, although their interest in discarded species increases when they receive specific information on ecolabels and discarding. Our outcomes also underline that consumers could be divided into specific groups according to their preferences, which could be useful for enhancing discarded species' consumption effectively.

1. Introduction

The overexploitation of fish stocks beyond their safe biological limit is well-documented (FAO, 2018), and particularly widespread in the Mediterranean area (Froese et al., 2018). One of the main threats to sustainable fishing is also represented by discards, that is, the accidental catches of species that are not relevant to market consumption and that are often thrown back into the sea in huge quantities. Discarding represents a waste of fish resources and has negative impacts from an ecological perspective (Davies et al., 2009; Bellido et al., 2011). Previous insights on the economics and management of discards have focused on the incentives of discarding practices, which are related to the short-term profits benefits mainly due to the price difference between different species or the cost of replacing the discards with other additional harvests[1] (Anderson, 1994; Arnason, 1994).

To avoid an excessive amount of discards, especially those of species subject to catch limits or of specimens below the minimum conservation reference size, the European Union has gradually introduced the so-called landing obligation (see EU Regulation 1380/2013), which limits the discarding of accidental catches to enhance the use of more selective fishing gears[2]. However, supply-side regulations have only been partially effective in taking care of discarding practices, given that demand-side issues have never been addressed by policymakers (van Putten et al., 2019). In this regard, different approaches could be developed to reduce fish waste by increasing the demand: less-common species could be marketed for direct food consumption or could be used as raw materials in the food, the cosmetic or the pharmaceutical industry (Zilia et al., 2021). These practices are aimed at pursuing a “zero waste” strategy (Caruso et al., 2020), adding value to waste products as implied by the circular economy (Korhonen et al., 2018).

Italy has a high demand for fish as it is the seventh-largest world importer of fish products (FAO, 2018). The average Italian per capita fish consumption was 30.9 kg per capita in 2018, while the EU average was 24.3 kg per capita (EUMOFA, 2019). In terms of household spending on fish products, Italy ranks first in the EU for aggregate spending and fourth for per capita spending and is always above the European average (EUMOFA, 2019). Fish is a key product in a healthy and balanced diet due to its low-fat content and high protein, vitamin, mineral and omega-3 fatty acid concentration (Thilsted et al., 2016). The consumption of fish and seafood has proven to be beneficial for human health in many ways, such as having an inverse association with all-cause mortality (Zhao et al., 2015), which is why many developed countries are recommending a minimum fish intake in their national dietary guidelines (Thilsted et al., 2016). Given the high

[1] See Anderson (1994) and Arnason (1994) for theoretical models on the economics and management of discarding and Poos et al. (2010) for empirical work on this issue.
[2] See Spedicato et al. (2018) for an overview of the landing obligation for Italian fisheries.

demand for fish and fish products[3], it is crucial to ensure that marine resource exploitation can be sustainable over time.

Besides the management policies with the direct intention of avoiding unsustainable fishing, good sustainable consumption practices could be promoted so that consumers can select the products that have been fished without damaging the marine environment. The consumption of underutilized species can be enhanced through the dissemination of media messages and campaigns aimed at spreading knowledge about the existence of undervalued fish species and raising public awareness of sustainability (Farmery et al., 2020). For this reason, sustainability certification (ecolabels) could be added to fish products to identify fish that come from sustainable exploitation practices (Washington and Ababouch, 2011; Bonanomi et al., 2017; Giacomarra et al., 2021; Asche et al., 2021). Ecolabels could be an effective tool to promote sustainable fish consumption, as well as other types of food products (Sogari et al., 2015). Moreover, new initiatives might arise to enhance and promote the consumption of discarded species. Discards are harvested while targeting other species and can be considered as a wasted opportunity because they could replace or complement the consumption of well-known species. Shifting fish consumption from highly targeted stocks toward underutilized or discarded species could indeed reduce the pressure on overfished stocks (Zhou et al., 2014), especially when discarded species can substitute the most common ones and information on discards is adequately conveyed (Farmery et al., 2020). In this scenario, consumers' preferences would play a fundamental role as they would have to make consumption choices based on alternative and often less-known species.

The number of studies focusing on consumers' perceptions of and attitudes toward fish products is growing. The perceived health benefits are indeed one main driver of fish and seafood consumption (Carlucci et al., 2015). Wild fish is always preferred to farmed fish in developed countries (Verbeke et al., 2007; Davidson et al., 2012; Cardoso et al., 2013; Jaffry et al., 2016; Bronnmann and Asche, 2017; Menozzi et al., 2020; Yang et al., 2020), but there is no significant difference in the willingness to pay a higher price for wild fish in developing ones (Alam and Alfnes, 2020). The preference for wild fish appears to be determined mainly by stereotypes and cultural beliefs as average consumers are not able to distinguish farmed and wild fish based on their sensory characteristics (Kole et al., 2009; Claret et al., 2016). Consumers are also willing to pay a premium

[3] Italy is indeed the seventh-largest world importer of fish products (FAO, 2018).

price for the country of origin, with domestic seafood being the preferred alternative (Claret et al., 2012; Fernández-Polanco et al., 2013; McClenachan et al., 2016; Hinkes and Schulze-Ehlers, 2018; Risius et al., 2019; Alam and Alfnes, 2020).

According to Mauracher et al. (2013), the country of origin can have multiple effects on fish and seafood preferences. Indeed, the country of origin can be perceived as a food quality indicator since local products need to undergo fewer conservation treatments. Local product purchases could also be a way of supporting the local or national economy. Additional evidence (Carlucci et al., 2015) shows that consumers tend to be less confident regarding food products from other countries as they may not have been subjected to the same treatments and regulations as in the country to which they are exported, but this often depends on the country from which fish originates as consumers are more willing to pay for products from developed countries than for products from developing countries (Claret et al., 2012). Consumption preferences toward fish products can be affected by sustainability certification, also known as ecolabels, and/or sustainability claims. Willingness to pay and preferences for sustainable fish and seafood products have been widely explored and confirmed by many studies during the last decade (Brécard et al., 2009; Risius et al., 2019; van Osch et al., 2019; Yang et al., 2020). Bronnmann and Asche (2017) and Bronnmann and Hoffmann (2018) provided evidence that consumers' willingness to pay for ecolabels increases when they are well informed about the environmental consequences of the fishing activity. However, the information effects on fish preferences are still heterogeneous. Uchida et al. (2014) proved that the premium price for ecolabels is related to the type of information available to consumers: the willingness to pay for fish products with sustainability certification increases if the information provided is considered to be reliable. Italian consumers' preferences tend toward wild and local or national products (Mauracher et al., 2013; Menozzi et al., 2020) and sustainability certification (Vitale et al., 2020). In Italy, the willingness to pay for ecolabeled fish products is greater than that in other European countries (Menozzi et al., 2020).

Only a few studies have estimated consumers' willingness to diversify their fish consumption considering both popular and underutilized fish products. Silva et al. (2020) proposed to reformulate existing fish products using discarded or unexploited species, revealing that consumers may find their taste to be pleasant or very pleasant. Witkin et al. (2015) determined the willingness to pay for minor species rather than historically popular and overfished species. They reported that consumers who had previously had the opportunity to try lesser-known species were more likely to choose them again for consumption, while others were reluctant to change their preferences.

With this work, we intend to provide new evidence on consumers' preferences concerning sustainable fresh fish consumption in an Italian Mediterranean coastal area. More specifically, we perform a discrete choice experiment to estimate the WTP for wild-caught shrimps. We address the following research questions: i) are consumers willing to pay for discarded species and ii) can we identify consumer profiles with the same preferences?

We make original contributions to the existing literature. First, our analysis focuses on new and rarely explored topics, such as consumer preferences for discarded species. Second, we aim to understand whether there is a market space for discarded species for direct consumption. Third, this is the first attempt to estimate the willingness to pay for discarded species in Italy.

The rest of the paper is organized as follows. Section 2 describes the survey design and methods, while Section 3 reports the model results and discussion. The conclusions are presented in Section 4.

2. Materials and methods

2.1 The discrete choice experiment methodology

Consumers' preferences are analyzed using a discrete choice experiment. In a discrete choice experiment, respondents have to select their preferred alternative among two or more options included within a single choice set. Each of the provided alternatives is described by a set of attributes that can assume different levels as they vary among the choice sets. Choice experiments are based on Lancaster's (1966) utility theory, which states that the utility of a specific good can be broken down according to the utility level associated with the good's characteristics or attributes. The purpose of a choice experiment is to derive consumers' preferences and willingness to pay for each of the selected attributes basing on their stated preferences (Hoyos, 2010).

In this study, we focus on Italian consumers. In some maritime districts, fish bycatches represent from 20% to 30% of the total catches on average, but they can sometimes exceed 50% of the total catches (see Tiralongo, 2016, for details of the Civitavecchia marine district). Among the most discarded species, we may find white shrimps (Pasiphaea sivado), which are smaller than deep-water rose shrimps (Tiralongo, 2016) but compatible with their habitual consumption and therefore could have a similar destination on the markets. Previous studies indicate that white shrimps are one of the most abundant species in the central Tyrrhenian Sea along the Italian coast (Fanelli et al., 2007; Tiralongo, 2016) and in the Ligurian Sea (Relini, 2019). They have also been found in Spanish territories (Simao, 2015). However, the systematic assessment of white shrimp biomass is lacking due to their low economic value, resulting in limited market interest. Consequently, obtaining specific and up-to-date information regarding the precise abundance and distribution of this species is nearly impossible. Shrimps are harvested by bottom trawling. The setup of bottom trawls is intended to make direct contact with the seabed during fishing. This contact potentially leads to the removal or damage of organisms, sediments, and stones. In the Mediterranean Sea, bottom trawling is recognized as one of the most environmentally impactful fishing methods, resulting in significant amounts of bycatches (Cautadella and Spagnolo, 2011). There are no systematically conducted studies on why white shrimp have been neglected in the market. The only mention of this issue can be found in Holthuis (1980), where it is attributed to the low economic value of the species. The data collected for this study reveals that the majority of surveyed respondents had no prior experience with purchasing white shrimp. The scarce consumers' awareness and the high level of discards, coupled with the low market value may explain the limited significance of this species in the market.

Our choice experiment focused on these two species to understand whether white shrimps could be used to diversify fish consumption and consequently avoid fish waste and marine pollution. Data were collected through a web-based survey. The attribute selection for the experimental design derived from the literature and from interviews with local fishermen and marine biologists with extended knowledge of the case study area. The attributes and their levels are summarized in Table 1. We excluded two attributes that are often included in choice experiments regarding fish products, specifically their freshness and the production process (wild or aquaculture). This is because our study focuses exclusively on wild fresh fish consumption.

Table 1—Selected attributes and attribute levels

Attribute		**Level**
Species	1.	Deep-water rose shrimp
	2.	White shrimp
Origin	1.	Local
	2.	Italian (non-local)
	3.	Foreign
Ecolabel	1.	Yes
	2.	No
Price (€)	1.	6.75
	2.	10.40
	3.	14.50

We created a fractional D-efficient design, which consisted of eight choice sets, with two choice options each and a "no-choice" alternative. The design was blocked into two sections so that each respondent could face four choice sets at a time. An example of a choice set is presented in Figure 1.

A graphic summary of the experimental design is shown in Figure 2. The experiment was composed of two steps: the first step collected stated preferences for shrimps with no prior information. Subsequently, we provided the respondents with some essential information on ecolabels and discarding practices to enable us to compare the model results before and after an information treatment. We carefully specified that ecolabels indicate that the impact of fishing on the marine environment is minimized as they ensure that seafood products are harvested using environmentally sustainable practices. The respondents also became aware of the discarding process and its consequences. We specifically mentioned that discarded species can sometimes substitute the most commercialized ones and that discarded white shrimps may replace rose shrimps.

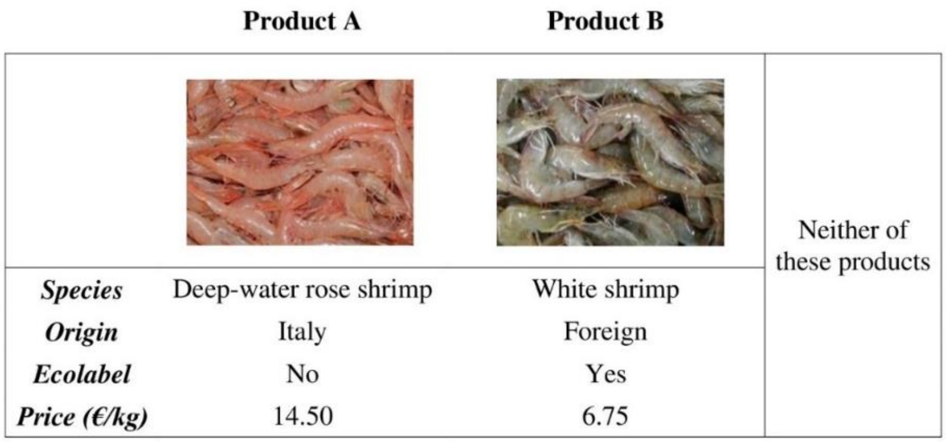

Figure 1—Example of a choice set

Our experimental design is included in a survey and partially deals with products that are not completely or yet marketed. We acknowledge that the hypothetical nature of the experimental design may lead to a WTP overestimation: as respondents are not involved in a real payment setting, their answers may be different from the real-world behavior (Stefani et al., 2014). To handle this hypothetical bias, we have implemented some mitigation strategies (Haghani et al., 2021). We have developed a cheap-talk script, to make our respondents aware of the hypothetical bias. We have also introduced a solemn oath at the beginning of the survey, binding consumers to give us honest answers throughout the interview. Finally, we introduced an opt-out option in our experimental design to avoid forcing our respondents to choose between two unwanted products.

The survey consisted of four sections. In the first section, the respondents indicated their preferences for each of the four choice sets without having received any kind of preliminary information. The second section contained questions aimed at understanding the respondents' habits and frequency of fish consumption. In the third section, the respondents were provided with some information on discarding and on the possible substitutability between rose and white shrimp. At this point, they were asked again to indicate their preferences in a choice experiment. In the fourth and last section, socio-demographic data were collected. The two blocks obtained through the D-efficient design were alternated in survey 1 and survey 2 so that the respondents did not answer the same questions twice.

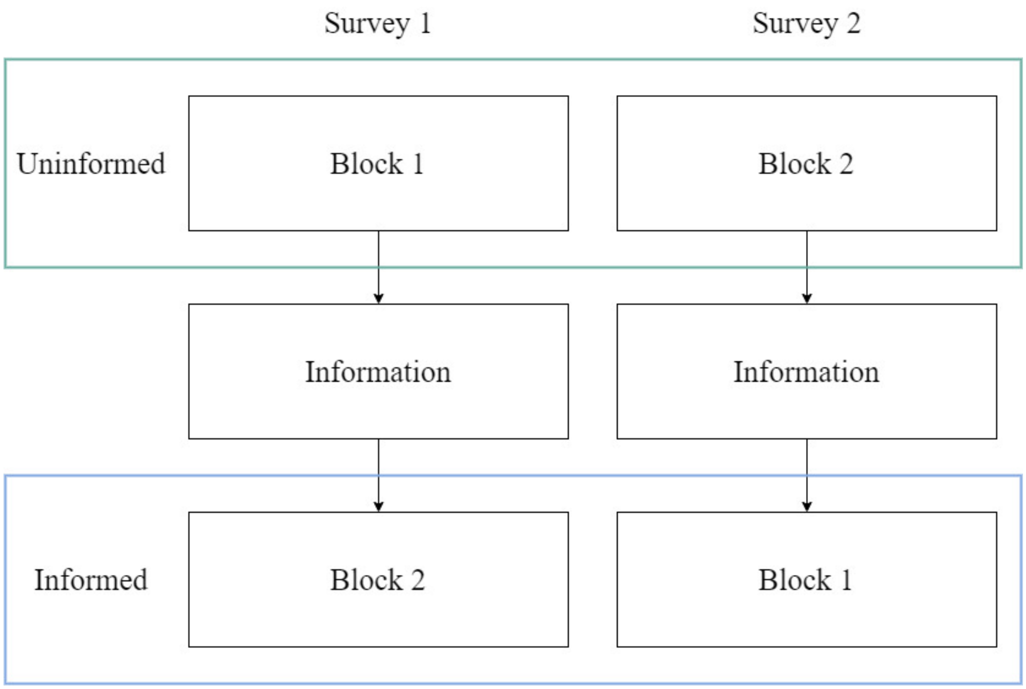

Figure 2—Experimental design

2.2 Empirical approach

Two different models were applied to estimate consumers' preferences and WTP: a mixed logit model and a latent-class logit model. Both models consider preference heterogeneity for fish products. The mixed logit models account for preference heterogeneity by allowing parameters to be distributed randomly among the sample population so that all individuals have their preferences. Heterogeneity can be captured by estimating the mean and variance of the model parameters (Hensher and Greene, 2003). On the other hand, the latent-class model identifies different groups of consumers whose preferences are identical within each group (Shen, 2009). The analysis of data from discrete choice experiments is based on the random utility theory (McFadden, 1973). The deterministic component of the utility function can be observed and quantified through the model's coefficients.

Once the parameters have been estimated, it is possible to compute the marginal willingness to pay (WTP) for each considered attribute, that is, the marginal rate of substitution between the attribute and the money. The WTP is calculated by taking the ratio of the attributes' coefficients (β_a) and the mean price coefficient (β_P):

$$WTP_A = -\frac{\beta_a}{\beta_p} \tag{1.1}$$

In applying the mixed logit model, we used a linear and additive utility function as follows:

$$U_{nit} = ASC + \beta_1 Local_{njt} + \beta_2 Foreign_{njt} + \beta_{3n} White_{njt} + \beta_{4n} Ecolab_{njt} + \beta_{5n} Price_{njt} + \varepsilon_{njt} \tag{2.1}$$

where ASC, the "alternative specific constant," is a dummy variable that takes the value 1 when the choice option is the no-buy option[4]. The origin attribute consists of three levels (foreign, Italian and local). In our model, Italian origin is taken as the base category. Therefore, Local is a dummy variable assuming the value 1 if shrimps are being fished in a local coastal area and 0 otherwise and Foreign is a dummy variable that takes the value 1 if shrimps come from abroad and 0 otherwise. $White$ is a dummy variable that takes the value 1 for white shrimps and 0 for rose shrimps. $Ecolab$ is a dummy variable that takes the value 1 if the product is certified and 0 otherwise. $Price$ is the variable referred to as the price attribute. The price coefficients in the mixed logit model are assumed to be log-normally distributed so that they can have the same negative sign for all the respondents (Train, 2003). Log-normally distributed coefficients have been transformed back to be used in WTP estimations (Hole, 2007). In both the mixed logit and the latent-class model, we did not consider heterogeneity for the origin's attribute and the alternative specific constant.

Two mixed logit models were estimated: the first one using answers from the first section of the survey (uninformed respondents) and the second one using answers collected after providing the information, to understand whether the preferences regarding the selected attributes are affected by respondents' increased awareness.

An additional objective of the paper is to identify different groups of consumers whose preferences are identical within each group and to estimate their willingness to pay for the considered attributes. The latent-class model allows the identification of clusters of respondents who share the same preferences within each group. We will use it to determine whether there are underlying profiles of respondents in our sample.

[4] The alternative specific constant (ASC) is needed when dealing with unlabeled experimental designs (Hensher et al., 2005).

2.3 Sample characteristics and fish consumption preferences

Data were collected through a web-based survey during October/December 2021, by using a quota sampling method. We are aware that the quota sampling method is a non-probability sampling approach, therefore our sample is not representative of the whole Italian population[5]. However, it reflects some specific population characteristics. In our case, the sample is relatively comparable of the Italian population in terms of age, gender, and regional residence. The sample includes 385 responses, which means that our sample size is coherent with the rule of thumb proposed by Johnson and Orme (2003).

The descriptive statistics of the sample are reported in Table 2: 51%of the respondents are female while about 70% of the sampled consumers are aged between 30 and 64 years.

There is a slight majority of people residing in the three Italian areas (North, Center and South) who live in a coastal area (less than 10 km from the coastline). Regarding education levels, 50% of the respondents have a university degree. Most respondents (45.2%) consume fish products once a week. The respondents were also asked whether the information available at the time of purchase is enough to determine whether their consumption choices are sustainable. Most of the respondents (59%) answered “no” to this question, while 18.4% of them declared that they “do not know.” It is interesting to note that more than 60% of the respondents stated that they have never purchased white shrimps before, which is the reason behind the need for further investigations into consumers’ attitudes toward and knowledge about this species.

[5] A comparison between probabilistic and non-probabilistic sampling approaches is provided by Ilyasu and Etikan (2021).

Table 2—Description and summary statistics of the variables (own elaborations)

		Frequency	%	Italian population[6]
Demographic variables				
Gender	Female	198	51.4	51.3
	Male	187	48.6	48.7
Age	18 – 29	69	17.9	17.1
	30 – 49	124	32.2	30.9
	50 – 64	144	37.4	27.4
	64+	48	12.5	24.6
Region	North	170	44.2	46.3
	Center	83	21.6	19.8
	South	132	34.2	33.9
Distance to coastline	<10 km	196	50.9	
	>10 km	189	49.1	
Education	High school or lower	192	49.9	
	High education (university)	193	50.1	
Attitudinal variables				
Previous purchase of white shrimp	Yes	133	34.5	
	No	252	65.5	
Respondent cares about sustainability	Likert scale 1–5	3.19 (mean)	1.29 (s.d.)	
Does the information available at the time of purchase allow you to make sustainable consumption choices?	Yes	83	21.6	
	No	227	59.0	
	Don't know	71	18.4	
Frequency of fish consumption	Once a month or less	107	27.8	
	Once a week	174	45.2	
	2–3 times per week	95	24.7	
	4+ times per week	9	2.3	

3. Results and discussion

3.1 Mixed logit model results

The estimation results of the mixed logit model, respectively for uninformed and informed choices, are reported in Table 3. Almost all of the included attributes have a statistically significant coefficient, but there are interesting differences between the choices of uninformed and informed consumers. The positive sign for the local origin variable coefficient in the uninformed sample means that those consumers are slightly more likely to choose locally harvested products than national ones, which is consistent with the literature results indicating that domestic and local

[6] Italian age population percentages are computed excluding people under 18 years old (ISTAT, 2021).

products are preferred by consumers (Mauracher et al., 2013). However, the local origin coefficient becomes non-significant for informed consumers, meaning that the probabilities of choosing a local or a national product after having received the information treatment become the same. On the contrary, it is less likely that both uninformed and informed consumers will choose foreign fish products over national ones as the foreign origin variable coefficient is negative in both models, indicating a strong preference for national fish products. The negative and significant coefficient of the white shrimp variable shows that uninformed consumers prefer to buy the most common species (rose shrimps). Although informed consumers also report negative preferences toward the white shrimp species, it is worthwhile pointing out an increase in the coefficient for white shrimps after the information treatment has been administered. This indicates that information reduces the perceived difference between rose and white shrimps. The ecolabel coefficient is positive and significant in both models, meaning that uninformed and informed consumers are more likely to purchase a sustainable certified product. In both models, the price effect is negative and significant at the 1% level, indicating that the probability of purchase decreases as the price increases. The coefficient for the alternative specific constant is negative and significant, indicating the negative utility associated with not purchasing either of the two shrimp options.

Most of the standard deviation parameters are statistically significant, meaning that there is heterogeneity in consumers' preferences and highlighting the importance of using the mixed logit model specification to capture this variability. Moreover, the magnitude of the standard deviation coefficients can give us additional information: contrary to what happens in the case of uninformed consumers, the distribution of the white shrimp parameter in the informed consumers' sample covers and exceeds the zero value, indicating that some informed respondents actively prefer white shrimps as their parameter for this attribute is positive.

Table 3—Estimation results for mixed logit models (own elaborations)

Variable	Uninformed	Informed
Local (base = Italy)	0.262** (0.124)	0.156 (0.121)
Foreign (base = Italy)	-2.511*** (0.196)	-1.589*** (0.151)
White (base = rose)	-0.600*** (0.107)	-0.351*** (0.102)
Ecolab (base = no)	1.659*** (0.171)	1.728*** (0.168)
Price	-0.162*** (0.041)	-0.226*** (0.028)
ST.DEV. OF PARAMETERS		
White (base = rose)	0.519** (0.234)	0.640*** (0.217)
Ecolab (base = no)	1.850*** (0.192)	1.947*** (0.183)
Price	0.409 (0.271)	-0.623*** (0.202)
ASC	-3.191*** (0.250)	-3.127*** (0.237)
Observations	4,620	4,620
Respondents	385	385
LL	-1108.768	-1176.503

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

The mixed logit model specification also allowed us to calculate the WTP for each attribute. The average WTP estimations are reported in Table 4.

Table 4—Average willingness to pay for selected attributes (own elaborations)

Variable	Uninformed	Informed	Variation	
Local (base=Italy)	1.613	0	- 1.613 €/kg	(- 100.0%)
Foreign (base=Italy)	-15.486	-7.037	+8.449 €/kg	(+54.56%)
White (base=rose)	-3.702	-1.553	+2.149 €/kg	(+58.05%)
Ecolab (base=no)	10.229	7.652	- 2.577 €/kg	(- 25.19%)

It is interesting to note that, in the informed consumer sample, the ecolabel's WTP has decreased, given that the increased awareness of respondents is reflected in their consumption choices. Uninformed consumers have no other options but to rely on ecolabels to make sustainable choices. On the other hand, informed consumers already know that buying white shrimps is a sustainable choice in itself and they do not exclusively need to rely on the ecolabel attribute. In their previous work, Bronnmann and Asche (2017) showed that the WTP for certified seafood increases after information on the certification system is provided. In our case, we obtained the opposite result: the WTP for ecolabels decreases after obtaining the information. In the uninformed sample model, the average WTP for ecolabeling is equal to 10.23. €/kg. For informed consumers, the WTP for ecolabels decreases to 7.65 €/kg. In the case of white shrimps, uninformed consumers are willing to pay on average 3.7 €/kg less than they would pay for rose shrimps. However, the willingness to pay for white shrimps is higher for informed consumers, who on average would pay 1.55 €/kg less than for rose shrimps, meaning that the information provided had a positive effect on consumers' attitudes toward white shrimps as it increased their willingness to pay for this species by 58.05%. The results indicate that rose shrimps would still be the preferred species, but they also underline that the attitudes toward and preferences for white shrimps become more similar to those for rose ones due to the effect of the information. In this work, the information provided is twofold as it concerns both the discarded species and the certification. The information on discarded species prevails over the ecolabel, channeling the positive effects of the information treatment into the increase in the white shrimps' WTP.

3.2 Latent-class logit model results

To identify some mutually exclusive homogeneous groups of respondents with the same peculiarities, we compared the main statistics for the latent-class model with two or three classes. According to the AIC and BIC criteria, the three-class model had to be preferred. The results of the latent-class model for the sample of uninformed consumers are shown in Table 5. Each class is characterized by a specific preference structure. They are labeled according to the most relevant characteristics that emerge within each group. Class 1 is the largest as more than 60% of the respondents fall into this group. Based on the relevance of the different attributes for the members of Class 1, they might be defined as "light green consumers with awareness of white shrimps." In fact, the respondents included in Class 1 show a mildly positive interest in ecolabels given that the Class 1 coefficient for sustainable certification is the lowest. Moreover, Class 1 contains those respondents who have previously tried white shrimps. They perceive less difference between the two species than members of the other classes as the coefficient for white shrimps in Class 1 is the highest, even if they do not prefer white shrimps to rose ones as the coefficient has a negative sign. Class 2 is the smallest group as only 13% of respondents are classified within it. The results associated with this group allow us to define it as "price-conscious consumers." It is made up of consumers who pay more attention to the price attribute than the other two classes as they have the lowest price coefficient. They prefer rose shrimps to white ones given the negative and significant coefficient for white shrimps, but they show more interest in sustainability than members of Class 1. The remaining individuals of the sample are classified within Class 3, which is made up of consumers who keep a strong focus on sustainability certification. This can be noticed by looking at the ecolabel coefficient. Concerning the white shrimp variable, their preferences are more aligned with Class 2. We will refer to this final group as "green consumers."

Table 5—Estimation results for the LCL model (own elaborations)

Variable	**Class 1**	**Class 2**	**Class 3**
White (base = rose)	-0.231** (0.101)	-1.474*** (0.413)	-1.484*** (0.399)
Ecolab (base = no)	0.381*** (0.121)	3.427*** (0.512)	4.297*** (0.484)
Price	-0.063*** (0.016)	-0.581*** (0.056)	-0.038 (0.056)
Local (base = Italy)	0.249** (0.115)	0.249** (0.115)	0.249** (0.115)
Foreign (base = Italy)	-2.085*** (0.144)	-2.085*** (0.144)	-2.085*** (0.144)
ASC	-2.854*** (0.203)	-2.854*** (0.203)	-2.854*** (0.203)
Covariates			
Age	-0.004 (0.012)	-0.012 (0.014)	0
Female	-0.696* (0.356)	0.265 (0.438)	0
High education	-0.173 (0.337)	0.120 (0.409)	0
Living nearby coastline	0.668* (0.354)	0.853** (0.418)	0
Previous purchase	0.815** (0.382)	-0.605 (0.556)	0
Care about sustainability	-0.588*** (0.158)	-0.550*** (0.176)	0
Constant	3.070*** (0.767)	1.334 (0.931)	0
Size (%)	63.4	13.0	23.6
Observations		4620	
Respondents		385	
LL		-1053.063	

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

4. Summary and conclusions

In this work, we investigated about the willingness of Italian consumers to buy commonly discarded white shrimps instead of rose shrimps, while accounting for consumers' preferences and the origin of fish products. We also explored consumers' preferences using a latent-class logit model to identify and describe homogeneous groups of respondents. During data collection, essential information on sustainability certification and discarded species was provided, allowing us to compare results before and after an increase in consumers' awareness. This work has two main limitations. First, the quota sampling is a non-probability sampling approach, therefore our sample is not representative of the whole Italian population. Moreover, in our experimental design we deal with hypothetical bias, which may lead to WTP overestimation.

Results show that white shrimps remain less preferred than rose shrimps, but the probability of choosing white shrimps increases when specific information is provided. Also, consumers' willingness to pay for white shrimps increases with their awareness while remaining lower than the willingness to pay for white shrimps, thus indicating that preferences are oriented toward the most commercialized species. Last, consumers could be segmented into different groups to pinpoint the most suitable marketing strategies for each group.

There may be a market space for underutilized species as informed consumers are more likely to increase their willingness to pay for discards provided that specific information is conveyed to raise awareness of discarded species' consumption and its potential benefits on resource conservation and sustainability of fishing activity. However, emphasizing the sustainability behind the choice of discarded species can be more effective for eco-friendly consumers, while price-conscious consumers would prefer to focus on the greater affordability of white shrimps.

Appropriate demand-side policies could be built on such demand characteristics and support the sustainable purchase of fish discards. For example, consumer information and education campaigns focusing on the environmental benefits of eating discarded species could be promoted. To improve consumer knowledge in decision-making, policy makers and stakeholders might introduce appropriate labeling rules or advocate the use of ecolabels or certification schemes. Given that white shrimps and rose shrimps are sold on the same market, and white shrimps are sold at a lower market price than rose shrimps, the consumer will be able to make better-informed decisions, gaining both private and social benefits.

The empirical findings have provided clear evidence that a significant portion of consumers lacks prior exposure to white shrimps. The examination of their willingness to pay has demonstrated a potential increase when they are presented with information regarding the environmental consequences of discarding practices. These outcomes highlight an evident communication gap between fishermen and consumers. To address this gap, targeted public interventions could play a crucial role in enhancing consumers' understanding and fostering their inclination to opt for sustainable choices. One viable approach may involve the implementation of specific certifications or claims for discarded products, enabling consumers to determine the sustainability of their purchases.

Few studies have addressed topics regarding consumption and preferences towards discarded species (Witkin et al., 2015). This research will contribute to fill this gap. Deep-water rose shrimps are also abundantly fished in other European countries (EUMOFA, 2019), and the results of this study may be expanded to other fishing areas. Data collection and experimental design adopted in our research can be easily replicated to expand the base data available and conduct interesting cross-country comparisons. Our study is also aimed at drawing the attention of consumers and policymakers to this resource, to potentially enhance future research on this species, its distribution, and its nutritional properties. Such analyses could support the design of policy options complementing the existing body of EU policies in the Mediterranean area which have mainly adopted a supply-side approach such as the effort limitation (Carpi et al., 2017), and have not been effective in addressing the discarding issue and the consequent ecological damages to the fish stocks. Further exploration of these issues remains an important area for future research.

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2. Policy management of small pelagic fisheries in the Adriatic Sea: a dynamic maximum economic yield approach

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Abstract

The well-being of most Mediterranean fisheries is heavily compromised, suggesting the need for an effective policy response to preserve fish stocks in the long run. We focus on the Italian small pelagic fleet in the Adriatic Sea to estimate the economic impact of selected policy scenarios from effort limitations to total allowable catch (TAC) management. The anchovy and sardine stocks included in this study are particularly relevant in the case study area as they account for most of the total catches in terms of landed weight. Our work examines the impact of such policies on the profitability of the fleet and on the biomass levels over a time span of 10 years. More specifically, we build an optimization model aimed at estimating the maximum economic yield (MEY) of this fishery under specific policy conditions to compare the economic profitability of the fishing system in the long run. The results underline the trade-off between biological and economic policy targets. We also acknowledge the uneven distribution of economic benefits within the fishing fleet, highlighting a persistent efficiency gap between the multiple fishing gears involved in small pelagic fishing.

1. Introduction

While the heated debate on fisheries management has been ongoing for decades, different policy measures have been adopted to limit fish stock depletion. 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 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, more than 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 Mediterranean Sea is bordered by many different EU and non-EU countries with diverse economic and political backgrounds. Second, 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 or even hindered by the heterogeneity of fishing gears and target species of its fisheries, and 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.

Our work focuses on the Adriatic Sea (located in the Mediterranean area between Italy and the Balkan peninsula) small pelagic fishery consisting of anchovy (*Engraulis encrasicolus*) and sardine (*Sardina pilchardus*) stocks. Research on small pelagics' management in the Adriatic area is crucial nowadays 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.

With this work, we aim to expand the economic research on the small pelagic fishery in the Adriatic Sea by estimating its dynamic maximum economic yield (MEY) under different policy scenarios through an optimization model. A no-policy scenario (open access) is confronted with input control measures such as fishing days and fleet capacity limitations and with output control measures such as quotas. 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 two quota scenarios, differentiating between mixed and separate TAC policies. 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.

The MEY was originally defined by Gordon (1954) as the level of harvests that leads to the maximum net economic benefits (profits). 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. In this regard, the MEY has been officially implemented as a management reference point in Australian fisheries (Kompas et al., 2010; Grafton et al., 2011). The recent work by Diop et al. (2018) has also shown that the MEY can be a relevant strategy to deal with climate change as a mitigation measure.

Previous studies have simulated pelagic and small pelagic fisheries' response to real or hypothetical management policies over time through a profit maximization strategy, but they have mostly referred 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, and there are not many recent studies. 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 can be retrieved in the GFCM and Scientific, Technical, and Economic Commission for Fisheries (STECF) databases. Simulation models and tools have recently been used by EU and FAO scientific committees to 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 management strategy.

Our paper aims to fill the research gap regarding how small pelagic fisheries management affects the fishery from a economic perspective by focusing on how current and future policies could affect the profitability of the fishing fleet. In doing so, we contribute to the literature by (i) deepening our understanding of the economic aspects of the small pelagic fishery in the Adriatic Sea, (ii) providing, for the first time, an estimate of the MEY for this fishery to offer a new policy management perspective, and (iii) adapting the most common utilized surplus production model to our case study to deal with the catch composition of the fishery better. More specifically, for part (iii), we define a specific optimization constraint to deal with differing catch selectivity at the gear level.

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 will focus 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 level are not provided by our main sources. Therefore, our analysis will be performed at the aggregated level. The results of this work could be used to define policy objectives compatible with biological sustainability while ensuring the economic efficiency of the Italian small pelagic fishing fleet.

The rest of the paper is structured as follows. The case study description and the methodological framework are presented in Section 2, while Section 3 reports the model results and discussion. Conclusions and policy implications are discussed in Section 4.

2. Materials and methods

2.1 Methodological framework

The theoretical framework identified by Gordon (1954) and Schaefer (1954) at the static level is briefly described below before discussing the dynamic optimization model used in the empirical analysis.

Schaefer (1954) describes the dynamics of the stock through Verhulst's logistic equation which is:

$$\frac{dB}{dt} = rB\left(1 - \frac{B}{K}\right)$$

Where r is the intrinsic growth rate, K the carrying capacity, and B the stock biomass. When the stock equals the carrying capacity $B = K$, the population growth will be 0. To identify the point at which the growth rate peaks, we can differentiate the growth function with respect to B and set it equal to zero obtaining:

$$B_{MSY} = \frac{K}{2}$$

This is the Maximum Sustainable Yield (MSY). The MSY is often used as a target reference point for policy makers because it allows the greatest amount of harvests without affecting the overall status of the main fish stock. Not exceeding the MSY point means risking that the growth rate of the stock is insufficient to guarantee its replenishment, and this increases the risk of resource depletion over time. Harvests can be described as:

$$h = qEB$$

Where E indicates the fishing effort, usually described in terms of fishing days and q is the catchability coefficient, which is a proxy for the efficiency of the fleet. A sustainable exploitation of the fish stock would entail an equality between the stock growth and the quantity harvested:

$$rB\left(1 - \frac{B}{K}\right) = qEB$$

which becomes:

$$B = K - \left(\frac{qK}{r}\right)E$$

This is the *population equilibrium curve* and describes the inverse relationship between fish stock and effort, where an increase in effort leads to a decrease in the quantity of stock. Different stock equilibria are possible depending on the level of exerted effort. Specifically, in the absence of fishing ($E = 0$), the stock corresponds to the actual environmental carrying capacity and reaches its maximum level ($B = K$). On the other hand, if $E = r/q$, the stock is completely depleted ($B = 0$). Replacing the population equilibrium curve into the harvest equation and setting $a = qK$ and $b = \frac{q^2K}{r}$ gives:

$$h = qEK\left(1 - \frac{qE}{r}\right) = aE - bE^2$$

Here $\frac{dh}{dE} = 0$ identifies the effort level needed to achieve the MSY point: $E_{MSY} = \frac{r}{2q} = \frac{a}{2b}$.

Now we can include the harvest price p and the cost of fishing per unit of effort c. These parameters are considered constant, as defined by Gordon (1954). The revenues from fishing are defined as:

$$R = pqEK\left(1 - \frac{qE}{r}\right) = p(aE - bE^2)$$

And the costs are:

$$C = cE$$

Hence, profits (revenues – costs) are defined as:

$$\pi = R - C = p(aE - bE^2) - cE$$

The profit equation allows for the calculation of two fundamental effort reference points: the bioeconomic equilibrium (BE) and the maximum economic yield (MEY). The BE is obtain equating the profit equation to 0, which implies:

$$E_{BE} = \frac{a}{b} - \frac{c}{Pb} = \frac{r}{q}\left(1 - \frac{c}{PqK}\right)$$

When E_{BE} is reached, the revenues obtained from fishing activities cover the incurred costs and do not encourage the entry or exit of new vessels operating in the fishery. However, in a situation of maximum economic efficiency, the goal of any fisherman is likely to be to maximize profit rather than achieving the BE. To maximize profit, we can equate its derivative to zero and solve for fishing effort, resulting in:

$$E_{MEY} = \frac{Pa}{2Pb} - \frac{c}{2Pb} = \frac{r}{2q}\left(1 - \frac{c}{PqK}\right)$$

The MEY level of effort guarantees the perfect correspondence between marginal costs and revenues, ensuring that resources used during the harvesting process are perfectly allocated. If they are not equal, these resources could be more efficiently used in other sectors of the economy.

Comparing the static levels of effort at the MSY (Maximum Sustainable Yield), BE (Biological Equilibrium), and MEY (Maximum Economic Yield) reference points, it is noticeable, as highlighted by Gordon (1954), that MEY is achieved at lower levels of effort compared to BE and MSY. This discrepancy is due to the nature of fishery resources: they are common goods, non-excludable but rivalrous, without specific access constraints or assigned property rights. According to economic theory, an unregulated fishery will automatically tend towards BE, with potential negative consequences for fish stocks and the marine environment. For this reason, specific policies and regulations aimed at reducing overfishing and protecting the marine environment have been introduced all around the world. Although the Common Fisheries Policy (CFP) tends to adopt MSY as a reference for defining fisheries management policies in European waters, we know that achieving MEY would require even lower levels of effort (and consequently, harvests), allowing the fishery to operate at maximum levels of economic efficiency and environmental sustainability. This basic principle underlies the model used for analyzing the Italian small pelagic fleet in the Adriatic, and it is extended to include considerations on the fleet dynamics over time.

2.2 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[7] (GSA) 17 and 18. The Adriatic Sea is over 800 km long and 150–200 km wide (Danovaro and Boero, 2019). 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 and therefore relevant from a production perspective. Anchovies are the main harvested species by weight at the overall national level, immediately followed by sardines, 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, 2021). On the Italian coastal side of the Adriatic, anchovies are considered the preferred species and have a significantly higher value, but the price difference between the two species in Croatian markets is less pronounced. These differences are mainly driven by the final usage 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).

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 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).

Specific policy measures have been implemented in the area to limit their stocks' depletion over the past 10 years, 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

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

reduction of the number of fishing days or the containment of the 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 soon extended to its southern area. The yearly fishing day limit was set to a maximum of 180 days per vessel until 2018 (GFCM/42/2018/8). Within this range, no more than 144 days could be spent targeting either sardines or anchovies. In 2016, the GFCM established a maximum amount of catches (GFCM/40/2016/3) equal to the 2014 level. Given that harvests achieved extremely high levels in 2014, this measure was never really enforced (Carpi et al., 2017). A complete shift toward output control measures happened in 2021. The GFCM (GFCM/44/2021/20) defined quota limits for both Italy and Croatia equal to 35,394 tonnes and 56,304 tonnes, respectively. The new management measures entered into force in 2022. The quota limits will be updated every year following the biological stock assessment performed by the FAO Scientific Advisory Committee for Fisheries. The actual quotas are supposed to represent the maximum amount of small pelagics allowed for both species, but single species quotas may be established in the coming years. Past, present, and future policies will be used in our empirical framework to assess their economic consequences.

2.3 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 and repair costs[8]. Revenues refer exclusively to the quantity of fish landed (in tons) 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).

[8] The variable and fixed costs are allocated based on the distinction made by Maiorano et al. (2019) which provide specific indications on how to treat the data collected under the national data collection program on fisheries.

Revenues and harvests can be attributed to single species, while costs are provided in an aggregate way.

Previous studies (e.g., Salenius, 2018) have attributed the costs of harvesting each species to their relative percentage of total catches. We make a slightly different assumption by distributing costs according to the relative percentage of small pelagic species' landed value in the total revenues. In this way, we implicitly acknowledge that sardines and anchovies usually have a lower landing value than other harvested species, such as tuna or cuttlefish (Maiorano et al., 2019), and letting the harvesting costs of other more profitable targets weigh on small pelagic costs would introduce a bias into our model. This assumption is needed to account for the small portion of non-sardine and non-anchovy high-value 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 exclusively refer to the western side of the Adriatic; therefore, they are a measure of stock abundance on the Italian side. Data for the eastern side are also assessed by the MEDIAS project but will not be included in the analysis.

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). Trawling is the fishing method that exerts the greatest fishing effort and has the highest environmental impact, as the nets come into direct contact with the seabed. The environmental impact of purse seining (PS) and pelagic trawls (TM) is more limited because pelagic species are not found near the seabed (Cautadella & Spagnolo, 2011). However, TM require a significantly higher amount of fuel and powerful engines to be towed at fishing speed, while circulatory nets have a lower fuel consumption (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.

2.4 Model description

We build an optimization model to estimate the dynamic MEY of the Adriatic small pelagic fishing system (Italian side). Many findings on the dynamic MEY refer to Australian fish stocks, for which such an indicator has been officially implemented as a policy objective (Kompas et al., 2010), but there is no evidence of this indicator being estimated for our case study. The dynamic MEY maximizes the discounted net present value of the fishery. These net benefits are the profits made by the fishing fleet and are defined as the difference between revenues and costs. The dynamic MEY incorporates a discount rate into the analysis. The discount rate indicates how much fishermen value the future monetary benefits compared with the current ones. The inclusion of discount rates in dynamic models is crucial to consider the fishing activity as an investment decision regarding how much fish should be harvested and how many specimens should be preserved over time (Hoshino et al., 2018).

Our optimization model accounts for the interaction between the biological and the economic complex of the fishery at the aggregated level. More specifically, our analysis considers two species (sardines and anchovies) with no biological interaction and one player (Italy) that uses the two different fishing gears previously described, the PS and TM. The gears 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. Both functional forms yield similar fittings and coefficients. However, the coefficients for sardines exhibit slightly better significance when using the Ricker equation. Conversely, the data for anchovies encounter more difficulties in fitting with both functional forms. As a result, we have ultimately chosen to employ the Ricker functional form in Eq. (1) for both species.

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

where B_{it} stands for the biomass of species $i = 1, 2$ (where 1 indicates anchovies and 2 indicates sardines) at time $t = 1, \dots, T$ (where $T = 10$), $j = 1, 2$ 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 $h_{mj,t}$ indicates the harvests of species i by gear m 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 current set-up does not include a constraint for the biomass level in the final year, which may result in abrupt harvest increases at the last model iteration, as occurred in Salenius's (2018) study. To avoid such unrealistic switches, we define a circularity constraint in the final year to set the minimum level of the final biomass at least equal to 40% of the initial biomass levels.

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

$$n_{j,t} = \varphi_j \frac{\pi_{j,t-1}}{(1+\delta)^{t-1}} \tag{2}$$

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 private discount rate applied to future profits every year. Eq. (2) 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 OLS on non-discounted past profits.

Our model also includes a relative abundance constraint to replicate the real fishing conditions, where two species are harvested at the same time, and a complete separation between the time and the effort spent targeting each of them is not feasible:

$$\frac{B_{1,t}}{B_{2,t}} \leq w_j \frac{h_{1j,t}}{h_{2j,t}} \tag{3}$$

The catch composition parameter w_j sets the relationship between the ratio of the biomasses of sardines and anchovies and the ratio of their harvests per each gear j. This newly formulated constraint is meant to deal with the catch composition of the total harvests. Indeed, the final harvest composition could be made of specimens of different maturity stages (Helgesen et al., 2018) or even different species. Eq. (3) states how the harvests' ratio of anchovies and sardines is linked to the relative abundance of their biomasses. In this model, w_j is the catch composition parameter associated with each fishing gear j. We assume that $0 < w_j \leq 1$. According to our specification, a greater amount of harvests for species 1 is associated with smaller values of the catch composition parameter. Dealing with the catch composition constraint also allows us to avoid discussing trivial results, such as zero harvests for the less profitable species as a consequence of profit maximization. This result, albeit mathematically correct, does not provide adequate or sufficient policy indications for the Adriatic small pelagics as both sardines and anchovies are regularly harvested despite their economic value.

The base optimization problem aims to maximize the sum of PS and TM discounted net benefits (profits) $\pi_{ij,t} = R_{ij,t} - V_{j,t} - C_{j,t} - F_j$ over a time horizon T. The maximization problem can be expressed as follows:

$$max \sum_{t=1}^{T} \sum_{m=1}^{j} \frac{\pi_{j,t}}{(1+\delta)^{t-1}} \tag{4}$$

This is subject to Eq. (1), Eq. (2), Eq. (3), and the following constraints:

$$E_{j,t} \leq dn_{j,t} \tag{5}$$

$$B_{i,t}, E_{j,t}, n_{j,t} \geq 0 \qquad \forall\, i, j, t \tag{6}$$

Additional policy-specific constraints are defined in paragraph 2.5. The optimization is restricted to the maximization of aggregated profits earned by the fishing fleet, using a private discount rate δ. As the model estimates the MEY of the fleet from the fishermen perspective, a public discount rate is not included. Cost-benefit analysis assessments on the policy scenarios considering both private and public discount rates could be pursued in further research. The private 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) 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. (5) 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. (6).

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

$$\pi_{j,t} = \sum_{l=1}^{i} R_{lj,t} - V_{j,t} - C_{j,t} - F_j \tag{7}$$

More specifically, revenues $R_{ij,t}$ are defined as the product between the ex-vessel fish price and the harvested quantities, while $V_{j,t}$, $C_{j,t}$, and F_j represent variable, crew, and fixed costs, respectively.

We consider 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 as the latter do not refer to what is directly earned by the fishers. 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 harvested amount of each species is modeled by using a Cobb–Douglas production function considering biomass B_i and fishing days E_{ij} as inputs, as has often been undertaken in previous studies (e.g., Salenius, 2018):

$$h_{ij,t} = q_{ij} B_{i,t}^{a_{ij}} E_{ij,t}^{b_{ij}} \tag{8}$$

where q_{ij} is the catchability coefficient (a proxy for the efficiency of the fleet) and a_{ij} and b_{ij} are the catch elasticities with respect to the stock size and the fishing days. There is an extensive literature discussing the various functional forms available to describe the harvesting function of a fishing system. Mulazzani (2011) offered a thorough overview of the commonly utilized functional forms such as the Cobb-Douglas function, the Constant Elasticity of Substitution function, and the Translog function, highlighting their strengths and weaknesses. The main objective of this work is to provide a comprehensive representation of the analyzed fishing system while maintaining computational simplicity. For this reason, the Cobb-Douglas functional form was chosen, as it has been already used to describe the economic impacts of small pelagic fisheries management policies in the Adriatic (SAC, 2018). The Cobb-Douglas functional form allows for ease of interpreting the estimated parameters as elasticities of production factors. The Cobb–Douglas functional form can be linearized to allow parameter estimation through OLS or similar methods. However, some of the parameter results are not consistent with the economic theory or are non-significant. Therefore, we build our own calibration model for the harvest parameters by minimizing the normalized root mean square error (NRMSD) between real (y) and calibrated ($\hat{y}$) data at time $t = 1, \dots, T$. The NRMSD is defined as follows:

$$NRMSD = \frac{RMSD}{y_{max} - y_{min}}, \qquad \text{where} \qquad RMSD = \sqrt{\sum_{t=1}^{T} \frac{(\hat{y}_t - y_t)^2}{T}} \tag{9}$$

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:

$$V_{j,t} = v_j E_{j,t} \tag{10}$$

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 with respect to the variable costs:

$$C_{j,t} = c_j\left(\sum_{l=1}^{i} R_{lj,t} - V_{j,t}\right) \tag{11}$$

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

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

$$F_{j,t} = f_j n_{j,t} \tag{12}$$

where f_j is the fixed cost per vessel specific to every fishing gear and n_{jt} 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.

2.5 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[9]. 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

[9] Here are the main steps of the legislative procedure.

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.

Table 1. Policy scenarios

Scenario	**Description**
No policy (NP)	Fishing can occur for a maximum of 365 days per year per vessel
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 (35,394 tons)
Separate quotas (SQ)	Separate quotas for anchovies (17,394.01 tons) and sardines (17,999.35 tons)

2.5.1 No policy

In the no-policy condition, there are no restraints on the number of days and vessels that can operate in the fishery. Note that this is not a complete open-access scenario: while we do not specify any constraint on the number of days and vessels for both gears, the resulting harvesting decisions will be based on maximizing the net benefits over a time span of 10 years without exploiting the resource over this period[10].

2.5.2 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 was set to 180 days per year, and they had to be distributed between anchovies and sardines.

[10] We compare the result of the no-policy optimization scenario with a basic simulation model: letting the existing vessels harvest both species for 365 days per year without allowing for long-run harvesting leads to anchovies' depletion.

2.5.3 Mixed quota

The mixed-quota scenario is based on the current GFCM recommendation, which defines a total allowable catch limit. This limit is divided between Italy and Croatia; therefore, specific country quotas have been established. The maximum small pelagic catch limits allowed at the country level are 35,394 tons and 56,304 tons for Italy and Croatia, respectively. 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:

$$\sum_{j,i=1}^{2} h_{ij,t} \leq TAC \tag{16}$$

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.

2.5.4 Separate quotas

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

$$\sum_{j=1}^{2} h_{ij,t} \leq TAC_i \tag{17}$$

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 (16.82%) 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.

2.5.5 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. The maximum vessel limit is established by the GFCM (GFCM/44/2021/20) at the 2014 level, with 36 purse seines and 130 mid-water pelagic pair trawls for a total maximum limit of 166 vessels.

3. Results and discussion

3.1 Calibration results

Table 2. Economic parameters

Symbol	Definition	PS	TM	Units
$j = 1,2$	Subscript (gear)			-
T	Time horizon	10		years
δ	Discount rate	5%		
p_{ij}	Unitary price of fish			€/ton
	Anchovies	1,530	1,562	
	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	1.8E-5	8.2E-4	
	Sardines	2.9E-3	8.0E-4	
a_j	Biomass elasticity			-
	Anchovies	0.61	0.10	
	Sardines	0.10	0.53	
b_j	Effort elasticity			-
	Anchovies	1.43	1.62	
	Sardines	1.36	1.02	
φ_j	Fleet dynamics	9.9E-6	1.6E-5	€$^{-1}$
w_j	Catch composition	0.24	0.57	-

Table 2 reports the values of all the calibrated economic parameters. The estimated prices per ton provide a clear idea of the profitability of 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 indicate that anchovies will most likely be sold on the market while sardines are less valuable; therefore, their physical condition and size can have a more pronounced impact on the final value.

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. For PS vessels, the coefficient for sardines is higher than that for anchovies, meaning that this gear is not as efficient in targeting the second species. For TM vessels, the catchability coefficient for sardine and anchovies is quite similar. Overall, we notice that TM vessels are more efficient at harvesting the most profitable species.

Parameters a and b represent the elasticity of each factor of production. The elasticity indicates whether harvests change less or more than proportionally with respect to changes in biomass and effort. More specifically, in the case of a Cobb-Douglas functional form, the elasticity indicates the percentage change in harvests resulting from a unitary percentage change in the other variables. The biomass elasticity coefficients are low (< 1) for all species and gears, meaning that fishing is less than proportionally affected by the biomass of the stocks. This is consistent with previous insights from other pelagic fisheries (Mulazzani, 2011; Mulazzani et al., 2015; Salenius, 2018) as they tend to be gregarious and move around in fish schools. The effort elasticities are > 1. This indicates that harvests are more than proportionally affected by the increase in fishing days, which are the most essential inputs of fishing activities. As reported in Table 2, the effort elasticities for anchovies are always higher than those for sardines, meaning that a greater fishing effort is more frequently associated with the capture of the most profitable species or, in other words, fishers are more prone to increase their effort to harvest more anchovies than sardines.

The entry/exit coefficient determines the change in the number of vessels according to the previous year's profits. There is a small difference between the two coefficients, which indicates that purse seines are slightly less responsive to profits than pelagic trawlers.

The catch composition parameter for PSs is more than two times lower than the one for TM vessels, meaning that PS vessels tend to be more selective toward anchovies. This reflects the historical trend of harvests as anchovy landings for PS vessels have been more than double the quantity of sardines landed every year, while the TM harvests for the two species tend to be more comparable, especially in more recent years.

More details on the parameter estimation and the significance of the economic coefficients are reported in Appendix B. The results for the harvest parameters are reported in Appendix C.

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	222,434	ton

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 2004–2018.

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 four different policy scenarios. Table 4 summarizes the results by showing the net present benefits. The benefits are reported by gear and for the Italian fishery as a whole complex.

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

Scenario	**PS**	**TM**	**Total**
No policy	1.84	117.81	119.65
Effort limitation	8.26	55.88	64.14
Mixed quota	3.65	48.77	52.42
Separate quotas	-0.93	36.38	35.45

By comparing the values in the last column of Table 4, we can see the economic effect of different policy management approaches on the fishery. The no-policy scenario leads to the highest aggregated present benefits over time. Conversely, the policy scenarios lead to lower values of net present benefits across the optimization period. The presented scenarios are quite different in terms of how the aggregated benefits are allocated between the two fishing gears, with PS vessels always earning the lowest amount of net present benefits. The net present value of PSs' profits for the separate-quotas scenario even contributes negatively to the overall net benefits of the fishery. 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 5. Biomass starting/final point and carrying capacity comparison in different scenarios

Scenario	**Anchovies (tons)**	**Anchovies (%)**	**Sardines (tons)**	**Sardines (%)**
All scenarios (starting point)	318,657	-	117,288	-
No policy (final point)	313,925	– 1.48 %	194,809	+ 66.09 %
Effort limitation (final point)	382,070	+ 19.90 %	204,757	+ 74.58 %
Mixed quota (final point)	384,943	+ 20.80 %	204,889	+ 74.69 %
Separate quotas (final point)	399,376	+ 25.33 %	208,041	+ 77.38 %
Carrying capacity	437,041	+ 37.15 %	222,434	+ 89.65 %

Table 5 reports the biomasses 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[11]. Neither the anchovy nor the sardine stock achieves its carrying capacity level, but the policy management scenarios are more supportive of their growth over time than the no-policy condition. The environmental benefits of such policy interventions are particularly evident in the case of the sardine stock, which reports lower levels of biomass 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 allows for the greater value of their biomasses. For the same reasons, the effort limitation scenario is the most prone to higher levels of exploitation among all the presented policies. However, we cannot provide sufficient policy indications by only showing the final year of the optimization, knowing that small pelagic biomasses do not grow steadily and tend to fluctuate over time. A comprehensive understanding of every scenario will therefore require us to look at the results for every year of our optimal solution.

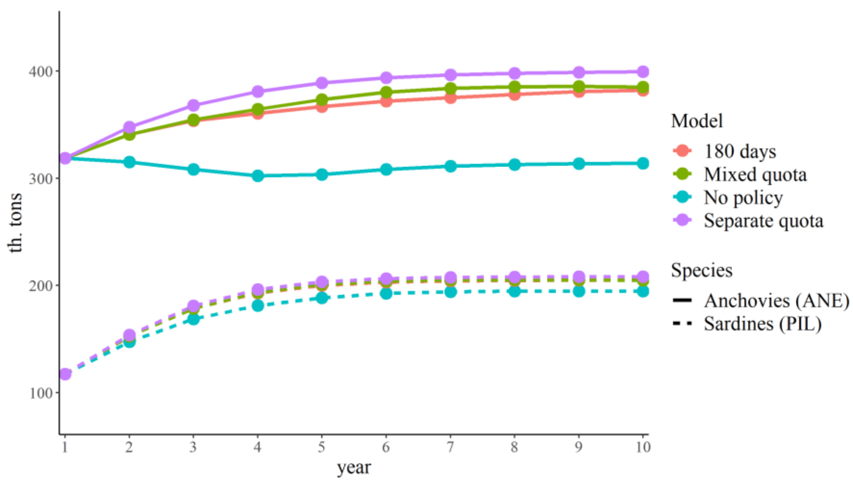

Figure 1. Long-run biomass levels (thousand tons)

Figure 1 offers a graphical representation of the biomass trend 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 possible values among all the selected scenarios in the shortest amount of time. Figure 1 clearly shows that policy management is effective from a biological perspective as, in the no-policy scenario, both stocks achieve lower (or even decreasing)

[11] Our optimal search is not global, which means that we could end up in a basin of attraction. 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.

biomass levels in the long run. On the contrary, under any policy scenario, both stocks steadily increase until the final year. The anchovy biomass curve is almost double the amount represented by the sardine curve as anchovies are the most abundant species on the Italian side of the Adriatic. The difference between the amounts of the two stocks is more pronounced for the separate-quotas scenarios, which implies that anchovies are the most targeted species when the enforced policies are less restrictive.

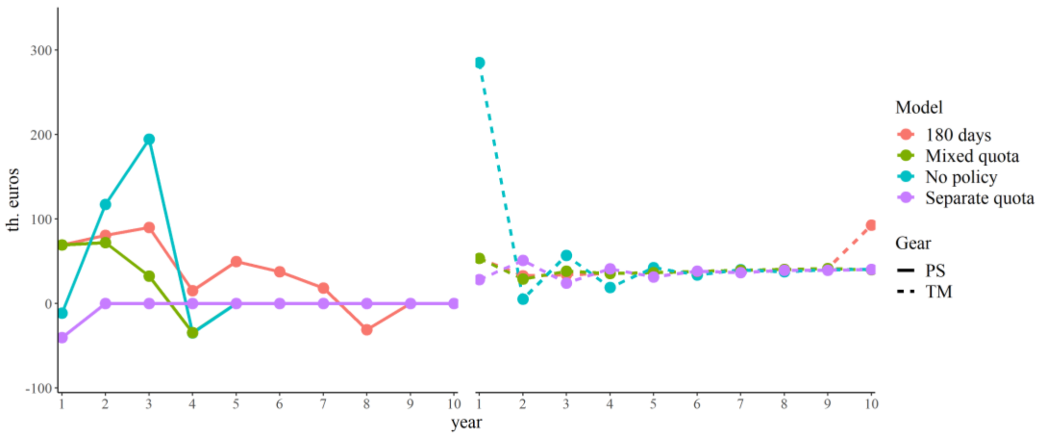

Figure 2. Long-run profit levels (thousand euros per vessel)

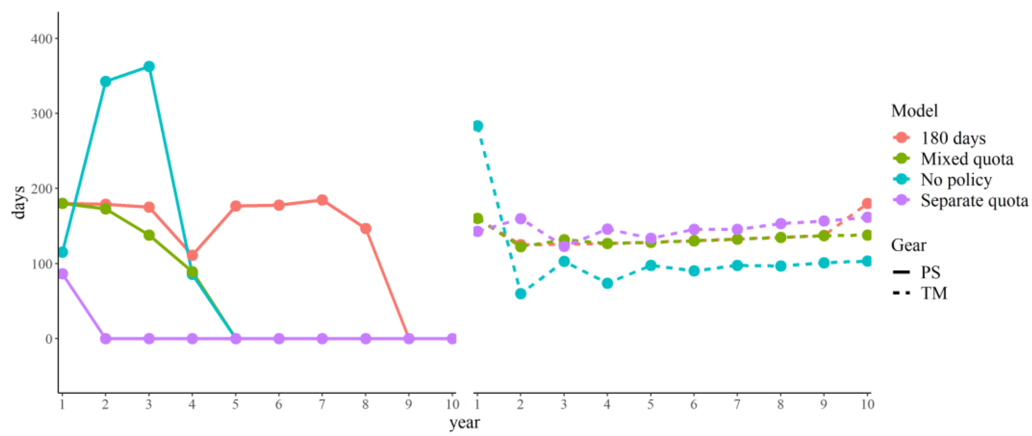

Figure 3. Long-run effort levels (fishing days per vessel)

The yearly discounted profits per vessel are reported in Figure 2, while the yearly fishing days per vessel are represented in Figure 3. Both figures show that the net present value of the benefits between the two operating fishing gears is unevenly spread among the fishing fleet as most of the profits are made by TM vessels. Our results show that PS vessels will shortly exit the small pelagic fishery even under MEY management. Within a time span of 10 years, such vessels will either be inactive or have to start harvesting a greater amount of non-small pelagic species. Depending on the implemented policies, PSs will stop harvesting during the final stages of the optimization period (see the no-policy and effort limitation scenarios), in the middle of such a period (see the mixed quota scenario), or at the very beginning (see the separate quotas management scenario). We acknowledge that 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 keep them actively operating in the market, 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. Overall, the no-policy scenario would grant them more profits, but those would be unevenly distributed across the entire period. The policy management approaches could grant them a steadier yearly net present value of profits per vessel. TM vessels would still be able to make profits under the quota scenarios, albeit in a slightly lower amount than under the no-policy or effort limitation policies[12]. The main differences between PS and TM outcomes are due to the calibrating parameters: PS vessels deal with higher costs and a lower efficiency value in harvesting the most profitable species.

One interesting finding is related to the number of yearly fishing days: when any policy is implemented, they are severely constrained up to 180 days per vessel per year. Nevertheless, the operating vessels (TM) do not need to use all those days to maximize their profits over time. Instead, they maximize their profits by using around 150 yearly fishing days per vessel or even less in all the scenarios (including the no-policy one, in which the constraint of no fishing days is present).

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

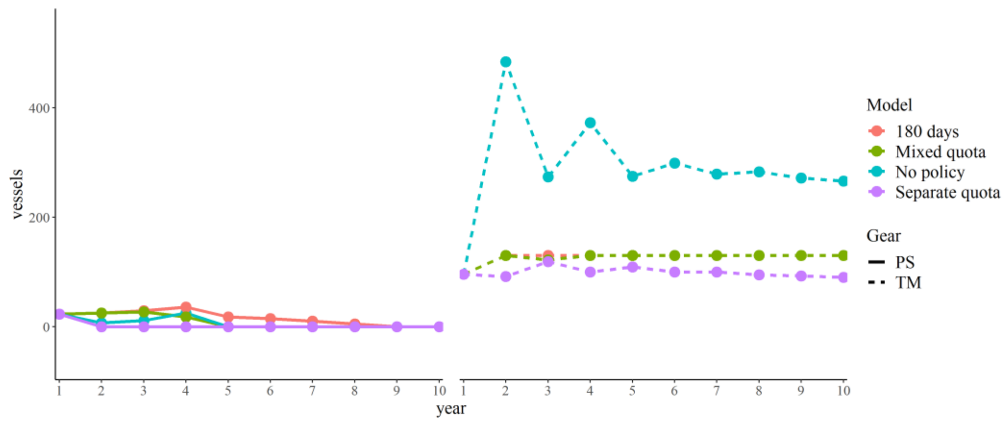

Figure 4. Yearly number of vessels

The number of vessels (Figure 4) is also affected by the selected policies. The more restrictive the policy, the faster PS vessels will exit the small pelagic fishery. Note that the number of vessels is bounded above in all the policy scenarios. The number of TM vessels operating is very close or equal to their fixed upper bound in the effort limitation and the mixed-quota scenario, but it never approaches that limit in the separate-quotas scenario as the aggregated profits are not enough to justify the same vessel increase of the other policies. The number of vessels in the no-policy scenario is not bounded above and results in high fluctuations. We acknowledge that similar fluctuations are not completely realistic as the number of vessels cannot suddenly vary in a single year. Such abrupt oscillations are due to not having 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. This unrealistic assumption affects the reliability of the no-policy scenario. While we remain extremely cautious in interpreting this result, we also point out that an increase in the number of vessels and, consequently, in the fishing mortality is likely to happen if policies are not enforced to prevent it.

The model results are consistent with the current fishing conditions: as of 2022, trawler vessels constitute most of the fishing fleet (104), while purse seiners are in the minority (22). However, it is difficult to disentangle the effect of the harvest quotas adopted in the last two years from that of the pandemic, which has severely impacted the sector as in 2020, the catches of anchovies and sardines decreased, reaching an all-time low for anchovies on the Italian side (SAC, 2022).

The current revenue/break-even point (CR/BEP) ratio is estimated to compare the economic statuses of the two fleets by using a profitability indicator. The CR/BEP ratio 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/BEP value greater than 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/BEP is computed as follows:

$$CR/BEP_{j,t} = \frac{F_{j,t}}{1 - \left(V_{j,t}/R_{j,t}\right)} \tag{18}$$

We use a traffic light approach to report the CR/BEP results in Table 6 following Maiorano et al. (2019).

Table 6. CR/BER performance in different scenarios

	No policy		**Effort limitation**		**Mixed quota**		**Separate quotas**	
Year	**PS**	**TM**	**PS**	**TM**	**PS**	**TM**	**PS**	**TM**
1	>1	>1	>1	>1	>1	>1	<1	>1
2	>1	>1	>1	>1	>1	>1	<0	>1
3	>1	>1	>1	>1	>1	>1	<0	>1
4	>1	>1	>1	>1	>1	>1	<0	>1
5	<0	>1	>1	>1	<0	>1	<0	>1
6	<0	>1	>1	>1	<0	>1	<0	>1
7	<0	>1	>1	>1	<0	>1	<0	>1
8	<0	>1	<1	>1	<0	>1	<0	>1
9	>1	>1	<0	>1	<0	>1	<0	>1
10	<0	>1	<0	>1	<0	>1	<0	>1

The CR/BEP 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. Even under the no-policy scenario, PS vessels would struggle to remain profitable in the long run as their CR/BEP ratio would be negative in the second half of the optimization period.

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

Table 7. Lagrange multipliers in selected scenarios

	Mixed quota	Separate quotas	
Year		**Anchovies**	**Sardines**
1	1.5E-5	261.79	8.6E-6
2	1.4E-5	264.55	8.7E-6
3	1.4E-5	261.15	8.7E-6
4	1.4E-5	264.05	8.8E-6
5	1.3E-5	252.27	8.8E-6
6	1.4E-5	264.89	8.9E-6
7	1.2E-5	216.85	8.8E-6
8	1.7E-5	303.90	8.8E-6
9	1.3E-5	101.45	8.5E-6
10	1.0E-3	451.45	9.1E-6

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. In our case, 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 unit (ton). 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 small, meaning that a one unit increase in the quota threshold would only lead to a small increase in profits. This is reasonable as, with mixed-quota management, fishers are granted more flexibility in managing the harvested species (always according to their catch composition parameter and their efficiency).

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[13]. 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 in the long run. This result highlights the contrast between conflicting biological and economic policy targets and reinforces Hilborn's (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. We also identify the current management measures (mixed quotas) as a compromise between the above-mentioned policies from both an economic and a biological perspective. 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 is derived from Gordon (1954) and Schaefer (1954) and adapted to the case study area by considering two fishing gears and specific constraints to deal with the catch composition of the fishery. This approach allows us to decompose the economic effects of the policies between the two selected fishing gears. Indeed, we highlight how maximizing the overall profits of the fishery affects PSs and TMs in each policy scenario differently. PS vessels are overall more negatively affected by the proposed policy limitations, and more restrictive policies (quotas) are associated with low 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

[13] 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).

difference between the two fishing techniques may therefore lead to an unequitable distribution of the economic benefits within the fishery.

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. The biological framework can also be perfected and expanded to account for the potential interaction between the two species (Salenius et al., 2018), to improve the fitting of the growth function, and possibly to account for the marine environmental conditions, which could enhance 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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Appendix A. Estimation of the growth parameters (Logistic and Ricker curve comparison)

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

	Logistic		**Ricker**	
Param.	**Anchovies**	**Sardines**	**Anchovies**	**Sardines**
α	6.013e-01	9.196e-01	5.026e-01	6.629e-01
	(0.1083)	(0.0467)	(0.132)	(0.0181)
β	-1.193e-06	-3.130e-06	-1.148e-06	-2.978e-06
	(0.0678)	(0.0150)	(0.112)	(0.0128)

p-value between parenthesis

Note: The growth rate is $r = \alpha$, and the carrying capacity is $K = -\alpha/\beta$.

Appendix B. Estimation of the economic parameters

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

	Variable costs		Crew costs		Fixed costs		Fleet dynamic		Catch composition	
Param.	**PS**	**TM**	**PS**	**TM**	**PS**	**TM**	**PS**	**TM**	**PS**	**TM**
Cons			-2.4E5	7.9E5						
			(2.1E5)	(9.7E5)						
v_j	644***	802***								
	(86)	(33)								
c_j			0.46***	0.42***						
			(0.01)	(0.04)						
f_j					8.7E4***	7.5E4***				
					(6.9E3)	(2.6E3)				
φ_j							9.9E-6***	1.6E-5***		
							(1.4E-06)	(1.9E-06)		
w_j									0.24***	0.57***
									(0.09)	(0.04)

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

Appendix C. Estimation of the harvest parameters

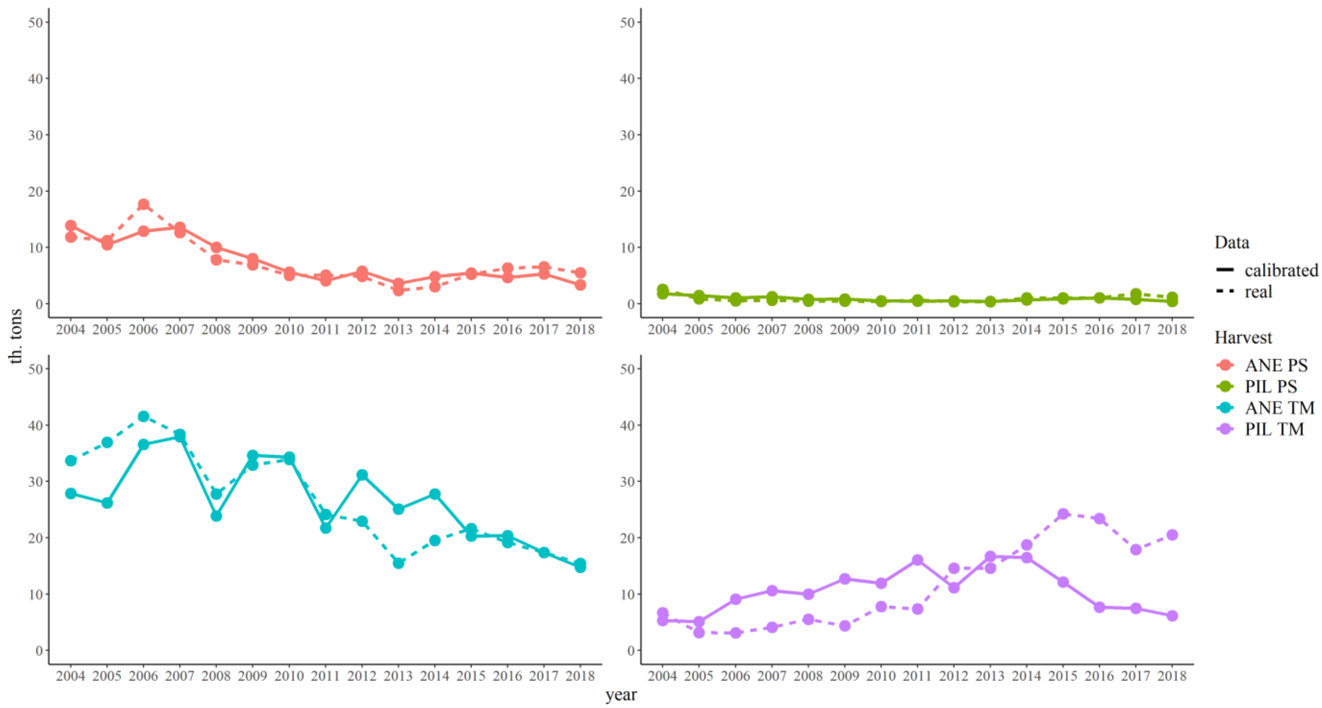

Figure C.1. – Harvest calibration vs real data

Estimation method: minimized NRMSE

Table C.1. Minimized NRMSE

NRMSE	PS	TM
ANE	0.12	0.21
PIL	0.23	0.39

3. Competing regulation of a common pool resource: an examination of the Adriatic small pelagic fishery

Abstract

Fisheries management is a critical topic especially due to the high rate of overexploitation of many fish stocks in the Mediterranean area. A greater understanding of the exploitation dynamics of fish stocks by various competitors may support the policy decision-making process as both the marine biological well-being and the economic interests of the fishing fleets are two main policy targets. This issue will be addressed by analyzing the small pelagic fish stocks in the Adriatic Sea through a bioeconomic model and a framework analysis based on game theory. Our main purpose is to analyze the fishing activity from an economic perspective. As small pelagics in this area are transboundary resources, we develop a profit maximization model for the Italian and Croatian fishing fleets to estimate their maximum economic yield accounting for their strategic interaction in non-cooperative games. In solving for the maximum economic yield under two different policy scenarios, we underline how the small pelagic fishery is inefficiently exploited from the economic perspective. With this work, we contribute to a more in-depth understanding of the small pelagic Adriatic fishery.

1. Introduction

Fish stocks' overexploitation is widespread and raises concerns regarding their availability and resilience in the long run (Colloca et al., 2017; Sumaila and Tai, 2020). Good governance and policy measures can help to prevent the extinction of marine species in an open-access condition and to ensure sustainable fishing over time (Ostrom, 2008). However, fisheries' objectives may be conflicting: biological, economic, social, and political goals do not always align (Hilborn, 2007) and might lead to controversies and prolonged debates on policy implementations.

Fisheries management becomes even more articulated in the case of transboundary stocks, where two or multiple countries or players compete to harvest the same resources. This is what happens to Italy and Croatia in the Adriatic Sea as both countries are simultaneously exploiting the small pelagic stocks of sardines (European pilchardus) and anchovies (Engraulis encrasicolus) and other species (Bastardie et al., 2014). Given the high number of countries involved in any fishing activity, transboundary stocks management is and will continue to be a crucial issue for policy makers (Liu and Molina, 2021).

As Italy and Croatia are EU member states, they need to abide to the Common Fishery Policy (CFP) measures. Since its establishment in 1983, the CFP and its following revisions[14] has been the main EU regulatory framework for fisheries management, while facing multiple criticism (Drouineau et al., 2023). The first CFP was mainly suited to managing the North Sea stocks. This top-down centralized management approach did not work for the mixed and multi-specific Mediterranean fisheries given the many intrinsic cultural, historical, and political differences in this area (Carpi et al., 2017). However, the subsequent attempt to increase the regionalization of the CFP have also not been completely successful, as Mediterranean stocks continue to be overexploited as opposed to the North EU Seas (Smith and Garcia, 2014; Froese et al., 2018).

The difficulties of achieving successful policy outcomes in the Mediterranean area also stems from the multiple overlapping advice from different international organizations. On one side, the General Fisheries Commission for the Mediterranean and Black Sea (GFCM) and its own Scientific Advisory Committee (SAC) regularly implements binding rules and recommendations to manage Mediterranean fisheries. On the other hand, the DG MARE and its Scientific, Technical and Economic Committee for Fisheries (STECF) try to do the same. Both authorities can provide management advice and evaluations, making difficult for policy makers and for stakeholders to properly coordinate on a clear and aligned vision (Cardinale et al., 2021).

In the Adriatic Sea, the interaction between EU and non-EU countries has also affected the management of the whole basin as the past instability of the Balkan area made difficult to achieve the right level of cooperation among the involved parties, at least not before Croatia entered the EU in 2013. The small pelagic fishery has since then been regulated by a series of GFCM recommendations. From Rec. GFCM/37/2013/1 small pelagic fishing in the Northern and Central Adriatic has been managed using input control and technical regulations including gear size, spatio-temporal closures, no fishing areas, capacity limits but most importantly effort limitations in terms of fishing days. More specifically, small pelagics could have been harvested using a maximum of

[14] Revisions occurred in 1992, 2002 and 2013.

180 days per vessel per year, with no more than 144 days targeting one species between sardines and anchovies. Subsequent GFCM recommendations reinforced and extended this limit to the Southern Adriatic. In 2016, Rec. GFCM/40/2016/3 established a total allowable catch limit equal to the 2014 levels, but this measure only enforced a business-as-usual scenario as the limit was too high to adequately reduce fish mortality (Carpi et al., 2017). The most recent GFCM recommendation continued to establish the transition towards output control measures. Rec. GFCM/44/2021/20 defined overall quota limits for small pelagic species at the country level starting from 2022. Following updates to the current policy scenario are expected as the final quota regime is meant to go towards single species catch limits in the coming years.

Management of small pelagic species in the Adriatic area has been quite articulated and complex. With the current measures tending towards an output-regulated fishery, the disagreement among fishers on both sides of the Adriatic and policy makers has sharpened. While the main goal of decision-makers is to achieve the MSY to avoid stock overexploitation, the main fishermen's goal is to maximize their profits. An exploratory analysis on transferable effort quotas for Italian fisheries (Mulazzani et al., 2018) outlined how fishers are rather reluctant to accept new management proposals and limitations, even though Adriatic stakeholders may be more prone to deal with additional policy measures in terms of fishing days restriction than Tyrrenian ones.

In this paper we look closely at the competition between Italy and Croatia for small pelagic stocks in the Adriatic Sea, including anchovies and sardines. More specifically, we use a bioeconomic model to understand if and how the strategic interaction between the two players leads to an equilibrium where both countries can maximize their profits. Our main objective is i) to understand how the strategic interaction between the two players leads to a steady state equilibrium without any policy implementation and, ii) to estimate the change in the equilibrium point due to the current total allowable catch (TAC) limit implementation. Such impacts are analyzed in terms of fishing effort (days)[15]. Equilibrium outcomes in the no-policy and the policy scenarios are illustrated and compared to additional results derived from the sensitivity analyses.

[15] Some studies (Mulazzani and Malorgio, 2013, Salenius, 2018) define effort as a combination of both fishing days and capacity (number of vessels, gross tonnage, fleet power). We defined effort only in terms of aggregate fishing days to provide clear and interpretable output in terms of the policy response exerted by the two fleets (also, fishing days are implicitly linked to the number of vessels). In this work, we consider fishing days as the key variable that affects the supply-side perspective of the fishery, as multiple limitations have already been imposed on the capacity of both fleets. Our model provides *ceteris paribus* solutions for the optimal value of fishing days, considering the fleet capacity

The small pelagic fishery in the Adriatic Sea is an interesting case study for multiple reasons. First, it embodies the concept of transboundary resources, as both sardines and anchovies are exploited by multiple countries such as Italy, Croatia and Slovenia[16]. Second, the two above-mentioned species represent about 90% of the small pelagic landings (STECF, 2018) only in the Northern Adriatic area that is, in the Geographical Sub-Area 17 (GSA 17). Third, Italian and Croatian landings of small pelagics in the GSA 17 represents more than 60% of the total landings by weight (FAO, 2018), making it one of the most relevant fisheries in the area.

In Italy anchovies have historically been the main target, while Croatia tends to catch sardines in a higher quantity (Carpi et al., 2017). The two countries have different market drivers behind their harvesting decisions: most of the Croatian small pelagic landings are used by the processing industry and in tuna farms, while they are usually sold fresh on the Italian market, with anchovies being the preferred species (STECF, 2018). However, in recent years the difference between sardines and anchovies' landings in Italy has narrowed. Additional differences between the two players are determined by their fleet composition: the Croatian fleet is constituted by purse seine vessels, and the Italian fleet is composed by mid-water pelagic pair trawl vessels for the most part and by a smaller number of purse seines.

Our bioeconomic model is defined at the basin level, including the Northern (GSA 17) and Southern (GSA 18) Adriatic Sea in our analysis for completeness, even though small pelagic landings in the GSA 18 are operated by Italy only and are not as high as in the GSA 17 (Maiorano et al., 2019).

This study contributes to fill the gap on research on the Adriatic small pelagic fisheries from a profit maximization perspective. We analyze the interaction between the two fleets at the aggregate level by mean of a surplus production model. Our work builds upon Mulazzani and Malorgio's (2013) model which previously defined the interaction between Italy and Croatia using a game theory framework comparing the open access equilibrium with the maximum economic yield point. We define a series of non-cooperative games using the maximum economic yield (MEY) scenario

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and additional factors as constant. Our maximum economic yield results are robust to other definitions of fishing effort: we did not find outcome differences when considering other indicators such as the product of the yearly average number of fishing days and the number of vessels/power /gross tonnage of the fleets.

[16] Even though harvests of sardines and anchovies from Slovenia are considered negligible if compared to the other players (STECF, 2018), therefore we did not include Slovenia in our analysis.

(no-policy scenario) from their existing framework. We provide an updated estimate of the MEY using more recent data and complement their work with the addition of a total allowable catch scenario.

The term "non-cooperative" does not refer to the mutual non-adherence of both countries to the GFCM policy system, but it rather refers to the mathematics underlying the optimization model. In a non-cooperative framework, both players involved seek to maximize their profits individually and separately, while in a cooperative model, the objective function is a combination of the profits from the two players. Although both countries are subject to the same policies, they are still competing for the same shared resource. The shared nature of the resource means that any increase in one country's harvest may potentially come at the expense of the other country's fishing opportunities.

Game theory can indeed support the analysis of strategic interaction. The main aim behind this approach is to determine the best response a player should have to the action taken by a competitor (Eatwell et al., 1989), assuming that all players are economically rational, and aim to maximize their payoffs. The main contributions in this field have been given by Nash, who defined the rationale behind non-cooperative (Nash, 1951) games, and they remain widely explored and have been extensively applied to fisheries management problems[17] (Bailey et al., 2010).

With this work, we aim to provide useful policy implications to interpret and define current and future applications of these measures. Additionally, we discuss the log-run distribution of the impacts deriving from such policies between the two players. An important assumption behind our study is that both countries maximize their profits in the long run achieving their maximum economic yield. With this in mind, we define a first-best scenario (no policy, unconstrained) and a second-best scenario (with quotas, constrained). In comparing them by mean of a graphical tool, we provide information on how to manage the potential response of the two players to the policy constraints.

Previous studies on quota application in the Adriatic (Mulazzani and Malorgio, 2013a) have mostly focused on the Italian fleet because of data availability without considering the Italian effort as a reaction to the Croatian one. Findings highlighted how quota management may have a different

[17] See Mulazzani and Malorgio (2013) and, more recently, Salenius (2018) or Mullon and Mullon (2018).

impact on profitability and discards: if harvests of the most valuable species are constrained the impact is not expected to be significant and vice versa.

This article is organized as follows: the case study description and the methodology are presented in Section 2; Section 3 briefly discuss the model approach and Section 4 includes the results. Conclusions and policy implications are discussed in Section 5.

2. Materials and methods

2.1 Data overview

Our model relies on the biological data from the General Fisheries Commission for the Mediterranean (GFCM). More specifically, we use the stock assessment estimates defined by the Scientific Advisory Committee (SAC). We use data from the 2019 stock assessment, which provides biomass estimates up to 2019[18]. Biomass data are collected by mean of acoustic surveys in the western and eastern part of the Adriatic. The main objectives of this data collection methods are to get biological data and parameters to develop yearly stock assessments of the targeted species to estimate their abundance and well-being. Data collected in the GSA 17 and 18 followed a shared collection protocol among the multiple countries bordering the Adriatic Sea and were later combined to estimate the harmonized stock assessment for the whole area.

Biomass values for anchovies have halved over the last 10 years, while sardine's biomass has increased overall. However, given the low levels of spawning stock biomass and the increased fishing mortality in the last years, both stocks are still considered as overfished (Maiorano et al., 2019). Confidence intervals represented in Figure 1 derive from the stock assessment data, as they provide mean, low, and high biomass assessments from the acoustic surveys' data collection and analysis. We use the mean biomass values in our main analysis, and we include the low and high values in our sensitivity analysis.

[18] As sardines' biomass estimates are provided starting from 2000, we delimit our analysis of anchovies' data to the same period for comparison.

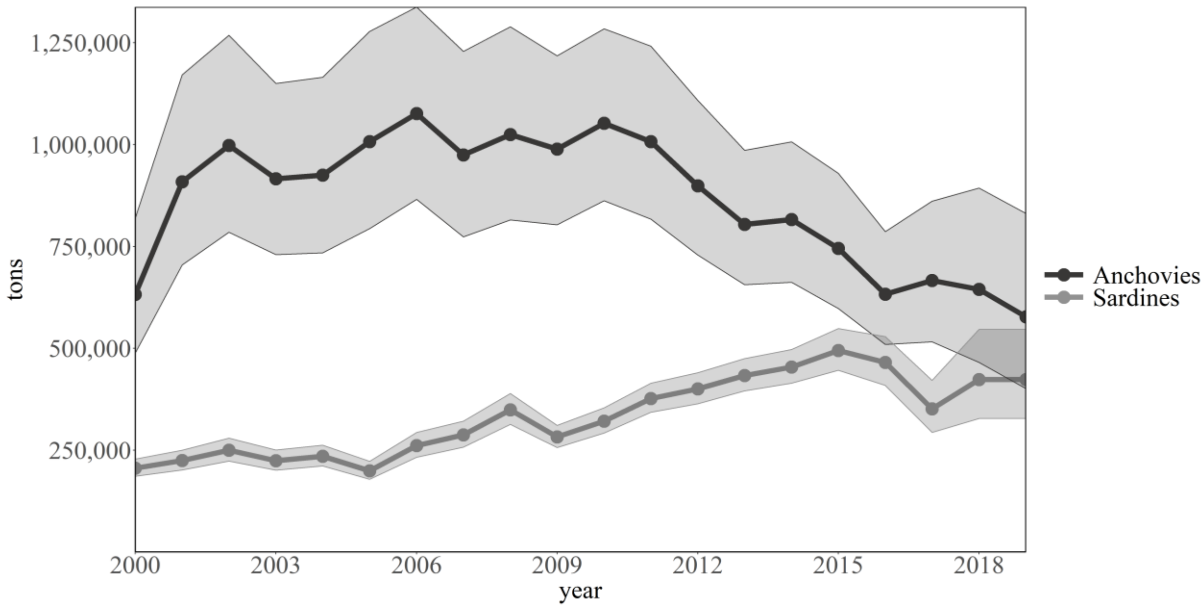

Figure 1 – Biomass historic trajectory. Source: GFCM

Economic data are retrieved by the EU Scientific, Technical and Economic Committee for Fisheries (STECF) database for Croatia and from the National Fisheries Data Collection Program for Italy and it is used at the aggregated GSA level (data on individual vessels are not available). Complete data for Croatia are available since 2014 (following its EU official entrance in 2013) up to 2020[19] (6 years) and data for Italy are used from 2004 up to 2018 (15 years). We acknowledge that the short data series may limit the goodness of estimation of the model parameters', but limited or short time series data have been previously used in parameter's estimation (e.g., see Ekerhovd and Steinshamn, 2016). Previous studies on the Adriatic area could not rely on real data for Croatia (Mulazzani and Malorgio, 2013) and had to rely on many assumptions to numerically implement their analysis. Therefore, despite its data limitations, our study provides an up-to-date estimate attempt of the Croatian fishery economic parameters. Key interest variables include value of production (income from landings), variable costs (mainly crew and energy costs) and fixed costs (such as maintenance and repair costs). Yearly capital depreciation costs are also provided and used in estimating the net profits. Subsidies and non-landing revenues are not used in this study as they can be considered negligible (Maiorano et al., 2019).

[19] In most of our estimation we will use data until 2019 because biomass values for 2020 are not available.

Figure 2 compares the number of vessels and of aggregate fishing effort (days) in Italy and Croatia. We notice that there are some magnitude differences as Croatia seems to exert effort levels, also due to its higher number of vessels. However, both countries have gone through a decrease in the amount of aggregate fishing days since 2013 intuitively following the GFCM Recommendation measures, even if the Italian data seem to suggest that the decreasing trend precedes the GFCM regulatory framework imposed on the Adriatic basin.

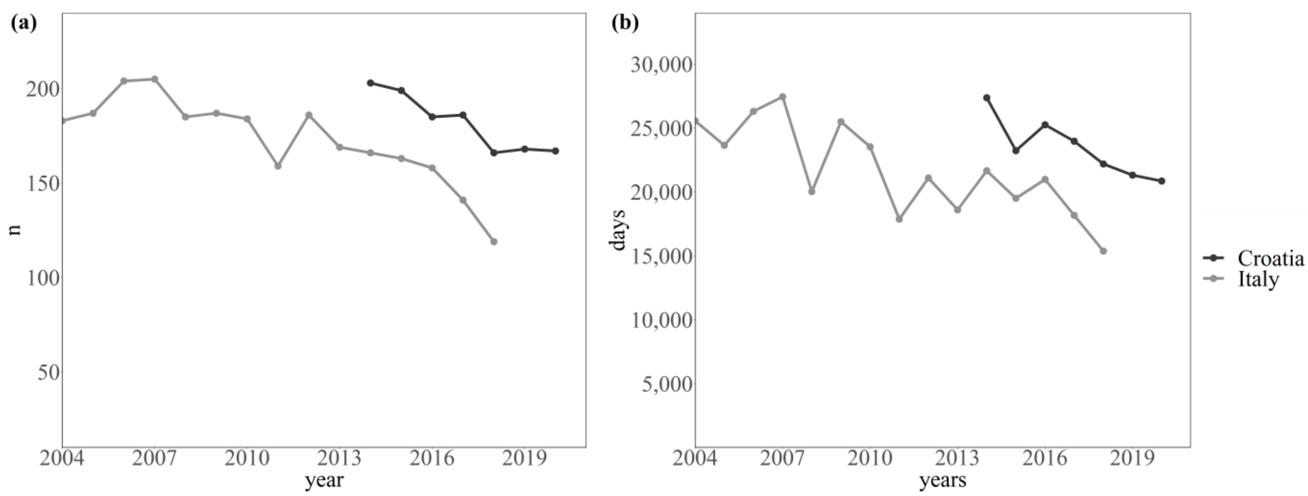

Figure 2 – Number of vessel (a) and aggregate fishing days (b) by country. Source: STECF

The available data underline a high price variability by species and by country: the average ex-vessel anchovies' price for 2017-18 was 1.70 €/kg for Italy and 0.89 €/kg for Croatia, while the average price for sardines was 0.70 €/kg for Italy and 0.40 €/kg for Croatia. This indicates that overall anchovies are the most valuable species on the market. The price difference could be explained by the final destination of the landed products, as in Italy small pelagics are mostly consumed fresh, while in Croatia it is destined to the processing industry or to tuna farms (STECF, 18). The lower Croatian prices may be one of the reasons behind the lower profitability of the Croatian fleet in the last years: computing the ration between current revenues and the breakeven point revenues (CR/BER), Croatian values are lower than the Italian ones.

Figure 3 highlights a structural difference regarding landings' composition. Anchovies have historically been Italy's main target until 2013, when the quantity landed of the two species almost evened out. On the contrary, Croatia mostly harvests sardines.

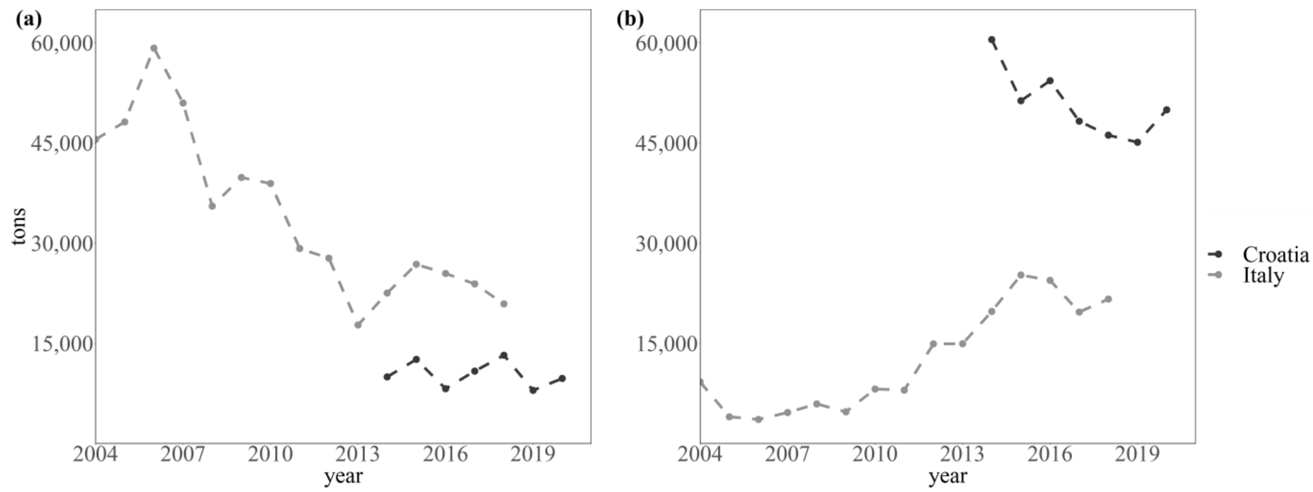

Figure 3 – Anchovies (a) and sardines (b) catches by country. Source: STECF

We exclusively consider small pelagic catches as they are the main targets in both countries. Mulazzani and Malorgio (2013) defined a specific coefficient and functional form to account for bycatches. However, our data indicates that, on average, more than 90% of total landings and total harvested value for the fishing gears included in the analysis (purse seines and mid-water pelagic pair trawls) referred to sardines and anchovies, therefore we do not include non-targeted species in our model as they are not the main focus of our analysis. Because of this assumption, we redistribute the harvesting costs according to the percentage of the landed value on total revenues.

2.2 Model

Our model is a steady-state equilibrium model. We therefore estimate the long-term Nash equilibrium point between the two fleets and cannot make any comment on the optimal trajectory the two players would need to follow to achieve their profit maximization goal. Other studies have explored dynamic MEY or MSY (Grafton et al., 2010; Holma et al., 2019) even in a game theory context (Salenius, 2018).

For the same reasons, we purposely avoid making in-depth considerations on the biological evolution trajectory of the small pelagics' stocks. The biological perspective of the fishery is carefully included in our model[20], but only at the aggregate level. Therefore, our model does not allow us to make detailed comments on the biological state of fish stocks.

We use a logistic functional form to describe stock growth (Schaefer, 1954):

$$B_{t+1} = B_t + rB_t(1 - B_t/K) - H_t \tag{1}$$

Where the subscript t indicates time, B represents the biomass, H is the total quantity harvested by both countries, and r and K are the intrinsic growth rate and the carrying capacity of the species respectively. Details on parameters estimations are described in the Appendix A. We acknowledge that small pelagic stock fluctuations can be affected by climate and additional biological features (Checkley et al., 2017). However, we do not consider these aspects in our growth model mainly because of data limitations.

Harvests H_t are also modeled following the Schaefer (1954) approach:

$$H_t = qB_tE_t \tag{2}$$

Where E_t is the aggregate number of fishing days. The q parameter is the catchability coefficient for the harvested species and indicates the efficiency of the fleet. Estimates of the catchability coefficients are be provided by species and by country in the Appendix A.

We use Gordon's (1954) approach to estimate the cost parameter c also used by Mulazzani and Malorgio (2013), where total costs C_t are proportional to the Italian fishing effort:

$$C_t = cE_t \tag{3}$$

As our model analyze the steady-state equilibrium in the long run, we do not distinguish between variable and fixed costs. Total costs include fuel, crew, maintenance, repair, depreciation and other variable or fixed costs. See Appendix A for detailed estimation results.

[20] See Appendix B for details on how the growth function has been incorporated into our model.

Price parameters p are also taken as exogenous and are computed using the mean ex-vessel price by species and by country using the last two years of data available[21].

We identify two optimization scenarios: a no-policy (MEY) unconstrained model, and a quota-based one which accounts for the imposition of total allowable catches (TAC) at the country level. Our goal is to maximize the net profits of the two players π in a series of non-cooperative games. The no-policy model takes the following specification:

$$\max \pi \tag{4}$$

While the quota scenario is written as a constrained optimization model:

$$\max \pi\,, \quad subject\ to\ H \leq TAC \tag{5}$$

3. Calculation

Net profits π are defined as the difference between revenues from landings R and total costs C. Profits are defined at the aggregated country level. For instance, profits for country i are:

$$\pi_i = R_i - C_i = p_{ai}(a_{ai}E_i - b_{ai}E_i^2 - d_aE_iE_c) + p_{pi}\left(a_{pi}E_i - b_{pi}E_i^2 - d_pE_iE_c\right) - c_iE_i \tag{6}$$

where subscripts a and p indicate the two exploited species, $a_{ai} = q_{ai}K_a$, $b_{ai} = \frac{q_{ai}^2K_a}{r_a}$, $d_a = \frac{q_{ai}q_{ac}K_a}{r_a}$, $a_{pi} = q_{pi}K_p$, $b_{pi} = \frac{q_{pi}^2K_p}{r_p}$ and $d_p = \frac{q_{pi}q_{pc}K_p}{r_p}$. A detailed specification of the profit equation is illustrated in Appendix B.

In the unconstrained model, the reaction function of country i is defined by taking the derivative of π_i with respect to E_i and equating it to 0 as indicated by Mulazzani and Malorgio (2013) As a result, we get:

[21] 2016-2018 for Italy, 2018-2020 for Croatia. We checked for any difference in Croatia mean prices by considering the 2018-2019 years to exclude the pandemic period, but there were no differences in price values, therefore we decided to use the most recent data available.

$$E_i = \frac{-(p_{ai}d_a + p_{pi}d_p)E_c + p_{ai}a_{ai} + p_{pi}a_{pi} - c_i}{2(p_{ai}b_{ai} + p_{pi}b_{pi})} \tag{7}$$

In the quota scenario we derived, the reaction function for country i are:

$$E_i = \frac{-(p_{ai}d_a + p_{pi}d_p - \lambda_i d_a - \lambda_i d_p)E_c + p_{ai}a_{ai} + p_{pi}a_{pi} - \lambda_i a_{ai} - \lambda_i a_{pi} - c_i}{2(p_{ai}b_{ai} + p_{pi}b_{pi} - \lambda_i b_{ai} - \lambda_i b_{pi})} \tag{8}$$

where λ_i is the Lagrange multiplier[22] of the optimization problem which shifts the reaction curves. Analytical details are provided in Appendix C. Quotas are established at the country level according to the EU Regulation 2022/110[23] (35,394 and 56,304 tons for Italy and Croatia respectively). Results are provided as a graphical representation of the steady state equilibrium for both countries. More specifically, we represent the reaction functions of both fleets to define their intersection point. The intersection between the reaction curves indicates the Nash equilibrium, that is, the point at which both countries are simultaneously maximizing their profits.

4. Results and discussion

4.1 Exogenous parameters

Table 1 summarizes the estimated exogenous parameters that are included in the optimization model. Additional details on parameters' estimation are provided in Appendix A. We can see how sardines and anchovies present different estimates for the growth rate and the carrying capacity. The intrinsic growth rate for sardines is higher than the anchovies' growth rate, but their carrying capacity is overall smaller, which is consistent with anchovies historically being the most abundant species. The catchability coefficient varies between the different species and countries. Croatia has a greater sardine's coefficient, which means that the Croatian fleet is overall more efficient at targeting sardines. On the contrary, the Italian fleet is more efficient at targeting anchovies. These

[22] To provide a numerical and graphical representation of our results, we empirically estimate the multipliers for our problems (including the sensitivity analysis) by using the fmincon routine in MATLAB.

[23] The Regulation is no longer in force and a new proposal on fishing opportunities and limit in the Mediterranean and Black Sea was drafted in October 2022. The proposed quota limits for Italy and Croatia are slightly lowered but they are overall consistent with the previous ones hence our results are still reliable and reflective of the current fishing conditions.

outcomes met our expectations and are overall consistent with similar studies (Mulazzani and Malorgio, 2013). The cost per unit of effort is higher in Italy. This is also consistent with previous studies. We hypothesize that the cost difference it is due to the most recent renewal of the Croatian fleet (Carpi et al., 2017). The mean price for both species is higher in Italy as outlined by the STECF (2018). Anchovies are sold at a much higher price than sardines in both countries, as they are considered the most profitable species.

Table 1 – Parameter's description and values

Symbol	**Description**	**Anchovies**	**Sardines**
r	Intrinsic growth rate	0.18	0.26
K	Carrying capacity	886,964.9	413,382.7
q_{italy}	Catchability (Italy)	3.3e-6	2.5e-6
$q_{croatia}$	Catchability (Croatia)	5.4e-6	7.6e-6
c_{italy}	Cost per unit of effort	1884.37	
$c_{croatia}$	Cost per unit of effort	1134.40	
p_{italy}	Mean price (€/ton)	1626.37	675.94
$p_{croatia}$	Mean price (€/ton)	906.11	433.96

4.2 Optimization results

Results provide a ceteris paribus comparison of the optimal value of fishing days, considering every other factor as constant. Figure 4 shows the reaction curves for both countries under the maximum economic yield scenario. The intersection between the reaction curves can be defined as the Nash equilibrium, that is, the point at which both fleets are maximizing their profits as a response to the level of effort exerted by their direct competitor. The equilibrium point is appropriately labeled in the figure, and a comparison with the current level of effort is graphically provided.

Figure 4 clearly indicates how the current effort for Croatia is way higher than the optimal level of effort under the maximum economic yield and the quota scenario. More precisely, Croatia is currently exerting double the amount of the required effort for profit maximization. The difference between the current and optimal maximum economic yield effort for Italy is less pronounced but still visible.

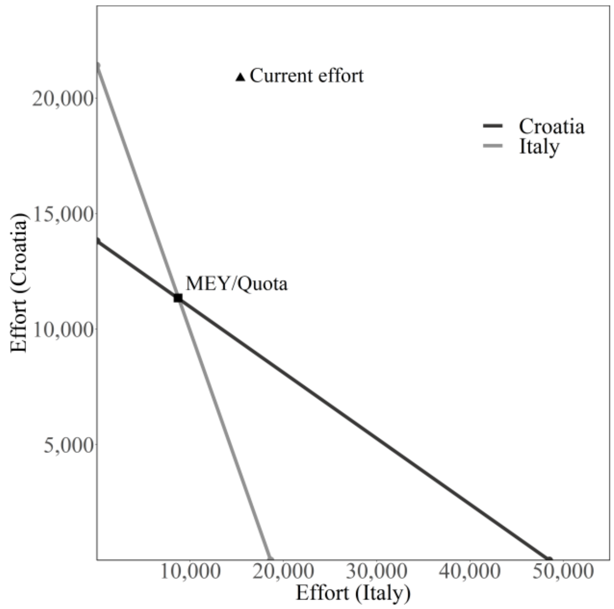

Figure 4 – Equilibrium solutions for the MEY and the quota scenarios

Values of the current and optimal level of effort in terms of fishing days are provided in Table 2.

Table 2 – Optimal effort values (days) and profit margins by country

Policy	**Country**	**Effort**	**Profit margin**
Current*	Italy	15,379	0.25
	Croatia	20,861	0.02
MEY/Quota	Italy	9,376	0.32
	Croatia	10,635	0.62

*Using the most recent data point available

We can refer to the maximum economic yield solution as the first-best equilibrium, as there is no constraint applied to the optimization model. On the contrary, the quota equilibrium represents the second-best optimization point. When the quota constraint is binding, results of our model should clearly indicate a shift downwards of both reaction curves and would therefore require a fishing days reduction from both players to achieve maximum profitability. However, our results do not show a consistent distinction between the first and the second-best steady states, as the maximum economic yield equilibrium and the quota equilibrium are achieved at the same level of effort. In other words, the imposed quota constraint is not binding: if the two countries decide to simultaneously adopt a profit maximization strategy, their small pelagic harvest level would be lower than the established total allowable catch limit.

In comparing the solutions for the two countries we can notice how Croatian optimal days' quantity is always higher than the Italian one. We attribute this result to a combined effect of the difference in the catchability and the cost coefficients of the two countries: Croatia has a higher catchability and a lower daily cost per unit of effort than Italy, which clearly indicates a higher potential to maximize profits in the long run. The difference in prices between the two players is not enough to offset the Croatian advantage.

Table 2 also compares the profit margin for the two countries. We use the profit margin as an indicator for profitability instead than the most used ratio between the current revenues and the break-even point revenues because that requires a differentiation between fixed and variable costs and, in our framework, we do not differentiate between them as all costs are considered variable in the long run. Any profit margin lower than 0 is considered non-profitable, while any value greater than 0.10 is considered a profitable indicator for the fleet. As illustrated in Table 2, the first-best condition would lead to an improved long-run profitability with respect to the current effort levels, particularly for Croatia, whose recent data indicate non-profitability.

Table 3 – Optimal harvests (tons)

Policy	Country	Anchovies	Sardines
Current*	Italy	20,928.9	21,657.3
	Croatia	9,773.4	49,992.1
MEY/Quota	Italy	13,657.1	5,728.9
	Croatia	25,460.8	20,021.5

*Using the most recent data point available

Table 3 summarizes total harvests by country and by species. Current harvests are beyond the established quota limits as graphically represented in Figure 5. However, the total allowable catch limit is also higher than the optimal harvest quantity. We easily note how under the maximum economic yield effort anchovies would be the preferred harvested species in both countries given their higher value on the market.

Besides the biological exploitation of the anchovies and sardines' stocks, this result indicates that the Adriatic small pelagic fishery is not efficient, and its economic returns are not maximized. There is, however, still potential to correct for this inefficiency by redesigning the current management policies to adequately restrict the economic exploitation levels of the fishery.

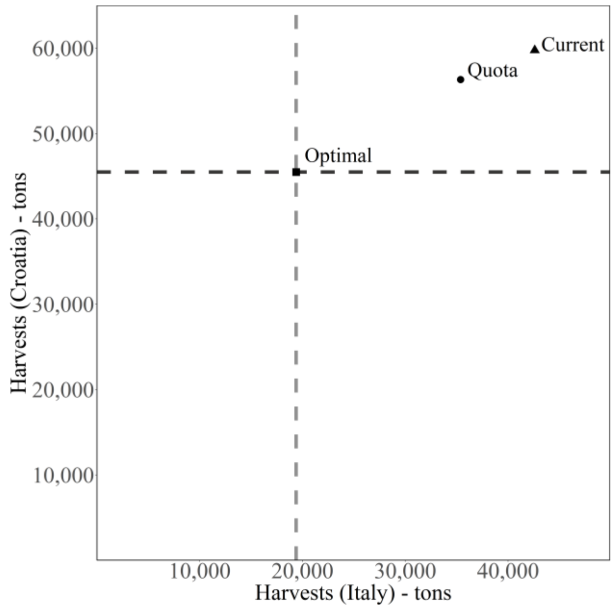

Figure 5 – Steady-state harvest comparison

Our findings are aligned with previous empirical research on the case study area. Mulazzani and Malorgio (2013) also highlighted the inefficiency of the fishing fleets particularly for Croatia, which was already operating beyond maximum economic yield equilibrium point at the time they carried on their study.

The results reported in Table 3 provide further policy implications regarding the potential evolution of fishing restriction measures aimed at implementing separate quotas. With mixed quotas, the quantity of small pelagic fish caught is calculated based on the combined total of sardines and anchovies, while separate quotas would impose specific limits for each of the two species. Assuming that the quotas for both countries used in this study (35,394 and 56,304 tons for Italy and Croatia, respectively) could be roughly halved, with each half attributed equally to sardines and anchovies (17,697 for Italy and 28,152 for Croatia), these quantities would still not be restrictive for either country, as the optimal catch quantities presented in Table 3 are lower. However, it is most likely than separated quotas would entail different threshold values according to the historical landing of each country. In this case, Croatia could be granted a higher quota for sardines and Italy could be assigned a higher one for anchovies. However, separate quotas should be carefully approached to avoid an increase in discarding of the less valuable species in favor of targeting the more valuable one. This could potentially be achieved by complementing the system of national quotas with individual quotas and/or transferable fishing permits.

4.3 Sensitivity analysis

We use different sets of biological and economic parameters to calculate the strategic optimal effort level of both fleets. Complete results are reported in Appendix D. Our alternative model configurations include biological parameters estimated by using the higher and lower GFCM biomass estimates, a simultaneous cost reduction (– 40 %) for both players and a single cost reduction for one country at a time (– 40%). The results are sensitive to the different ecosystem and economic structures: quotas can be effectively binding only if both species are considered abundant (high biomass) and never binding in the other scenarios, which reinforces our main conclusions that the current policies are not economically efficient. A reduction of harvesting cost would benefit the Italian fleet more as their current costs are already significantly higher than Croatia and would allow Italy to operate around the maximum efficiency levels. On the contrary, Croatia is already operating beyond its optimal effort limit and a cost reduction would place further distance between the country's effort and its economically efficient equilibrium.

5. Discussion and conclusions

Our work provides a revised perspective on achieving the maximum economic yield in the Adriatic small pelagic fishery under competitive settings. Results outline how there is no difference between the unconstrained and the constrained maximum economic yield in the long run, which indicates how the current total allowable catch limit is not binding for both countries. The economic performance of both countries could potentially be improved by either adjusting the quota limits towards a more efficient exploitation level or by reinforcing the existing measures on effort limitations. Our outcomes highlight that the quota or effort reduction could particularly benefit the Croatian small pelagic fleet, as Italy is operating closer to the steady state equilibrium.

Our results align with previous analytical studies by Mulazzani and Malorgio (2013), who also outlined how the Croatian effort is disproportionate to its current levels. In addition to that, we underline how the optimal levels of effort for both Italy and Croatia being significantly lower than the current ones indicates a reiterated overexploitation pattern of the current fishery which has been ongoing from years despite the multiple GFCM Recommendations. There are also multiple differences between the two countries in terms of their efficiency levels, with Croatia being overall more efficient than Italy, possibly because of its most recent fleet renovation (Carpi et al., 2017). This affects the steady state equilibrium allowing Croatia to harvest overall for ah higher number of days than Italy.

We argue that the fishery is not efficiently exploited. The current quota limits are still very high and do not call for an appropriate effort reduction, which would consequently increase the profitability of both players in the long run. An adequate revision of those limits could therefore be beneficial to the fishery not only from an economic perspective, but also in terms of reduced aggregated fishing mortality. The main challenge behind future revisions and implementation of harvesting policies in the Adriatic Sea will be to effectively coordinate the multiple stakeholders involved in the policy-definition process, who notoriously have different and sometimes contrasting policy objectives and goals (Hilborn, 2007). Given that our model only provides the steady-state optimal amount of aggregate fishing days, an additional effort would be needed to ease the transition from the current to the optimal exploitation levels minimizing the economic losses throughout the intermediate time period when the less efficient vessels could potentially and progressively leave the fishery. Replacing aggregated quota limits with transferable quota limits could be a viable option to facilitate this process from an economic perspective. However, Lucchetti et al. (2014) have previously indicated that transferable quota management may not be fully or easily accepted by fishermen operating in the Mediterranean Sea, as they can cause some vessels (most likely the smaller ones) to disappear. Mulazzani et al. (2018) have assessed the viability of transferable effort quotas as an alternative policy option, but also acknowledged the need for extra policy coordination and transferability restrictions to prevent quota accumulation in favor of bigger fishing enterprises (Mulazzani et al., 2013). In the Adriatic area, policymakers would face the additional issues of dealing with a transboundary resource, where the two main exploiting countries have different economic specificities and preferences.

The optimization model proposed here is static, and the calculated equilibrium provides a long-term solution considering constant prices for both species over time. However, it is reasonable to expect that these prices may undergo variations over time as a consequence of the decrease in fishing effort towards an economically efficient exploitation level. The level of price variation depends on the markets of the countries involved and their trading partners. Previous work

(Mulazzani et al., 2013; STECF, 2018) suggests that Croatian harvests are mostly destined to processed industries and tuna farms, while Italian ones are sold as fresh products on the market. Additionally, both countries have historically been net exporters of anchovies towards Spain which is a net importer. The optimal outcome suggested by our model indicates that both Italy and Croatia would suffer a severe reduction of small pelagic harvests in the long run. On the Italian side, harvests would undergo a percentage decrease of approximately 35% and 70% for anchovies and sardines respectively. On the Croatian side, harvests would increase by roughly 160% for anchovies and decrease by 60% for sardines. The Italian market would therefore experience a decrease in the quantity of fresh products available. Prices of such products could increase due to their scarcity, and being able to satisfy the internal demand for fresh products could require Italy to become a net importer of small pelagics (mostly anchovies). Croatia would experience a significant decrease in the harvest of sardines, which are currently their main targeted species. However, they would harvest more anchovies, which can be sold domestically and traded internationally to traditional importers such as Spain, and potentially new importers like Italy, at a higher price. The internal demand for sardines could also be satisfied importing such products from other EU exporters such as Portugal (EUMOFA, 2017). The magnitude of such price increases should be further investigated in future research as it will depend on the response of foreign markets and the long-term availability of their small pelagic stocks.

There are two main limitations of this study. The first one resides in the data aggregation level: as individual vessel data is not publicly available, we cannot infer any conclusion on how the optimal exploitation level will affect the members of the fleet, and more studies on the distribution of the economic benefits need to be carried out to determine whether such impacts may unevenly affect different vessels.

The second one resides in the definition of the catch composition of the involved countries: our results suggest that Croatia is inefficiently harvesting more sardines than anchovies as the latter have a higher market value and should therefore be more targeted. This result does not consider any market preference for the above-mentioned species, and there may be one or more market reasons why anchovies constitute a lower proportion of Croatian small pelagic harvests. In this work, we only take the mean price as a proxy of market preference and do not investigate this condition further, which may result in a different economic equilibrium point. However, current data have shown that the current Croatian levels of exploitation are not economically viable and should go towards a reduction for the fleet to increase their economic benefits, which is still consistent with our results.

Further research on these topics should be encouraged, possibly disentangling the effects of achieving the maximum economic yield at the fleet segment or even vessel level and investigating more the economic benefits stemming from transferable quotas.

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Appendix A. Estimation of the growth and economic parameters

Growth parameters have been estimating according to the following approach. First, we linearize the logistic equation, which becomes:

$$B_{t+1} - B_t + H_t = \alpha B_t + \beta B_t^2 \qquad (1a)$$

Where α and β are parameters such that $r = \alpha$ and $K = -\alpha/\beta$. We then use the ordinary least squares (OLS) method to derive the parameters. We also applied the Newey–West estimators (Newey and West, 1987) to correct for heteroskedasticity and autocorrelation but results did not significantly differ from the standard OLS approach. Some parameters in the biological growth models are not statistically significant. This highlights the limitations in using an aggregated surplus production model, and other studies have reported non-significant results in similar model specifications (Salenius, 2018). However, the sign and magnitude of our coefficients appear to be reasonable when compared to similar studies (see Mulazzani and Malorgio, 2013). As our main goal in carrying out this estimation is to give an approximation of the stock growth in our profit maximization model, we include them in our analysis.

Results are reported in Table 1a. Mean, low and high indicates the set of biomass values used in the estimation. Mean values are used in the main analysis, while low and high values are used in the sensitivity analysis.

Table 1a – Statistical estimation of the growth function

		Anchovies		**Sardines**	
	Parameter	**Estimate**	**Std. error**	**Estimate**	**Std. error**
Mean	α	0.18	0.18	0.26*	0.14
	β	-2.0e-7	2.1e-7	-6.3e-7*	3.5e-7
Low	α	0.13	0.18	0.25*	0.14
	β	-1.8e-7	2.4e-7	-7.1e-7*	3.9e-7
High	α	0.25	0.18	0.24	0.14
	β	-2.2e-7	1.6e-7	-4.7e-7	3.1e-7

Signif. codes: '***' 0.01; '**' 0.05; '*' 0.1

From these results we derive the following parameters:

Table 2a – Statistical estimation of the growth function

	Parameter	Anchovies	Sardines
Mean	r	0.18	0.26
	K	886,964.9	413,382.7
Low	r	0.13	0.25
	K	688,210.7	352,834.7
High	r	0.25	0.24
	K	1,134,706.0	503,073.8

The catchability coefficient q from Eq. 2 has been estimated by species and by country using the OLS approach. Results are reported in Table 3a.

Table 3a – Statistical estimation of the harvest function

		Anchovies		Sardines	
	Parameter	**Estimate**	**Std. error**	**Estimate**	**Std. error**
Italy	q	3.3e-6***	3.3e-7	2.5e-6***	5.4e-7
Croatia	q	5.4e-6***	6.2e-7	7.6e-6***	2.5e-7
Signif. codes: '***' 0.01; '**' 0.05; '*' 0.1					

The cost coefficients c from Eq. 3 have been estimated by country using the OLS approach. Results are reported in Table 4a.

Table 4a – Statistical estimation of the cost function

	Parameter	Estimate	Std. error
Italy	c	1884.37***	59.72
Croatia	c	1134.40***	45.22
Signif. codes: '***' 0.01; '**' 0.05; '*' 0.1			

Note that both the harvest and the cost function have been estimated without intercept, as we assume that when fishing effort (days) E_t goes to zero there will be no harvests and the fleets will incur in zero costs.

Prices p are calculated using the mean ex-vessel price by species and by country. Parameters are reported in table 5a.

Table 5a – Computation of price parameters

	Parameter	**Anchovies**	**Sardines**	**Period**
Italy	p	1626.37	675.94	2016-18
Croatia	p	906.11	433.96	2018-20

Appendix B. Model specification

The model assumes two different players: Italy and Croatia (subscripts subscript i and c). It also accounts for two exploited species: sardines (subscript s) and anchovies (subscript a). For brevity, we illustrate most of the analytical steps using species a. Computations for species p are analogous and therefore omitted. We rely on the Gordon-Schaefer (1954) framework: fishing will be considered sustainable in the long-run when total harvests by species $H_a = q_{ai}B_aE_i + q_{ac}B_aE_c$ in a year do not exceed the logistic stock growth G_a in the same year, where $G_a = B_{a,t+1} - B_{a,t} + H_{a,t} = r_aB_{a,t}\left(1 - B_{a,t}/K_a\right)$. Hence, to achieve a sustainable exploitation of the fish stocks, it must be:

$$G_a = H_a \tag{1b}$$

Replacing Eq. 1 and 2 into Eq. 1b and solving for B_a we get:

$$B_a = K_a - \frac{q_{ai}K_a}{r_a}E_i - \frac{q_{ac}K_a}{r_a}E_c \tag{2b}$$

By plugging Eq. 2b into the single countries harvest equations we obtain a new specification for country i fleet $H_{ai} = q_{ai}B_aE_i = q_{ai}K_aE_i - \frac{q_{ai}^2K_a}{r_a}E_i^2 - \frac{q_{ai}q_{ac}K_a}{r_a}E_iE_c$ and equivalently for country c (not reported). We write: $H_{ai} = a_{ai}E_i - b_{ai}E_i^2 - d_aE_iE_c$ where $a_{ai} = q_{ai}K_a$, $b_{ai} = \frac{q_{ai}^2K_a}{r_a}$, and $d_a = \frac{q_{ai}q_{ac}K_a}{r_a}$. Consequently, the net profit equation for country i is:

$$\pi_i = p_{ai}(a_{ai}E_i - b_{ai}E_i^2 - d_aE_iE_c) + p_{pi}\left(a_{pi}E_i - b_{pi}E_i^2 - d_pE_iE_c\right) - c_iE_i \tag{3b}$$

And depends on revenues from species a and p landings and total costs. Note that country i profits also depend on country c effort E_c and vice versa.

Appendix C. Model derivation

In the quota scenario, for country i the maximization problem is:

$$\max\ \pi_i = p_{ai}(a_{ai}E_i - b_{ai}E_i^2 - d_a E_i E_c) + p_{pi}\left(a_{pi}E_i - b_{pi}E_i^2 - d_p E_i E_c\right) - c_i E_i$$

$$subject\ to\ H_i = (a_{ai}E_i - b_{ai}E_i^2 - d_a E_i E_c) + \left(a_{pi}E_i - b_{pi}E_i^2 - d_p E_i E_c\right) \leq TAC_i \qquad (1c)$$

where the total allowable catch limit (TAC) is established at the country level. The Lagrangian for this problem is:

$$\mathcal{L} = p_{ai}(a_{ai}E_i - b_{ai}E_i^2 - d_a E_i E_c) + p_{pi}\left(a_{pi}E_i - b_{pi}E_i^2 - d_p E_i E_c\right) - c_i E_i$$

$$-\lambda_i\left[(a_{ai}E_i - b_{ai}E_i^2 - d_a E_i E_c) + \left(a_{pi}E_i - b_{pi}E_i^2 - d_p E_i E_c\right) - TAC_i\right] \qquad (2c)$$

where λ_i is the Lagrange multiplier.

Results for country c are analogous and therefore omitted.

Appendix D. Sensitivity analysis results

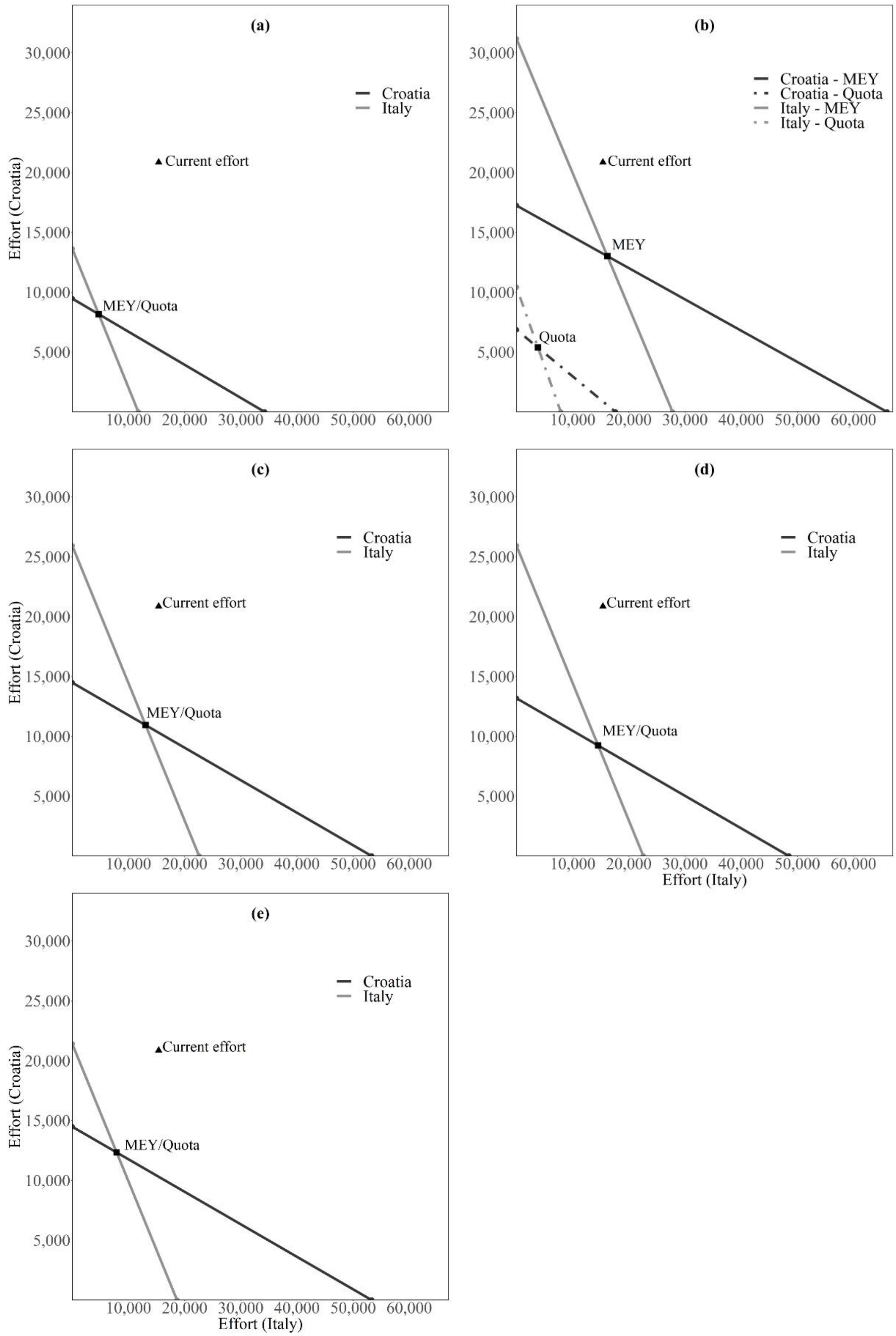

Figure 1d – Statistical estimation of the growth function

Table 1d – Optimal effort values (days) and profit margins by country

	Scenario	Policy	Effort (days)		Profit margin	
			Croatia	**Italy**	**Croatia**	**Italy**
(a)	Low biomass	MEY/Quota	8,174	4,703	0.56	0.20
(b)	High biomass	MEY	13,018	16,176	0.81	0.67
		Quota	5,384	3,811	0.67	0.44
(c)	Cost (– 40%)	MEY/Quota	10,941	13,047	0.74	0.52
(d)	Cost Italy (-40%)	MEY	9,234	14,534	0.59	0.55
(e)	Cost Croatia (-40%)	MEY/Quota	12,342.1	7,889.6	0.76	0.29

Table 2d – Optimal harvests (tons)

	Scenario	Policy	Anchovies		Sardines	
			Croatia	**Italy**	**Croatia**	**Italy**
(a)	Low biomass	MEY/Quota	16,098.8	5,635.4	15,487.7	2’892.1
(b)	High biomass	MEY	39,588.8	29,928.5	20,488.6	8,262.5
		Quota	27,503.5	11,843.7	16,189.4	3,718.9
(c)	Cost (– 40%)	MEY/Quota	22,077.7	16,018.3	19,090.9	7,388.9
(d)	Cost Italy (-40%)	MEY/Quota	19,730.8	18,894.5	17,152.1	8,761.8
(e)	Cost Croatia (-40%)	MEY/Quota	28,080.3	10,921.1	21,845.4	4,532.2

Conclusion

This thesis highlighted the economic impacts and benefits determined by current or potential policy measures in the Mediterranean Sea. More specifically, it focuses on sustainable seafood consumption to prevent discarding issues and complements this analysis with an estimation of the consequences of standard management regulations in the fisheries sector.

The concerning level of overexploitation of Mediterranean marine resources calls for immediate and appropriate action to address the issue from a decision-maker policy perspective. Multiple sources of inefficiencies can be targeted by shifting the management approach or the main policy objectives. This work provides two clear examples of how and when this shift can be acknowledged as appropriate, by considering discards at the national level and a case study on small pelagic fishing.

The discarding process is detrimental to the well-being of the ecosystem. To prevent further damage, the European Union has introduced the landing obligation which tackles the problem from the production perspective by making fishermen and fishing enterprises accountable for measuring and reducing the issue. While they are certainly depauperating the marine environment, recent research suggests that the discarding issue is mostly-demand driven.

The first chapter outlines how there is indeed more space to convey adequate information to seafood consumers to make them more willing to buy discarding products. More specifically, the results outline how the willingness to pay for the discarded species increases after consumers are provided with information on the environmental sustainability of their food choices. Multiple communication strategies can be defined to target specific socio-demographic segments of the Italian population. This section clearly outlines how complementing the landing obligation with consumption-oriented policies may enhance its effectiveness.

The second and third chapters both focus on the case of small pelagic fishing, particularly on sardines and anchovies. The combination of the two species encompasses most of the live weight of total landings in the Adriatic Sea and it is worthy of attention given the multiple and subsequent regulations that have been established to avoid their overexploitation. The recent change from effort limitation to quota management requires an in-depth analysis of the long-run economic consequences and has been analyzed from the static and dynamic perspective. In both cases, the analyzed policy target is the maximum economic yield (MEY) which is the point at which the fleet maximized its profits. The MEY choice as the preferred indicator, albeit in contrast with the declared objectives of the European Common Fishery Policy, allows for an in-depth understanding of the economic efficiency of the Adriatic small pelagic fleet under different policy circumstances and stands out as a valid alternative to the current policy objectives and goals. Both chapters account for the biological growth of sardines and anchovies as an optimization constraint or incorporating it in the objective function.

Results show that Italy and Croatia's exploitation of the small pelagic fishery is economically inefficient. A massive effort reduction in the long run particularly on the Croatian side could increase the economic benefits of both countries. The current total allowable catch limits are also set inefficiently and will need to be revised if economic efficiency is a long-term concern for decision-makers. However, the dynamic analysis of the Italian MEY illustrates how the path towards the long-run optimal equilibrium is challenging and demands an economic effort which will partially hurt the fleet in the short and medium terms depending on the efficiency of the fishing gears involved in the harvesting process. Results from the dynamic optimization highlights how the pronounced efficiency disparity among multiple fishing gears can potentially cause an unequal profit distribution among the fleet.

The main limitations of this work reside in the model specification of the growth function, which can only account for the overall biomass without distinguishing by age class. Economic and production data are not available at the individual vessel level and precludes the exploration of further policy alternatives such as transferable fishing rights. Another limitation lies in the availability of data, which have been released/obtained in different stages and were not all immediately available in previous years. This initially limited the choice of the case study in Chapter 2 to the Italian fishery. However, future research should encourage the examination of the Croatian fleet to complement and enhance the findings of this study. This would provide a more comprehensive understanding of fisheries management in the region.

Further research should also target the expansion of the current models towards the demand side, considering price fluctuations and their determinants from the market perspective. Despite these limitations, this thesis provides a detailed analysis of the current inefficiencies of fisheries management in the Mediterranean area and suggests policy alternatives aimed at improving the well-being of its marine ecosystem while also accounting for the economic benefits stemming from a sustainable exploitation of its fisheries.